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Environmental sustainability and Occupational Safety and Health in the forest energy chain for small generation systems

By

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Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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Abstract

Among the different renewable energies, there has been in recent years a great spreading of the use of wood biomass. In particular the short wood energy chain with the implementation of micro-generation plants supplied by near woods is considered a particularly sustainable solution for the production of heat. This solution, because of the limited economic resources and small size, has often management issues as regards the implementation of the best available solutions regarding the environmental sustainability and the Occupational Safety and Health. The aim of this work is the identification of a methodology to analyze the different design solutions that is exhaustive regarding the considered points of view but it is also easily applicable to small work activities and processes. This methodology is aimed both at business managers, which require an expeditious and comprehensive method of analysis, and at the local authorities, who need to be able to determine whether a territorial implementation of these solutions can be environmentally sustainable. Given the identified end user, moreover the method need to be usable and applicable also by people which do not have an in-depth knowledge in the field.

The draft version of the method have been defined by analyzing the different activities and processes composing the forest energy chain. The developed methodology of analysis was implemented by applying it to several real cases different for type, work environment, processes and work activities. The resulting methodology allows a parallel assessment of the research subject both from the points of view of Occupational Safety and Health and environmental sustainability.

The method has been applied also to a prototype plant in order to observe if it is suitable to the application in the design phase.

To validate the method, codified and recognized methodologies for the analysis of the Occupational Safety and Health and of the environmental sustainability have been applied to the same prototype plant.

The method highlighted the need of a further assessment of the cumulative impacts which can be caused by the presence of different source of emissions in the same territory. Regarding them, the results obtained with the first draft of the

method have not been considered sufficient. Therefore the method has been integrated with a further analysis. Considering atmospheric pollutant emissions, one of the factors that can cause greater alteration of the territory for the considered design hypotheses, along with the consumption of forest resources, a model for the dispersion of pollutants was applied to determine the modifications caused on the air quality. This phase of the analysis is essential in a feasibility assessment done by the local authorities.

The final identified method of analysis allows an exhaustive evaluation of the whole forest energy chain and the identification for each phase of the process of the best technological alternatives from the points of view of Occupational Safety and Health and environmental sustainability. It can be the basis of analysis to obtain quality certifications and the necessary documentation of compliance for the activities and processes carried out. According to the obtained results is possible to determine the technical interventions and the procedures to be put in place to minimize the risk for the workers and the responses to be implemented to reduce the impacts on the territory.

To meet the targeted goals of direct use by operators of the forest energy chain, a document tool has been excerpted from the developed method. It can be provided directly to private managers, as well as to local government decision-makers.

Contents

1 INTRODUCTION 15

1.1 TOPIC OF THE RESEARCH 15
1.2 AIMS OF THE RESEARCH 19
1.3 STEPS OF THE RESEARCH 21

SECTION 1: THEORY 25

2 LITERATURE REVIEW 27

2.1 WOOD BIOMASS 27
2.1.1 Chemical-physical characteristics 27
2.1.2 Origin and commercial types 30
2.2 FOREST WOOD ENERGY CHAIN 34
2.2.1 Harvesting the biomass from a forest 35
2.2.2 In-forest handling and transport 37
2.2.3 Transportation 38
2.2.4 Loading and unloading from transportation 40
2.2.5 Processing 40
2.3 ENERGY CONVERSION SYSTEMS 43
2.3.1 Primary conversion technologies 44
2.3.2 Secondary conversion technologies 52
2.3.3 Cogeneration 53
2.4 BASIC CONCEPT OF OCCUPATIONAL SAFETY AND HEALTH 54
2.5 OCCUPATIONAL SAFETY AND HEALTH OF FOREST ENERGY CHAIN 55
2.5.1 Forest yards and the Occupational Safety and Health legislation 55
2.5.2 Heating systems Occupational Safety and Health 57
2.6 BASIC CONCEPTS OF ENVIRONMENTAL SUSTAINABILITY 59
2.7 ENVIRONMENTAL SUSTAINABILITY OF FOREST ENERGY CHAIN 62
2.7.1 Forestry environmental impact 62
2.7.2 Heating systems environmental impact 63

3 METHOD DESCRIPTION 75

3.1 RESEARCH SUBJECT 76
3.2 IDENTIFICATION OF THE HAZARD FACTORS SOURCES 77
3.3 OCCUPATIONAL SAFETY AND HEALTH 79
3.4 ENVIRONMENTAL IMPACT ASSESSMENT 81
3.5 METHOD VALIDATION 84
3.5.1 Failure mode effects analysis 85
3.5.2 Job safety analysis (JSA) 86
3.5.3 Measurement of emissions 87

SECTION 2: APPLICATION OF THE METHOD 93

4 MATERIALS 95

4.1 FOREST YARDS 95
4.2 FUEL WOOD TERMINAL 102
4.3 HEATING SYSTEMS 103

5 APPLICATION OF THE METHOD TO STANDARD ACTIVITIES 107

5.1 FOREST YARDS 107
  5.1.1 Occupational risk analysis ... *111*
  5.1.2 Environmental impact assessment ... *117*
5.2 FUEL WOOD TERMINAL 123
5.3 HEATING SYSTEMS 125
5.4 CUMULATIVE IMPACTS 128

6 APPLICATION OF THE METHOD TO A PROTOTYPE PLANT 131

6.1 DESCRIPTION OF THE PROTOTYPE PLANT 131
6.2 APPLICATION OF THE METHODOLOGY TO THE PROTOTYPE PANT 135
  6.2.1 Occupational risk analysis ... *137*
  6.2.2 Environmental impact assessment ... *142*

SECTION 3: VALIDATION OF THE METHOD 151

7 VALIDATION OF THE METHOD 153

7.1 APPLICATION OF THE FMEA TO THE PROTOTYPE PLANT 155
7.2 JOB SAFETY ANALYSIS 162
  7.2.1 Loading activities of the wood chips storage tank ... *162*
  7.2.2 Loading and unloading activities of the dryer ... *165*
7.3 MEASUREMENTS OF THE EMISSIONS 168
  7.3.1 Measurements of the atmospheric emissions at the chimney ... *168*
  7.3.2 Monitoring of PM_{10} ... *168*
  7.3.3 Monitoring for noise impact assessment ... *171*

8 CUMULATIVE IMPACTS 177

8.1 DEFINITION OF THE EMISSION SCENARIOS 178
8.2 ATMOSPHERIC DISPERSION MODELING 181
8.3 SENSITIVITY ANALYSIS 187
8.4 SCENARIO WITH IMPROVED ENERGY CLASSIFICATION OF BUILDINGS 190

SECTION 4: CONCLUSIONS 195

9 FINAL RESULTS 197

9.1 CHECK LIST 198
9.2 DOCUMENT TOOL 200
  9.2.1 Example 1: Forest yards ... *200*
  9.2.3 Example 2: Fuel wood terminals ... *204*
  9.2.3 Example 3: Energy conversion systems ... *208*

10 CONCLUDING REMARKS 213

10.1 DRAFTING PROCESS OF THE PROPOSED METHOD 213
10.2 REVIEW OF THE ENVIRONMENTAL SUSTAINABILITY AND THE LAND MANAGEMENT 214
10.3 REVIEW OF THE OCCUPATIONAL SAFETY AND HEALTH 217

11 CONCLUSIONS 219

APPENDICES 221

APPENDIX 1 – EXAMPLE OF SCHEME OF THE ANALYZED SYSTEM FOR HEAT GENERATION 222

APPENDIX 2 – APPLICATION OF THE FMEA TO THE PLANT 223

APPENDIX 3 – METEOROLOGICAL DATA FOR THE PERIOD OF MEASUREMENTS 259

APPENDIX 4 – SHEETS OF NOISE MONITORING RESULTS 260

REFERENCES 267

List of tables*

Table 1.1 - Biofuel classification[4]....16
Table 1.2 - Availability of wood biomass in Europe[8]....18
Table 2.1 – Chemical composition of wood different species[32]....28
Table 2.2 – Average ash contents of different wood fuels[34]....29
Table 2.3 - Advantages and disadvantages of the main commercial types of wood fuels....33
Table 2.4 - Main combustion reactor types and characteristics[70,76]....48
Table 2.5 - Main gasifier types and characteristics[78,80]....51
Table 2.6 – Main secondary conversion technologies[70,80,81]....52
Table 2.7 – Major energy conversion technologies of biomass-fuelled CHP systems [83]....54
Table 2.8 – Solid fuel combustion (1-50 MW) EU limit values[140]....64
Table 2.9 – Solid fuel combustion plants Italian limit values[3]....65
Table 2.10 - Average concentrations of plant nutrients in usable ash mixtures depending on the biofuel used[141]....66
Table 3.1 – Example of a set of indicators defined for the description of the environmental state....83
Table 3.2 – Criteria to assign value to effect, occurrence and detection[161]....86
Table 3.3 – PM_{10} limit values for the ambient air[166]....87
Table 4.1 – Main working phases of the forestry....97
Table 5.1 - Sources of hazard for the phase of timber handling with yarder....109
Table 5.2- Sources of hazard for the phase of timber limbing and cutting with harvester....110
Table 5.3 – Occupational risk identification of the harvester....112
Table 5.4 – Occupational risk identification of the cable crane....113
Table 5.5 - Occupational risk identification of the materials....114
Table 5.6 – Occupational risk identification of the work environment....116
Table 5.7 - Occupational risk identification of the work organization....117
Table 5.8 – Pressures for the felling, limbing and cutting sub phases....119
Table 5.9 – Environmental state of the lot and the surrounding area....121
Table 5.10 – Impacts for the felling, limbing and cutting sub phases....122
Table 5.11 - Responses for the felling, limbing and cutting sub phases....123
Table 5.12 – Sources of hazard for the fuel wood terminal....124
Table 5.13 - Hazard sources for the process phases....125
Table 5.14 – Hazard sources for the fuel storage and maintenance phases....126
Table 5.15 – Main cumulative impacts of the forest energy chain....128
Table 6.1 – Sources of hazard for the prototype plant....136

Table 6.2 – Correlation matrix of the prototype plant main functions 137
Table 6.3 – Occupational risk identification of the prototype plant machinery ..138
Table 6.4 – Occupational risk identification of prototype plant materials 139
Table 6.5 - Occupational risk identification of the prototype plant work environment 140
Table 6.6 - Occupational risk identification of the prototype plant work organization 141
Table 6.7 – Pressures on the environment deriving from the prototype plant.....143
Table 6.8 – Indicators describing the state of the surrounding environment.......145
Table 6.9 – State description[183–185] 146
Table 6.10 - Impacts on the environment deriving from the prototype plant......148
Table 7.1 – Correlation matrix for forest energy chain 154
Table 7.2 – Hazard source for the forest energy chain considered in the FMEA 155
Table 7.3 – Correlation matrix of the prototype plant – Correlation matrix of the prototype plant 157
Table 7.4 - Seriousness assessment of the three criteria.....................................158
Table 7.5 – Example of FMEA application at the dryer ventilation process phase 160
Table 7.6 - Risk identification for storage tank loading operation 164
Table 7.7- Risk analysis of the storage tank loading operation...........................164
Table 7.8 - Risk identification for dryer loading operation 166
Table 7.9 - Risk analysis of the storage tank loading operation..........................167
Table 7.10 - PM_{10} concentration 171
Table 7.11 – Results of the measurements 173
Table 7.12 – Overall results of the measurements...173
Table 7.13 – Assessment results of the source contribution during the night 174
Table 7.14 - Assessment results of the source contribution during the night......175
Table 8.1 - Emission factors for wood and natural gas[189,190] 178

*The tables without references are a product of analysis done by the author

List of figures*

Figure 1.1 - 2004 and 2013 European inland consumption of renewable energy[6] 17
Figure 2.1 - Processes at the fuel wood terminal [61] 41
Figure 2.2 - Thermochemical biomass processes and their products[69]..................43
Figure 2.3 – Phases of the combustion process[73]..45
Figure 3.1 - Forest-wood-energy chain...77
Figure 3.2 – Scheme of the analytical method..79
Figure 3.3 – Description of the method for the analysis of occupational safety ...80
Figure 4.1 – Location of the forest yards...99
Figure 4.2 - Location (a) and extension (b) of the "Pera Pluc" wood lot 99
Figure 4.3 - Harvester 100
Figure 4.4 – Location (a) and extension (b) of the "Chatelard" wood lot 101
Figure 4.5 – Cable crane 102
Figure 4.6 – Location of the examined boilers 104
Figure 4.7 – Example of analyzed chips boiler 104
Figure 4.8 – Puffer 105
Figure 4.9 – Chips storage tank 106
Figure 5.1 – Chips storage (a) and screw conveyor system (b) 127
Figure 6.1 – Location of the analyzed plant 132
Figure 6.2 – Flow chart of the prototype plant 133
Figure 6.3 – Hot air generator and chips "tower" dryer 134
Figure 6.4 – Timber plank dryer...135
Figure 6.5 – Area of influence of the prototype plant 144
Figure 7.1 - Part of the plant to which the FMEA was applied 156
Figure 7.2 – RPN value before and after the interventions 161
Figure 7.3 – Daily time/operations graph for the chips tank loading activities...163
Figure 7.4 - Daily time/operations graph for the dryer loading and unloading activities 166
Figure 7.5 - Analysis of pollutant concentration in the flue gas 168
Figure 7.6 – Strumentation for the sampling of PM_{10} concentration..................169
Figure 7.7 – Location of the sampling point...170
Figure 7.8 – Positioning of the measuring point relatively to the emission source 172
Figure 8.1 - Location and power of point sources, road network, receptors and the storage place 180
Figure 8.2 - Annual concentration of PM due to emissions of traditional wood stoves 183
Figure 8.3 - Annual concentration of PM due to emissions of biomass boilers ..183

Figure 8.4 - Annual concentration of NO_X from the emissions natural gas boilers (a) and wood biomass boilers (b)..184
Figure 8.5 – Annual concentration of PM from the emissions of biomass boilers (a) and timber means of transport (b) 185
Figure 8.6 - Annual concentration of PM from the emissions of biomass boilers in the three scenarios considered: with scheduled working conditions for the whole year (a), with modulated, according to the external temperature, working conditions for the whole year (b) and switching off in the summer months (c)..186
Figure 8.7 – Average daily concentration [µg/m^3] trend for the scenarios 1 and 3 in receptors R1(a), R2(b), R3(c) and R4(d)...187
Figure 8.8 – Average daily concentration trend at varying wind speeds in correspondence of the receptor R2 188
Figure 8.9 – Average daily concentration trend at varying the height of boilers emission point in correspondence of the receptor R2...188
Figure 8.10 - January concentration of PM from the emissions of biomass boilers in Scenario 2 (a) and with increased (b) and decreased (c) of 2°C temperature input data...189
Figure 8.11 - January concentration of PM from the emissions of biomass boilers in the hypothesis of improved buildings energy performance............................191
Figure 8.12 - January concentration of PM from the emissions of biomass boilers in Scenario 2 in the hypothesis of actual buildings energy performance 191
Figure 9.1 – Development of the method and flow chart applicable for the analysis 197
Figure 10.1 – Implementation of the method of analysis 214

*The figures without references are a product of analysis done by the author

Chapter 1

Introduction

1.1 Topic of the research

In recent years there has been a growing spread of the use of renewable energy sources (solar, wind, geothermal, biomass, hydroelectric and ocean energy). Among them, a predominant role is played by biomass to produce heat and energy.

The directive on the promotion of the use of energy from renewable sources[1] defines:

- «energy from renewable sources»: energy from renewable non-fossil sources, namely wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases;

[…]

- «biomass»: the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste.

"Biomass is contemporaneous (non-fossil) and complex biogenic organic-inorganic solid product generated by natural and anthropogenic (technogenic) processes"[2], and comprises: natural constituents originated from growing land and water-based vegetation via photosynthesis or generated via animal and human food digestion; and technogenic products derived via processing of the above natural constituents[2]. More generally, the term biomass is used to define all the organic materials which can be used as solid, liquid or gaseous fuel, either directly or through a process of transformation.

The Italian legislation[3] regulating the authorization of atmospheric emissions for fuels that are not included under waste legislation states that the allowed biomass are essentially forestry or agricultural materials. Only mechanical treatment processes are allowed.

The classification of biofuels can be made following different criteria. In this discussion, the reference classification is defined by the Food and Agriculture Organization of the United Nations (FAO)[4]. It was chosen because it takes into account the different points of view that can differentiate the biofuels such as: origins, types and distinctive parameters (Table 1.1).

Table 1.1 - Biofuel classification[4]

Production side, supply	**Common groups**	**Users side, demand examples**
Direct woodfuels **Indirect woodfuels** **Recovered woodfuels** Wood-derived fuels	**Woodfuels**	Solid: **Fuelwood (wood in the rough, chips, sawdust, pellets)**, Charcoal Liquid: Black liquor, Methanol, Pyrolic oil Gases: Products from gasification and pyrolysis, gases of above fuels
Fuel crops Agricultural by-products Animal by-products Agro-industrial by-products	Agrofuels	Solid: Straw, Stalks, Husks, Bagasse, Charcoal from the above biofuels Liquid: Ethanol, Raw vegetable oil, Oil diester, Methanol, Pyrolitic oil from solid agrofuels Gases: Biogas, Producer gas, Pyrolisis gases from agrofuels
Municipal by-products	Municipal by-products	Solid: Municipal solid wastes (MSW) Liquid: Sewage sludge, Pyrolitic oil from MSW Gases: Landfill gas, Sludge gas

The biomass is the raw material with vegetable origin that starting from the reaction between the present in the air carbon dioxide, water and sunlight, through the process of photosynthesis, produces the carbohydrates that compose the biomass. The process of photosynthesis converts less than 1% of the sunlight available in stored chemical energy. If the biomass is converted efficiently, extracting the energy which is stored in the chemical bonds, the only products of the process are CO_2 and water. For this reason, the biomass energy conversion processes are considered CO_2 neutral, because during these processes only the molecules of CO_2 that were fixed during the growth process of the trees are released. This assertion is not entirely true, because the emissions due to the production, especially with regard to energy crops, and to the fuel transport phases should be considered[5].

The research subjects are the solid lignocellulosic biomass. In Table 1.1 they are highlighted with bold characters.

Figure 1.1 shows how wood biomass is the most widespread form of renewable energy in Europe and the growth in the last decade, compatible with a general growth of all the renewable energies also due at the subsidies from the EU.

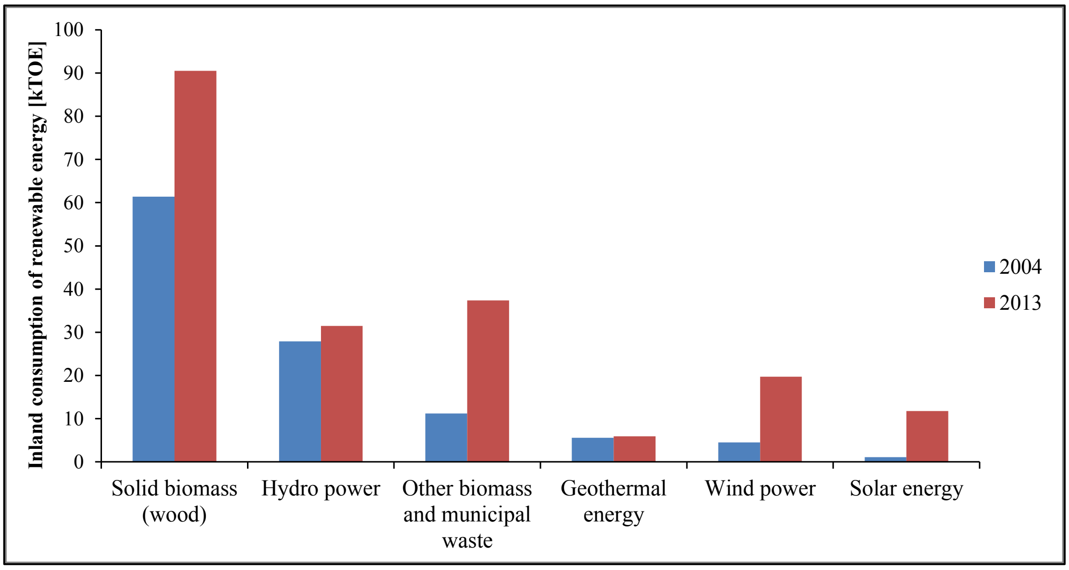

Figure 1.1 - 2004 and 2013 European inland consumption of renewable energy[6]

This spread is also due to the high availability of wood in Europe (Table 1.2), especially in the Northern states. The table shows also how the percentage of usable timber for energy purposes is very significant. The biomass resulting from conventional forestry should ensure both the demands arising from the manufacture of wood and those intended for energy purposes[7].

Table 1.2 - Availability of wood biomass in Europe[8]

Region	**Forest**			**Of which available for wood supply**	
	km^2	**% of total land**	**ha per inhabitant**	**km^2**	**% of forest land**
North Europe	708.32	53.2	2.2	552.23	78
Central-West Europe	385.82	27.6	0.1	362.9	94.1
Central-East Europe	444.94	27.1	0.3	310.19	70.4
South-Weast Europe	309.13	35	0.3	250.16	81
South-East Europe	304.46	23.5	0.3	183.91	74.1

Different studies have shown that, as a source of energy, wood biomass proves to be highly competitive if compared with fossil fuels, especially as regards domestic heating[9–11].

The wood biomass is characterized by a low energy density and an high diffusion on the territory. This determines distant from each other small areas to be harvested, with the increase of the felling and extraction costs. This problem is particularly significant in the Southern Europe states, especially with regard to the alpine areas, where the amounts of available biomass is lower than in other parts of Europe. Large heating systems are clearly not sustainable in regions where the timber availability is limited[8]. Their adoption would require the transportation of huge amount of wood fuel, which would imply relevant pollutant emissions during the phase of transport. Moreover the forest lots available for energy purpose in these areas are often very disaggregated and away from each other. Therefore the most sustainable use of wood biomass in these territories derives from small-scale projects.

Short forest-wood-energy chains are therefore strongly spreading. They are composed by reduced power plants spread across the territory, relatively close to the supply woods[12]. This solution is the most sustainable from an environmental point of view[13]. Indeed, in addition to a lower local impact on the territory, there is also a strong reduction of the transport phase and consequently of the emissions due to it[14].

This solution consists in the creation of small district heating networks consisting in low power biomass boilers (100-2000 kW). Their requirements can be guaranteed by the forest resources coming from the surrounding area. The size of these plants is significantly dependent on the local wood availability, but also by existing forest management policies. They must be designed in order to prevent excessive depletion of territories[15] and cumulative impacts. The production of wood biomass and his energetic utilization on a local scale, if realized by applying quality standards, is also an important way to develop rural areas. It is possible to achieve economic, social and environmental targets by maintaining vital these areas, braking and reversing the phenomenon of depopulation and contributing on the improvement of the quality of life. The forests have a role of paramount importance for the soil hydrogeological protection and for the preservation of the landscapes and air quality.

In order to achieve a truly sustainable solution, the goal in the constitution of the forest-wood energy chain is to differentiate the possible uses of timber in order to encourage the local economy and not cause wasting of resources. The use of wood industry by-products for energy purpose is therefore an ideal solution. In this way, wastes are reduced to the minimum and consequently the disposal costs. In this perspective, wood chipping allows to use all parts of the tree, even those that would normally be discarded, such as branches and treetops. However, in a perspective of whole supply chain it is important to allocate the higher quality timber to the wood industry.

1.2 Aims of the research

Although local wood district heating systems have clear advantages in terms of environmental sustainability, they are critical with regard to Occupational Safety and Health (OS&H) and the environmental impacts on the surrounding area. The smaller financial resources make more difficult the identification and use of the Best Available Technologies (BAT) and appropriate operating procedures to reduce the risks for the workers, the inhabitants of the territory and the environment[16].

The small businesses have more difficulties in complying with environmental legislation than large companies. Often the environmental legislation is very unspecific and targeted to reduce and prevent environmental impacts on a large scale. Thus it does not take into account specifically the Small-Medium Enterprises (SMEs)[17].

Moreover, numerous research suggest that SMEs have significant problems with regard to the OS&H[16,18,19] and the relative compliance with the regulatory obligations . Agriculture, construction and wood industry are among the sectors in which this problem is more present. The main reasons are generally the low human and economic resources. Concurrent causes can be due to the work organization and the used technology[20].

For the management of these systems, quality labeling of such devices, as well of the fuel they use, have been developed at national and international[21–23] level.

Some European countries are active in the respective national and regional regulations and equivalent quality labels. In most countries, however, either these regulations are inexistent or the countries have decided to wait for common EU regulations, standards and quality labels for biomass heating systems and for biomass fuels[9]. Governmental regulations are necessary in order to ensure a safe, environmental friendly and healthy operation of the boilers by requiring the manufacturers to optimize the performance of theirs products. There is, however, the need of a methodology which allows to cover all this aspects and considers also whose not comprise in the legislation.

The fields which are subject of this research are covered also by management systems. The management standards cover a wide range of aspects of business activity, such as quality management[24], environmental management[25,26], the prevention of occupational hazards and the provision of health and safety regulation in the workplace[27] and corporate social responsibility. These standards generally use quite similar methodology with regard to their creation, structure, implementation process and monitoring by a third party[28]. "The implementation of such methods has different benefits both internal and external"[29]. However, small activities and processes often found that more resources than expected, in terms of costs, time and skills were required for the implementation of management systems. The main issues for SMEs are the cost of the certification and validation process and finding a specialist and dedicated staff to implement the management systems. All these factors cause a diffuse lack of implementation of management systems in the short forest energy chain and in the energy conversion systems. Therefore, while being clear the positive advantage of the management systems regarding the OS&H and environmental sustainability, these methods are rarely implemented in small activities and processes.

It is therefore evident how in plants of small size and in theirs supply chain ensuring the conditions of Occupational Safety and Health and environmental sustainability is not an easily attainable goal. This need has also been recognized at the ministerial level, as it is the subject of a doctoral fellowships for the Ministerial project "Fondo per il sostegno dei giovani 2012". This Ph.D. project aims to avoid the contrast between the best choice for environmental sustainability and the difficulty to control Occupational Safety and Health of small plants of distributed energy, carrying out an analysis of the existing solutions, studying solutions dedicated and capable in order to reach the design stage with efficiency improvements from a technical and procedural point of view.

This doctoral project is the object of the present discussion. To ensure these objectives, the need arose to develop a method of analysis that can be applied by the plants and activities managers that could not have extensive knowledge in the field of OS&H and environmental sustainability. Furthermore, this methodology should also take into account the needs of local authorities of a method for assessing the compatibility of the proposed solutions with the territory. It should allow to identify the risks for the safety of workers and the potential impacts on the surrounding environment. According to the obtained results, the identification of the most appropriate technologies and procedures applicable to each case should be possible. The existing methods do not provide for the simultaneous assessment of both aspects.

The research which has been carried in this thesis has therefore a dual purpose:

- analyze the forest-wood-energy chain from the points of view of OS&H and environmental impact to assess the risks for the workers and the environment by identifying the best technologies and the most suitable operating procedures;
- identify a methodology for expeditious analysis, suitable to be applied to small business activities and plants.

1.3 Steps of the research

During these three years a method of analysis, that was applicable to small systems or activities but which, however, would allow a comprehensive assessment, has been developed. It has been applied, in order to determine the need of implementation or variation, to different case studies by type, location and significant criticalities.

The first phase of the research project consisted in an analysis of the forest-wood-energy chain, through the examination of the literature on the topic and through observation of case studies. The scope was to identify for each phase of the forest energy chain the main work activities and processes and the procedures and technologies through which they can be carried out. This preliminary analysis allowed to identify the critical issues from an environmental sustainability and OS&H perspective that must be addressed in the design and management of the supply chain. According to the gathered information for each process phase, the most significant technologies have been identified both from the point of view of greater spread and for the significance according to the project objectives.

The objective of the analysis is a comprehensive evaluation of different design choices in order to have an overview of the scenarios analyzed and identify the possible sources of hazard.

To do so, in a second phase of the research, a methodology that enables parallel analysis of the scenarios from the points of view of OS&H and environmental sustainability has been developed and applied. The methodology allows to take into account the various problems that may result from the use of different technologies and operative procedures. The aim is a methodology that can be used not only by experts but also by the workers in the wood biomass sector. The methodology had to be therefore expeditious and easy to implement. The implemented methodology especially as regards the Occupational Safety and Health can be a starting point in the fulfillment of legal obligations.

The methodology has been implemented through the application to real cases, both standard activities and prototype plant. In this way, the necessary integrations of the method have been identified in order to take into account all the aspect needed for a complete analysis. Once the method has been defined, it has been validated in order to observe its consistency with the aims of the research. To fulfill this need, standard method has been identified. They have been applied in parallel with the developed method to the same research subjects in order to observe if the results are consistent.

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Section 1: Theory

Chapter 2

Literature review

2.1 Wood biomass

2.1.1 Chemical-physical characteristics

The lignocellulosic biomass includes all plant, herbaceous and wood species, whose structure is made up of lignin, cellulose, hemicellulose, extractives and minerals[30].

Cellulose is a natural polysaccharide whose general formula is $(C_6H_{10}O_5)_n$. It is the main structural component of wood (50% of the wood dry weight), it has a support function and it grants mechanical resistance to the plant structure. Hemicellulose is a polysaccharide complex that is placed coupled with the cellulose in the cell walls. It has the function of lignified plant parts cementing substance. Hemicellulose constitutes between 10% and 30% of the wood. Lignin is a complex natural molecule made up of several units of phenylpropane. It guarantees the structural integrity of the plants. It facilitates the combustion process because it possesses a high calorific value. It is present inside the wood in percentages ranging from 20% to 30%. Extractives includes simple sugars, fats, waxes, rubbers, pectins, terpenes, resins, mono-unsaturated. They have an high calorific value. They are so defined because they can be extracted through chemical or physical processes[31]. The minerals are inorganic elements such as nitrogen, sulfur, chlorine and heavy metals (magnesium, sodium, potassium). These minerals are found almost unchanged after the combustion in the ashes.

These components are present in different amounts in the different species of wood. Table 2.1 shows their quantities for deciduous and coniferous trees, together with the corresponding energy content values.

Table 2.1 – Chemical composition of wood different species[32]

	Cellulose (%)	**Hemi-cellulose (%)**	**Lignin (%)**	**Extractives (%)**	**Minerals (%)**	**Heating value (MJ/kg)**
Heating value for the component (MJ/kg)	16	15	25	32	0	
Hardwood	43-50	20-25	16-25	2-8	0.2-0.8	18.5-19.5
Softwood	35-44	25-30	27-33	1-5	0.2-0.4	19-20.5

The main features of biomass for the purpose of using them for energy production are: moisture, ashes, fixed carbon, volatile matter, calorific value, density, bulk density, energy density and size.

Moisture

The water that is present in wood can be defined as water content and/or humidity. Water content expresses the mass of water in the entire moist biomass. This measure is used in the wood fuels trade. Wood humidity expresses the mass of water present in relation to the mass of oven-dry wood. This values describes the ratio of water mass to dry mass. The biomass water content can be intrinsic, linked to the structure of the biomass itself, and extrinsic, induced by external environmental and meteorological conditions.

Moisture assumes a meaningful importance during the combustion processes, in addition to its influence on the chemical characteristics of the wood and its specific weight. The water content presents within the wood varies depending on the species, age, different part of the plant and the harvesting year season. The wood basic density, the ratio between dry and wet mass, varies between 0.3 and 0.7 kg/m^3 according to the seasonal conditions, the species, age, the part of the plant, the form of wood governance and management[33].

Ashes

The ashes are a mixture of mineral elements and unburned organic components. They are formed from the inorganic material (salts and minerals) of the wood biomass. Table 2.2 shows the ash content for the main types of wood fuels.

Table 2.2 – Average ash contents of different wood fuels[34]

Wood fuel	Ash content in dry matter [%]
Chopped firewood	1.2
Whole tree chips, pine	0.6
Whole tree chips, mixed species	0.5
Birch chips	0.4-0.6
Forest residue chips	1.3
Stump chips	0.5
Sawdust, with bark	1.1
Sawdust, pine, without bark	0.08
Cutter chips	0.4
Pine bark	1.7
Spruce bark	2.3-2.8
Birch bark	1.6

The oxidized form of the main components of the timber comprises the main fraction of ash (85-95%). They are also constituted by the so-called unburned that are composed of organic matter (cellulose) that has undergone only a partial combustion. Specifically, the ash content changes according to the type of plant and its considered parts. The content and, above all, the characteristics of the ash also change depending on the soil conditions, the heavy metal deposit and the used fertilizer.

Fixed carbon

It is the carbon fraction that does not volatilize during the heating phase and which is oxidized by way of heterogeneous reactions

Volatile matter

It is the fraction of biomass, consisting primarily of carbon, hydrogen and oxygen and of fractions containing nitrogen and sulfur, which volatilizes during the heating and volatilization phases by passing to a gaseous state. A percentage from 70% to 80% by weight of wood biomass dry matter consists of volatile matter.

Calorific value

The calorific value of the fuel is the maximum thermal energy that can be developed by its complete oxidation under adiabatic conditions and with the products reported at the process initial temperature. It decreases with the increasing of the water content present in it. For this reason there are two types of heating value:

- Higher heating value (HHV) is the total energy content released when the fuel is burnt in air, including the contained in the water vapor latent heat and therefore it represents the maximum amount of energy which is potentially recoverable from a given biomass source[35].

- Lower heating value (LHV) is the energy released during the combustion taking into account that the water content is already considered in a steam state.

The calorific value of the biomass is significantly lower than that of fossil fuels. If referred to the unit of weight, the wood calorific value scarcely varies in different species, with the same water content. The anhydride wood average calorific value amounts to 18.5 MJ/kg. There are slight calorific value differences between diverse species. They are due to the different composition of the wood[36].

Bulk density and apparent density

The apparent density is the ratio between the mass and the volume of a material. Given the wood biomass high presence of voids, which can vary greatly in the different commercial types, this value is critical, especially as regards the assessment of the most suitable transport mode.

Energy density

The energy density of a fuel is measured as the ratio of its lower calorific value and the apparent density. This parameter affects both the logistical of the biomass transport and storage, as well as the supply management to the energy conversion systems.

Size

The size of the biomass influences the energy conversion process, but also the choice of the most suitable storage, power supply and pretreatment systems. It is strictly relates to the commercial type.

2.1.2 Origin and commercial types

The available sources for lignocellulosic biomasses include forests, short rotation coppice (SRC), short rotation forestry (SRF), young stands of conifers, deciduous hardwood forests, road windbreak, urban parks-originated trees, residues originated from agricultural activities related to wood crops, solid wood industry, other (than sawmill) wood industries, municipal solid wood wastes, construction and demolition wood wastes[32].

The technical standard[37] distinguishes the wood biomasses according to their origin:

- forest, plantation, and other virgin wood (whole tree with and without roots, stem wood, logging residues, bark from forestry operations, segregated wood from gardens, parks, roadside maintenance, vineyards, fruit orchards, driftwood from fresh water). They may only be subjected to size reduction, debarking, drying or wetting.

- by-products and residues from wood processing industry (chemically untreated or treated wood by-products, residues, wood constituents). They cannot contain heavy metals or halogenated organic compounds.
- used wood (chemically untreated or treated used wood). It shall not contain heavy metals more than in virgin wood or halogenated organic compounds as a result of treatment with wood preservatives or coating.
- blends and mixtures.

The main biomass sizes which can arrive at the user are:

- *Firewood*: Cut and split oven-ready fuelwood used in household wood burning appliances like stoves, fireplaces and central heating systems[38]. The technical standard defines with this term only the firewood deriving from the following raw materials: whole trees without roots, wood residues not chemically treated, logs and prunings. Its size depends strictly by the power or heating installation in which it will be used. The woodcutting and splitting can occur at the forest, in specific process squares or at the final destination (the energy conversion itself). The wood logs represent the traditional form of use for energy purposes in applications ranging from traditional stoves to modern boilers.
- *Chips*: Chipped wood biomass consists of pieces with a defined particle size produced by mechanical treatment with sharp tools such as knives. Wood chips have a subrectangular shape with a typical length of 5 mm to 50 mm and a low thickness compared to other dimensions[39]. The technical standard only applies to wood chips obtained from the following raw materials: wood, plantation or other virgin wood, products and residues of wood processing, from recycled wood not treated chemically. The chips can be green (when there are also the leaves), brown (if branches and logs with bark are chipped) and white (if the timber has been previously debarked). Chips size depends from typology of the used chipper and the setting of the cutting devices. Chips homogeneity is the most important feature for this kind of wood fuel. The presence of inhomogeneous chips can cause blockages in the supply systems of the plants. There is a difference between wood chips and flakes. Wood flakes are composed by different size and shape pieces. Compared to chips they may contain higher proportions of fine fractions and size classes which averagely contain greater length flakes.

- *Pellets*: Densified biofuel from woody biomass with or without additives usually with a cylindrical form, random length (typically 5 to 40 mm) and diameter up to 25 mm and brokend ends[40]. The standard only applies to wood pellets made from the following raw materials: wood, plantation or other virgin wood, products and residues from the wood processing, from recycled wood. The standard does not include the wood resulting from demolition of buildings or installations of civil engineering, nor that from heating treatment through torrefaction system, consisting of a mild pretreatment of biomass at a temperature comprised between 200 °C and 300 °C. This fuel is characterized by low moisture, high density and material regularity. Pellets used for energetic purposes are classified for their origin, raw material source and their chemical-physical characteristics or rather the content of additives. The last should be added in small amounts so as not to increase the ash content.
- *Briquettes*: Densified biofuel made with or without additives in form of cubiform, prismatic or cylindrical unit with diameter of more than 25 mm produced by compressing milled biomass[41]. The standard refers to the wooden briquettes made from the following raw materials: wood, plantation or other virgin wood, products and residues from the wood processing, from recycled wood not chemically treated. The standard does not include the wood resulting from demolition of buildings or installations of civil engineering, nor that from heating treatment by means of torrefaction system, consisting of a mild pretreatment of biomass at a temperature comprised between 200 °C and 300 °C.

All the different described commercial types can have advantages and disadvantages for the end-user (Table 2.3).

Table 2.3 - Advantages and disadvantages of the main commercial types of wood fuels

Commercial types	Advantages	Disadvantages
Firewood	Easy to find on the market Lower costs compared to densified fuel wood Easy outside stacking	Difficulty in automation of the boiler loading Poor efficiency of energy equipment using this type of fuel Need for a suitable storage place High need for cleaning and removal of produced during combustion ash
Chips	Completely automatic boiler loading Lower purchase price Economic and environmental benefits due to the use of wood normally not managed	High purchasing cost of the silo supply system Complex supply chain Increased need for ash cleaning and disposal operations Fermentation hazard of wet wood chips Need for a suitable storage place
Pellet /briquettes	Easy storage High automation and low need for boilers cleaning and maintenance Combustion reliability thanks to high product homogeneity Easy to supply for the consumer	More high prices Difficulty to have guarantees on the products origins and contents High energy consumption of the processing operations

Along the supply chain, the solid biofuels shall be characterized by the following parameters: origin and source, size, moisture, mechanical durability, presence of wood dust in the package, ashes, presence of binding agents, lower calorific value, bulk density , presence of particular chemical elements (nitrogen, sulfur, chlorine, arsenic, cadmium, chromium, copper, lead, mercury, nickel and zinc).

The available wood biomass commercial assortments for the production of heat and energy are numerous. Wood chipping is the option with higher diffusion in recent years. Indeed, chips can be obtained easily and they do not require additional treatments, such as densification process or additional energy for drying. This results in lower energy consumption and environmental impacts. In addition, the chips have a lower ash content and they provide better combustion conditions than the firewood, thanks to the larger contact area. Regarding the comparison with pellets, they usually arrive from Eastern Europe countries with high emissions deriving from the transport phase. Moreover, the higher number of intermediate production processes for the pellets compared to wood chips determines a greater environmental impact also from the point of view of Life Cycle Analysis (LCA). However, pellets are still ranked first in the wood biomass market[42].

2.2 Forest wood energy chain

The research subjects, as mentioned before, are small size wood biomass systems. They are supplied by the timber that is present in the surrounding area through the realization of a short wood-energy supply chain and they are localized on the territory.

Four basic criteria for the definition of the concept of short chain can be identified[13]: geographical proximity between producers and consumers, ability to produce added value and profits on local scale, social equity and balanced redistribution of the value along the supply chain, environmental sustainability. As for biofuels[43], the supply chain must comply with sustainability criteria so that the energy from these products can contribute to the achievement of national targets on renewable energies. Moreover, different initiatives to provide guarantees of the supply chain sustainability and transparency towards the market are spreading for forest wood biomass.

Criteria and indicators for sustainable forest management have been developed since the adoption of “Statement of principles for the sustainable management of forests”[44] during Rio de Janeiro Earth Summit. The goals of Sustainable Forest Management were defined as “stewardship and use of forests and forest land in a way and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological economic and social functions, at local, national and global levels and that does not cause damage to other ecosystems”[45]. Different criteria and indicators have been adopted to promote Sustainable Forest Management (SFM) and facilitate the assessment of progress towards it. Seven globally applicable criteria for the SFM can be find: extent of forest resources, forest health and vitality, productive functions of forests, biological diversity, protective function of forests, socio-economic benefits and needs, legal policy and institutional framework[46].

To ensure compliance with these criteria, there is a growing need to certify forest products in order to trace the supply chain from forest to the end-user. “Chain of custody” certification has a growing influence in the forest products market. Currently there are ten certification processes that define criteria for SFM[47]. Globally the most widespread forest certifications are the Forest Stewardship Council (FSC)[48] and the Programme for the Endorsement of Forest Certification (PEFC)[49]. Currently almost all forests are certified to one of these two schemes. Both of them allow sustainable forest management and product traceability along the supply chain. The PEFC and FSC logo ensures consumers that the purchased wood comes from forests managed on a sustainable basis.

In compliance with the criteria defining the short chain (ability to generate added value and profits on local scale), it must be designed and built so as to encourage local economic development. With this objective, a truly sustainable supply chain must focus not only on using all the available resources, through the chipping of forest residues, but also to differentiate when possible potential uses. For this reason the highest quality timber is destined to the timber industry. It will not be the subject of analysis in this study, falling outside the purpose of this work, but it is considered part of the supply chain. The wood processing by-products can indeed be used for energetic purposes (i.e. pellets).

The main activities required to supply biomass from its collecting point to a power plant[50] are the following: harvesting the biomass from a forest, in-forest handling and transport, loading of and unloading from transportation, transportation, storage, processing.

2.2.1 Harvesting the biomass from a forest

Silvicultural systems are defined as "the process by which crops constituting a forest are tended, removed, and replaced by new crops, resulting in the production of stands of distinctive form"[51].

The silviculture is the science that studies the implant, the cultivation and exploitation of forests, in order to sustainably manage forest complexes. Strictly speaking, forestry includes the set of measures that allow the exploitation of the forests guaranteeing their renewability. The government of a forest is the way in which the latter is renewed and it depends on the type of plant propagation. There are usually two distinct forest management modes: high forest and coppice. A third option is the composed coppice in which along with the coppice plants, few hundred tall plants per ha also grow.

Coppice is a forest in which the renewal of the plants after the cutting takes place with root suckers (new stems), arising from present on the stump buds. In the high forests the renewal of tree species occurs from the germination of the seeds that the plants produce.

The forms of forest governance influence the procedures for treatment of the same or those followed during the cutting.

Regarding the high forests close-cropped cuts (contemporary plants are felled at the same time), following cuts (plants with the same age are cut down in several steps over a period of renewal that can have variable duration and it occurs naturally) and occasional cuts (the plants are cut when they reach maturity) can be made.

For coppice there are the following types of treatments: stump (the plants are periodically cut very close to the ground), topping (cutting is performed at a certain height above the ground) and “sgamollo” (side branches are cut, while the covered with vegetation apical stretch remains).

There are three main working systems in forest harvesting:

- Cut-to-length or Short Wood System (S.W.S.), the felled tree is set up at the stump and it is extracted from the forest already sectioned. It is the traditional work system.
- Tree Length System (T.L.S.), the delimbed stems are extracted then cut at the stump site. This system is used to better exploit the payload of powerful extraction means of transport and when the extraction does not present difficulty.
- Full-tree harvesting or Full Tree System (F.T.S.), the trees are extracted whole, before proceeding to limbing and cutting them at the landing. This system of working is used when even the prunings are harvested, whether the land should also be cleared or when using the whole plant to produce wood chips.

The used techniques and equipment depend mainly on some key features such as the slope of the lot, the height, type and quantity of plants to cut and to handle and the future uses of timber.

The removal of roots and stumps is part of the timber harvesting stage. The purpose of the stump removal is not only to gain more available biofuel, but it is also useful for silvicultural reasons[52]. The roots removal allows to increase the quantity of available as fuel timber and it improves the conditions of the site for future use. However, this practice can result in environmental impacts such as reduction of forest soil carbon storage, removal of organic matter, loss of habitat for microorganisms and it increases soil erosion and compaction[53]. This activity is rarely performed for both the high environmental impacts and the high extraction costs.

The harvesting phase is generally further divided into trees felling and processing phases.

Felling means the trees cutting and their knockdown. Trees processing includes all the following work phases which get ready the tree for the transport phase:

- delimbing, consists in cutting branches and tree tops and the prunings preparation or rather their sawing in ready for use set;

- cutting or sawing, the stem is divided into different size assortments according to the future use;
- debarking, it is the total or partial bark removal.

Generally, a difference is made according to whether the felling is done manually, with a chain saw, or with harvester machines.

2.2.2 In-forest handling and transport

The phase of transport within the forest yards are generally divided into concentration and extraction.

The term concentration indicates the timber handling phases which move the plant from the felling point to the extraction point. The techniques for timber concentration are: dragging with animals, tractors with winch or for gravity.

The extraction operations are performed along specially equipped paths, the paths or ways of extraction, through which the material gathered in loads is brought to the landing, the loading point of the vehicles for the transport. The extraction way can be permanent (dragging way or gravity path) or temporary (through cable crane or metal or polyethylene logway). The distance of extraction are usually around one hundred meters.

The main extraction techniques are by gravity, with pack animals, dragging with tractors, with tractor and trailer, with carrier tractor, with cable crane or with helicopter. The choice of the most suitable technique to extract the timber depends on several factors which will be addressed in more detail hereinafter.

The work phases which cannot be done at the stump for their high mechanization take place at the landing.

The main activities which are done at the landing are:

- *Chipping.* This work phase can be done both at the landing and at the fuel wood terminal. It will be therefore better described hereinafter. Chipping can be performed in industrial facilities, but since handling and transport of material of small dimensions are very expensive, in some case can be more convenient the chipping at the landing. Certain types of chipper are able to chip whole stems. In this case the stages of timber limbing and cutting are eliminated, allowing to reduce the processing time and relative costs.
- *Debarking with machines.* The most sustainable solution is barking on the stump, because in this way most of the useful for the soil minerals are left in the forest. However this solution involves too high costs given the difficulties of mechanizing this operation. The generally implemented alternative is, therefore, barking at the landing or in the primary processing

industries. By using movable barkers at the landing, the wood shall be extracted with bark, the place for the landing site should be large enough for the processing operations and the movement of the timber is complex regarding the organization of machines and workers.

- *Bundling.* It is a technology used to create a compressed and uniform handling unit from logging residues and other small size energy wood[54].

2.2.3 Transportation

The transport of wood is a stage that significantly influences the convenience and sustainability of the wood energy chain. Transport includes the movement of the raw material from the place of harvesting to their final use and it can be divided into different steps.

The procedures and distances that characterize the harvested biomass transport are a decisive economic and logistic factor in the choice of the transport system. This is mainly due to the geographical dispersion of the timber, which comes from different and far between places. It is then concentrated at service areas intended for storage and processing (fuel wood terminal) or it is directly used as fuel. The distance of timber transport, the timing of journeys, the type and the number of used means of transport are parameters which impact heavily on the organization and the costs of the whole chain.

Road transport is generally considered the most suitable transport way for short distances, under 100 km. Moreover, small and different forest lots require more flexibility in order to reach them[55]. Therefore, given the research subject of the present work (short supply chain), only this method of transport will be considered, excluding the transport by train or ship.

The choice of the methods to be used depends on the characteristics of the road (width and slope) and the volume and size of the wood to be transported.

The wood may be moved from the forest site to the next processing steps in the following assortments: residues of silvicultural activities, small trunks or whole trees, roots and stumps, bundles or wood chips[56]. The disadvantage of forest residues or chips transporting is the low density which does not allow to reach a cost-effective load[57]. Transporting whole material to the fuel wood terminal allows the use of stationary chippers, more economically convenient than those used at the landing. For shorter than 40 km distances, it is cheaper than chips transport[58]. Whole trees transport appears to be comparable with the transport of forest residues, with a not significantly higher density. In the “tree section method”, stems are transported with attached branches to the pulp mills where the branches are separated to be used for energetic purposes[59]. Stumps and roots are usually chipped at the fuel wood terminal by stationary chippers. Special trucks are needed for their transport and to be cost-effective the distances have to be short[60].

The timber may be handled in the various commercial forms previously described.

Generally, if possible, the better choice is to carry the entire round wood, because of its higher density, compared to the wood chips. The transportable load depends on numerous factors, among which the main one is the load capacity of the vehicle, which normally varies between 3 and 30 t. In case of wood chips, the volumetric capacity of the vehicle must also be considered, particularly important when the material to be moved is lightweight.

The type of material to be transported, in particular its steric density, determines the ability to use the maximum capacity of the vehicle. The stacked density is the ratio between the overall dimensions and the weight of the product. It increases with the size of individual pieces and their regularity. Another important parameter in the choice of the most suitable mean of transport is the critical density. It is an ideal load density which allows the simultaneous use of the entire payload and the entire volumetric capacity of the vehicle. The bulk density of the transported material depends on the wood species, specific density, particle size distribution, particle shapes and orientation, moisture content and the applied pressure when loaded[56].

The usable means of transport are:

- Agricultural tractor and trailer (3-8 t). Generally it is used for the handling of the biomass on short journeys. The loading bed mounted on the trailer is usually soft-top or equipped with devices to download the transported material. It is suitable for the transport of all the main wood biomass commercial types.
- Truck (10-13 t).
- Container truck (9-12 t). This solution is generally used for the transport of the wood chips with the use of multiple containers to reduce the time between two loads.
- Tractor trailer (20-26 t).
- Car (100-200 kg). It is used to transport small amount of wood.

The different wood commercial forms can be transported:

- Unpackaged on trucks or tractors trailer (not suitable for briquettes).
- In individual bag on cars or trucks (briquettes and pellets).
- In bag on pallet with trucks (briquettes and pellets).
- On pallet with trucks or tractors trailers (briquettes and firewood).

2.2.4 Loading and unloading from transportation

At the landing the extracted timber is loaded on the means of transport to reach the end-user or the primary processing industries. This phase takes place at the forest yard and at the end-user, but also in the possible halfway process phases. The loading and unloading can be done in different ways according to the wood biomass typologies:

- Various size wood. The displacement can take place via forestry pliers mounted on the means of transport themself, by gravity, through soft-tops unloading systems.
- Wood logs. They can be downloaded from the means of transport manually, with mechanical lifting equipment mounted on the vehicle of transport itself, by gravity, through soft-tops unloading systems.
- Briquettes. Usually they are packed in bags sold individually or in bags on pallets. They can be downloaded from the means of transport manually, with mechanical lifting equipment mounted on the vehicle of transport itself, by gravity, through soft-tops unloading systems.
- Pellets. Usually they are conferred in bags, in big bags, in bags on pallets or unpackaged. If the material is conferred packaged on pallets using articulated lorries with opening sides, the downloading takes place through forklift. For unpackaged pellets trucks with folding platform, articulated lorries with sliding loading bed, road tankers with pneumatic conveying systems and trucks with screws are generally used.
- Chips. They are transported with trucks with folding platform, articulated lorries with sliding loading bed, road tankers with pneumatic conveying systems and trucks with screws are generally used.

2.2.5 Processing

The step of processing in the different trade assortments can take place either at the landing or at the fuel wood terminal.

The process phase at the fuel wood terminal includes all available intermediate stages from the timber delivery to the energetic conversion. Figure 2.1 differentiates between essential (always carried out) and optional processes.

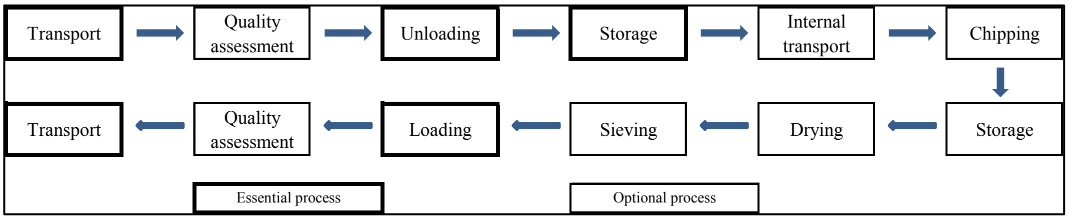

Figure 2.1 - Processes at the fuel wood terminal [61]

The main function of the fuel wood terminal is to offset seasonal fluctuations in supply and demand of timber[62,63]. The seasonal nature of both and the subsequent maximum quantity of stored in a certain period of the year timber determines the optimum capacity of the collecting square[62]. The storage, correctly performed, also offers the advantage of increasing the calorific value through the natural drying although with losses due to the deterioration of dry material.

Storage

The wood biomass systems require a fuel storage to ensure continuous operation, due to the absence of a direct network of fuel supply[50]. The biomass is stored in deposits from which it must be extracted with a manual intervention, or, if unpackaged, in silos from where it is automatically transported to the supply line of the heating generator or the gasifier.

The deposit is a structure for the containment of both packaged and unpackaged biomass. It is not equipped with mechanized handling systems. The fuel is transferred to the deposit with various means of transport, and from there it is moved, manually or by handling systems (wheel loader, pneumatic system, etc.), to the silo or directly to the heat generator or the gasifier. The deposit can be covered (usually constructed of masonry or wood, as a shed or a barn and usually it is on the ground floor) or outside (usually as pile or heap, left outdoors and possibly protected by a breathable fabric).

The silo is a structure for the containment of unpackaged wood biomass and it is equipped with automatic extraction systems. Depending on its size and location different types of materials can be used in its construction: stone, wood, steel, plastic, fabric. It can have extremely variable dimensions and be placed at ground level, buried or lifted. For the automatic extraction of unpackaged biomass from the silo, there are: pneumatic systems (for pellets), flexible and rigid screw conveyors (for pellets and wood chips), flexible and rotating leaf springs (for chips with homogeneous characteristics) and hydraulic rakes.

Drying

The drying process can be natural or artificial. The natural drying process is regulated by solar and convective drying and it occurs mainly during the storage period. For this reason, the storage and drying place have to be located in sunny and airy areas. The process is regulated by air and soil moisture and temperature, solar radiation and ventilation[62]. These parameters are closely related to seasonal and climatic conditions and therefore they are difficult to predict and program.

Chipping

In designing the operations of chipping at the fuel wood terminal, the proximity of residential areas should be considered regarding the noise and dust produced during the activities. Usually the chipping at the fuel wood terminal is more economically convenient[64]. The productivity of the different chippers can vary from a few m^3 to 200 m^3 per hour.

Sieving

The sieving process is conducted mainly for gasification plants and it has substantially two different aims:

- separate from the supply flow rate foreign materials of coarse size (stones, rocks, pieces of metal, etc.);
- eliminate the finest fraction (<1mm) of the input material, often also comprising inorganic particles (sand, soil, etc.).

Particularly with regard to the second aspect, this operation is important for the proper management of gasification plants, in particular in the case of fixed-bed gasifiers. A maximum percentage of fine (<1 mm) in the starting fuel between 2% and 5% is indicated to provide at the most reliable configurations.

The major operational difficulties arising from supply biomass with high percentages of fine mainly concern the correct functioning of the fuel supply systems and the ash discharge systems.

Sifters and rotating drums are used to sieve the biomass.

Pelletizing

The moisture content of the raw material which can become pellets should be in the range of 12-17% wet basis[65]. The raw material coming from the storage area, where it is subject to a partial reduction of the moisture content by the action of the surrounding air, is first purified by heavy contaminant (rock metal and other foreign material), chipped, dried (when required) up to a final mixture content lower than 10% and finally ground by a hammer mill[66]. The particles are then fed by a conveyor to a mill where the pellets are made by the action exerted by a number of rollers on a perforated matrix. As a consequence of this extrusion process, the pellets are very hot (90-100°C) and, in order to avoid fire, they are immediately air quenched down to 25°C. In order to obtain the commercial product, the residual fines have to be separated and re-circulated back to the pelleting process. Dust free pellets are addressed to the storage silos or to the automatic packaging and storage area. Usually, the energy required by the dryer is produced by using part of the same raw material used to feed the phase of pelletizing of the process in order to improve both economic and energetic balances and to operate coherently with the sustainable development principles.

2.3 Energy conversion systems

The primary processes of energetic biomass conversion can be divided into three main categories: thermo-chemical, biological and physical-chemical. The selection process is made according to: properties of the biomass, forms of final energy, amount of biomass, economic conditions, environmental standards and other design-specific factors[67].

The main properties that influence the energy conversion process are: moisture, calorific value, fixed carbon/volatile matter ratio, carbon residue/ashes ratio, the alkali metal content and cellulose/lignin[35].

The parameters that most influence the choice of the biomass energy conversion processes are the moisture content and the ratio between carbon and nitrogen. Wood biomass are generally considered non-fermentable, given their low moisture content, and therefore cannot be completely decomposed by biological process, so they mostly undergo thermochemical processes[68] (Figure 2.2).

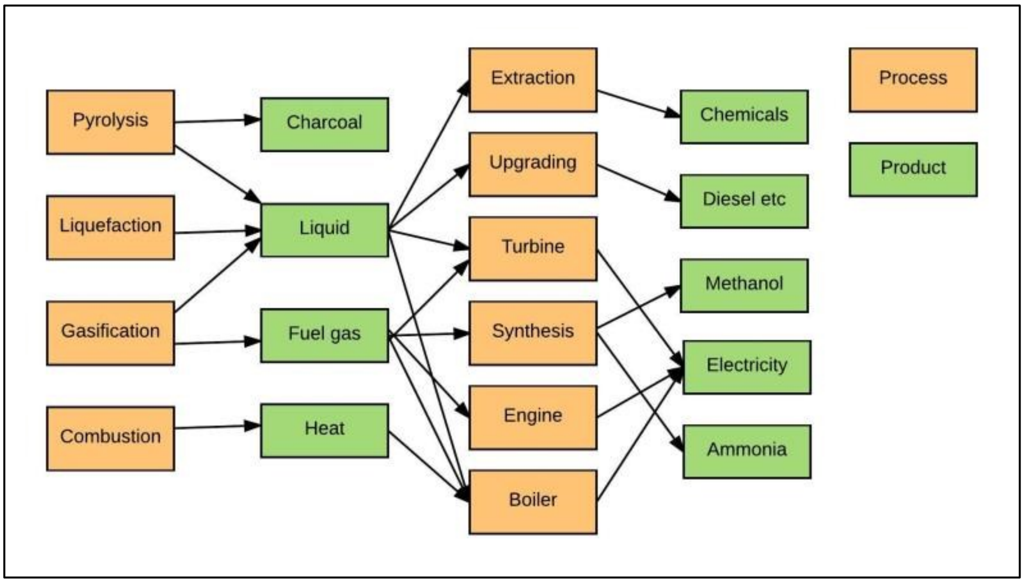

Figure 2.2 - Thermochemical biomass processes and their products[69]

The thermochemical conversion of woody biomass into another form of energy usable for the production of electricity and heat can be done basically in two ways (primary conversion processes): combustion and gasification. The aim of the pyrolysis, the third primary conversion process, is the production of a transportation fuel due to the maximization of liquid fraction in the process. Since nowadays there are no commercial plants for electricity production base on this process[70], pyrolysis is omitted in the present analysis.

These primary conversion technologies are coupled with secondary conversion technologies reliable for the electricity production and, additionally, heat production. These technologies enable the use of both electricity production and combined heat and power (CHP), depending on the exploitation or not of the excess heat available after electricity generation. Some CHP layouts may combine two different secondary technologies[70].

2.3.1 Primary conversion technologies

Combustion

Combustion was the first developed mode for using biomass for energetic purposes. This process is responsible for more than 97% of the world production of bioenergy[71] so the pyrolysis and gasification processes still represent a minority option. “Combustion is a complex phenomenon involving simultaneous coupled heat and mass transfer with chemical reaction and fluid flow”[68]. “Combustion is a series of chemical reactions by which carbon is oxided to carbon dioxide, and hydrogen is oxided to water”[72].

In the case of fuels, the process can be divided into three phases: heating and drying, gasification, combustion. They, however, occur simultaneously inside a bed of burning biomass while, at the molecular level, are in sequence[73].

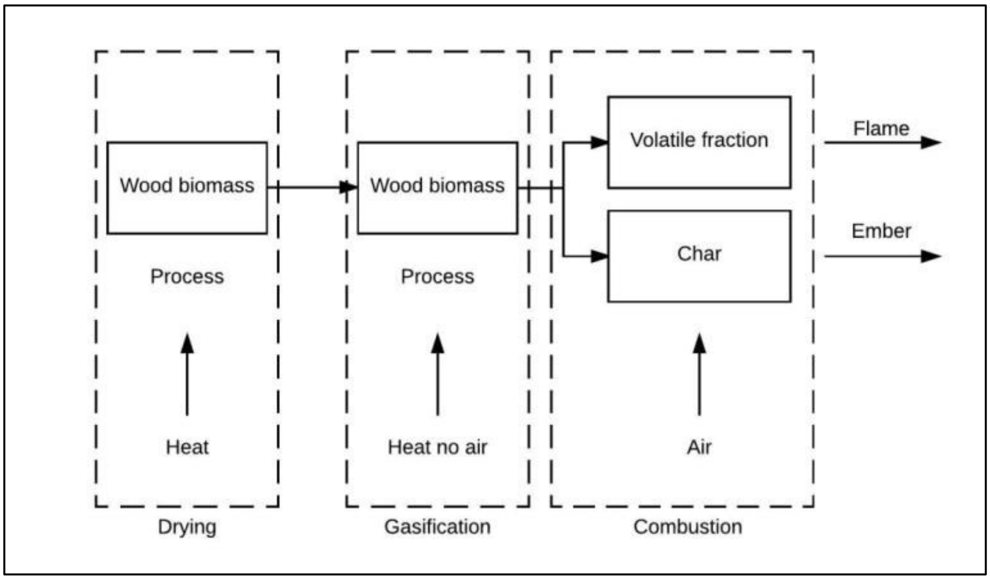

Figure 2.3 – Phases of the combustion process[73]

In the drying step, the particles receive heat from the surrounding environment and they increase their temperature until it reaches the evaporation threshold (about 105 °C) and, once the water is eliminated, until it reaches the pyrolysis threshold. The water evaporation process starts at temperatures below 100 °C. This process by absorbing part of the energy released during combustion, lowers the temperature inside the combustion chamber slowing down the process itself. If the input biomass has an excessive water content the energy required at this stage is so high that the temperatures drop below the minimum temperature which is required to sustain combustion. The process cannot, therefore, sustain itself. For this reason, the water content of the wood is one of the most significant parameters concerning the qualitative determination of wood fuels. This parameter also adjusts the forced-air control systems.

In the gasification step, the heat is transmitted to the particle inner layers, in absence of oxygen, and it transforms the biomass in two separate fractions. The solid fraction (char), consisting of fixed carbon and ash, and the volatile fraction. After the drying, starting from a temperature around 200 °C, the fuel undergoes a stage of thermal degradation that determines the evaporation of the volatile fraction. It constitutes more than 75% of the mass. The first components to undergo this process are hemicellulose and cellulose. The process starts to decrease once the temperature exceeds 400 °C. At this temperature most of the volatile substances have been released. There is still a drop of mass, between 400 °C and 500 °C, caused by the degradation of the lignin.

The products of gasification, in contact with the oxygen present in the air, determine the actual combustion. Above the char bed, a very fast exothermic reaction takes place due to the volatile fraction with emission of light radiation in the visible spectrum (flame). In the char bed, a slower reaction takes place for the fixed carbon with infrared light radiation emission (ember).

Under ideal wood combustion conditions, there is the complete oxidation of the fuel, with the formation of CO_2, H_2O, and traces of NO_X, SO_2, and some other compounds, in relation to the chemical composition of the wood. If the proper conditions are not maintained, there is incomplete combustion. It can determine the emission of unburned substances. The main cause of incomplete combustion are:

- inadequate mixing between air and fuel in the combustion chamber,
- overall deficiency of oxygen,
- too low combustion temperatures,
- too short residence times.

Temperature, turbulence and residence time are, therefore, the three parameters that mostly influence the combustion, together with the amount of combustive air. It has to ensure the complete oxidation. The conditions of complete combustion are difficult to achieve in solid fuels. A proper mixing degree is difficult to achieve in a limited time period. The quantity of combustive air is indicated with the term excess air (λ) representing the relationship between the availability of oxygen in the combustion chamber and the stoichiometric amount of oxygen required to complete the oxidation[74]. The plants for the combustion of biomass generally require λ values between 1.5 and 2 according to the combustion technology.

The wood biomass heating systems produce, through combustion, heat. They can warm-up air, water or both through specific heat exchangers.

The three main combustion techniques for biomass in heat and power applications are the same as for coal[75]:

- Grate firing (GF): biomass is placed on a grate and material is moved slowly through the boiler as it combusts with air being supplied through holes in the grate. Maximus size is limited to approximately 150 MWth/50MWe. The plant type is flexible and relatively simple.
- Fluidised bed (FB): biomass is mixed with a medium (typically sand) and kept suspended in a mix with incoming air. The temperature in the bed allows a partial gasification of the biomass and it reduces the NO_X and SO_X emissions associated with the combustion. The sizes of the plant vary

from 30-300 MWe. The relatively complex set-up and the difficulty of running a plant with a part load causes that this system is less widespread.

- Pulverised fuel: biomass is grinded to powder and combusted. This method achieves high efficiency in combustion and can be applied in large scale (up to 600 MWe), but during and grinding, the feedstock requires energy.

The boilers may be distinguished according to the type of grid (fixed, reverse flame or mobile) and the type of used fuel (firewood, chips or pellets).

The common elements that characterize all types of systems are:

- Feeding system: The manual loading system is generally used for low power boilers that use large size wood. It is constituted by a flap which allows to position the fuel directly inside the oven. The automatic feeding system can use screw conveyor or hydraulic pusher. The screw conveyor is constituted by a large rotating screw toward which the wood chips are conveyed by a conveyor belt or an automatic rake. The hydraulic pusher uses the thrust of a hydraulic cylinder to directly insert the fuel into the boiler.
- Combustion chamber: It is made of refractory material (ceramic, refractory brick or steel). It is the zone where there is complete oxidation of volatile gasification products (mainly CO and H_2), pyrolysis products (light hydrocarbons) and organic-based particulate. The combustion chamber should ensure good conditions of turbulence and the availability of oxygen to ensure the mixing of the gases coming from the combustion bed and the secondary air.
- Post combustion refractory chamber: It has the purpose of ensuring controlled combustion conditions to allow the completion of the oxidation reactions.
- Heat exchangers: Bundles of tubes which have the function of increasing the exchange surface of heat energy between the fumes coming from the combustion chamber and the water present in them that constitutes the heat carrier.
- Primary and secondary air supply: The oxygen required for the combustion is supplied inside the oven by input of air beneath the grid (primary air) and above the combustion bed (secondary air).
- Ash extractor: It is a collection tank and it is located below the grid. The heavy ashes deriving from the combustion process are deposited inside it.

Table 2.4 describes the main type of combustion boilers.

Table 2.4 - Main combustion reactor types and characteristics[70,76]

Reactors	**Characteristics**
Pile burner	It represents the historic industrial method and it consists of a two-stage combustion chamber. The combustion chamber is separated into a lower pile section for primary combustion and an upper secondary combustion section. Fuel is fed forming a pile. Limited to cyclic operation because of the ash removal. It can handle wet, dirty fuels. It has low efficiencies, 50 to 60%.
Stoker grate	Improved version of the pile burner by moving the grate and thus improving ash collection and spreading of the fuel. It can have continuous operation. Underfire air rate defines the maximum temperature of the grate and thus the allowable moisture content of the feed.
Bubbling fluidized bed	Fuel has free movement in the combustor while an air or oxygen stream passes through it and a bed of free-flowing granular materials. The bed is usually sand or limestone. The air acts as the fluidizing medium and air is the oxidant for biomass combustion. To obtain the total desired gas-phase residence time for complete combustion and heat transfer to the boiler walls the larger cross-sectional area zone is extended. A cyclone is used to either return fines to the bed or to removes ash-rich fines from the system. Advantages are extremely good mixing and high heat transfer, resulting in very uniform bed conditions.
Circulating fluidized bed	Same as bubbling fluidized bed with increased fluid velocities thus the fluid entrains the fuel. The turbulent bed solids are collected, separated from the gas and returned to the bed, forming a solid circular loop. The residence time of the solids is determined by the solid circulation rate, the attritibility of the solids and the collection efficiency of the solid separations device.
Suspension burners	Fuel is burned suspended within the fluid. The requirements are a feed moisture content of less than 15% and a particle size less than 0.0015 m. Higher efficiency, up to 80%.
WholeTree energy	Integrated wood conversion process including growing, harvesting, transportation and combustion of whole trees as wood fuel. Whole trees are burned in a staged combustion system with the use of low temperature gas to dry the trees. The advantages are reduced operating cost achieved by elimination of wood chipping and increased efficiency by almost complete use of waste heat in the condensing heat exchange system.

For the characteristic of the research subjects, the analysis in the next chapters will concentrate on stoker grate chips boiler.

Gasification

“This process consists of the partial oxidation of biomass in a low-oxygen content environment”[35]. The main product of this process is a low calorific gas, called syngas containing hydrogen, methane, carbon monoxide and carbon dioxide. The percentages in which the various components are present mainly depends on the oxidant which may be air, oxygen, water vapor or carbon dioxide[77]. Syngas can produce heat or power, synthesize other liquid fuels or produce hydrogen.

Gasification occurs in three sequential steps[78]:

- drying to evaporate moisture,
- pyrolysis to give gas, vaporized tars or oils and a solid char residue,
- gasification or partial oxidation of the solid char, pyrolysis tars and gas.

The process starts with an initial heating of the fuel up to the temperature for which the water content bound to the solid matrix evaporates. Following an additional supply of heat, the solid undergoes a first thermal degradation which leads to the breaking of the weakest links and the release of low molecular weight gases, volatile matter, primary tar and other condensable at ambient temperature gaseous products. These first two stages may be regarded as processes in series, while the phases of oxidation and gasification take place in different time and ways depending on the used technology. They consist of a series of chemical reactions between the products of pyrolysis and other gaseous reactants (air, oxygen, water vapor and exhaust gas). Oxygen is employed in partial oxidation reactions, which provide the thermal energy needed for the self-sustenance of the process. Alongside these reactions, the development of various endothermic reactions determine the recombination of the gaseous compounds with each other and the transformation into gas of the solid residue of the previous stages.

The gaseous mixture obtained is formed by gases with varying calorific value (CO, H_2, CH_4) and inert gases (CO_2, H_2O, N_2). Such a mixture has a lower energy content than the initial content of the solid fuel according of its calorific value. The ratio between the two amount is defined Cold Gas Efficiency (CGE) and it is a fundamental parameter to estimate the success of the transformation.

Other solid or liquid by-products of the gasification process does not participate in the calculation of the CGE and in many applications they cannot be used for the energy production cycle. They are mainly high percentage of carbon solid substances and high molecular weight hydrocarbons. These substances make difficult the management of a gasification plant, especially for the need to adopt suitable removal systems from the gas stream.

The inevitable by-product of the process is the solid residue from the gasification. It is composed by the inert substances already initially present in the biomass and the part of the solid carbon resulting from the non-complete transformation of the starting fuel.

The combustion of the fuel gas is closely influenced by the type of supplied gasifying agents. They determine the distinction of the gasification process in the following types:

- Gasification with air is applied to produce energy in small-medium scale plants.
- Gasification with O_2. is applied mainly in medium and high power plants.
- Gasification with water vapor, CO_2 or exhaust gases. The reaction gas are free of strong oxidizing agents. Therefore, the deriving reactions cannot meet the heat requirement necessary for the energetic self-sustenance of the system. The thermal energy for the development of the processing needs to be supplied from outside.
- Pyrolysis. This term does not only indicates a certain phase of the thermochemical process. It is also used to define an application on its own, in which occurs the fuel thermal degradation without the entry of gaseous reactants. The products that are obtained in this way are light gases, bio-oils and char. Their different amounts depend substantially by the maximum operating temperature which is reached inside the unit of pyrolysis, by the speed of fuel heating and its residence time within the reaction zone. There are the following types of pyrolysis: carbonization, conventional pyrolysis, slow pyrolysis, flash pyrolysis, fast pyrolysis.

The main factors that influence the gasification process are temperature, initial moisture of the fuel, residence time, speed of fuel heating and its contact with the gaseous reactants.

This process has the advantage of being easily coupled with secondary conversion technologies. It also allows to use fuel with a wider range of water content compared to the combustion process.

The gasification can take place in different types of reactors (gasifiers), that can be distinguished according to the reagent, the process pressure (atmospheric or pressurized), the source of heat (direct or indirect) or the area of fluid-biomass contact (Table 2.5). Gasifiers are generally divided in two groups: fixed bed or fluidized bed[79]. Separate category is the entrained flow.

Table 2.5 - Main gasifier types and characteristics[78,80]

Reactors	Characteristics
Downdraft-fixe bed reactor	Solid moves slowly down a vertical shaft and air is introduced and reacts at a throat that supports the gasifying biomass Solid and product gas move downward in co-current mode The technology is simple, reliable and proven for fuels that are relatively uniform in size and have a low content of fines (below 5 mm) A relatively clean gas is produced with low tar and usually with high carbon conversion There is limited scale-up potential to about 500 kg/h feed rate There is a maximum feed moisture content of around 35% wet basis Favorable economics on a small scale
Updraft-fixed bed reactor	Solid moves down a vertical shaft and contacts a counter-current moving product gas stream The technology is simple, reliable and proven for fuels that are relatively uniform in size and have a low content of fines (below 5 mm) The product gas is very dirty with high levels of tars, although tar crackers have been developed Scale up limited to around 4 dry t/h feed rate There is high thermal efficiency and high carbon conversion The gas exit temperature is low Good turn-down capability Favorable economics on a small scale
Bubbling fluid bed	Good temperature control & high reaction rates Higher particulates in the product gas and moderate tar levels in product gas Good scale-up potential to 10-15 dry t/h with high specific capacity and easily started and stopped Greater tolerance to particle size range Tar cracking catalyst can be added to bed Limited turn-down capability There is some carbon loss with ash Favorable economics on a medium to large scale
Circulating fluid bed	All the features of bubbling beds Large minimum size for viability, above around 15 t/h dry feed rate and high cost at low capacity In-bed catalytic processing not easy Favorable economics on a medium to large scale
Entrained flow	Inherently simple reactor design, but only potentially viable above around 20 dry t/h feed rate and with good scale-up potential Costly feed preparation needed for woody biomass Carbon loss with ash Little experience with biomass available Favorable economics on a medium to large scale
Twin fluid bed	Complex process with two close-coupled reactors with difficult scale-up and high cost The gasifier is usually a circulating fluid bed, while the char combustor can be either a bubbling bed or a second circulating fluid bed Complexity requires capacities of > 10 t/h for viability MHV gas production produced with air and without requiring oxygen Low carbon conversion to gas as carbon in char is lost to reheat sand for recycling High tar levels in gas Tar cracking catalyst can be added to bed Favorable economics on a medium to large scale

2.3.2 Secondary conversion technologies

These energy conversion technologies are usually combined with the primary technologies to convert the produced energy in a different form of energy. The main technologies are described in Table 2.6.

Table 2.6 – Main secondary conversion technologies[70,80,81]

Secondary conversion tehcnology	Characteristics
Steam engine	Uses the steam produced through thermal evaporation of water to drive an engine Can be fuelled with all kinds of fuels Relatively to other technology, has low performance (inability to use the excess heat)
Steam turbine	Is based on the thermodynamic Rankine cycle Combustion takes place in a boiler before transferring the heat through a heat exchanger to evaporate the working fluid Accepts all kind of fuels A pre-drying stage is recommendable before the combustion to increase efficiency High time availability
Stirling engine	Combustion takes place in an external combustion chamber so the technology is suitable for fuels in all phases, solid, liquid or gaseous Low maintenance requirements and noise levels Good performance and high thermal efficiency and output
Organic Rankin Cycle (ORC)	Variation of steam turbine in which water is replaced as a working fluid by organic fluids (toluene and n-pentane for high temperature ORCS and hydrocarbons for low temperature ORCS) The low vaporization temperature of these organic fluids make it possible to use low-heating value fuels without lowering the efficiency Good part-load operation and lack of requirement of a pre-heating stage.
Internal combustion engine (ICE)	Comprises the Otto engine that works with spark-ignition and the Diesel engine, both requiring a liquid or gaseous fuel which is combusted in an internal combustion chamber For small-scale application Otto engine is more suitable Better performances with smooth consumption profiles, otherwise some storage system can be added Low upfront costs and good part-load performance
Gas turbine	Combustion of compressed gaseous fuels in an internal combustion chamber and the subsequent expansion of the combustion gases in a turbine When a gasification unit, gas cleaning unit and a heat recovery steam generator (HRSG) are integrated together with the gas turbine, the system is called Biomass Integrated Gasification Combined Cycle (BIGCC) Is more suited for large-scale application
Micro-turbine	Down-scaled versions of gas turbine, it is more suitable for small-scale applications Less maintenance requirements are necessary due to their simplicity Less commercially proven
Fuel cell	Uses H_2 and O_2 to produce electricity and the by-product of heat in the presence of an electrically conductive electrolyte material An individual cell is comprised of a membrane-electrode assembly (MEA) and a current-collection system. Individual cells are usually connected electrically in series as stack Fuel cells are classified in molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs)

Among the technologies described, the BIGCC is more suited for large installations, it comes out therefore from the subject of the present research. The main application of these technologies are plants for combined heat and power (CHP) or cogeneration.

2.3.3 Cogeneration

The combined production of electricity and heat from solid biofuels can take place through two different cogeneration systems[82]:

- The biomass is directly combusted in a boiler with heat production and it is transferred to a carrier of energy that feeds the thermodynamic cycle of the electricity generation system. In this category there are the thermodynamic cycles utilizing the following fluids: water vapor (steam turbines), organic fluid (Organic Rankin Cycle), hot air (hot air turbine), inert gases such as helium and nitrogen (Stirling engines).
- Biomass is chemically decomposed into volatile molecules in special thermo-chemical reactor (pyrogasifiers) with syngas production. It can be directly combusted in alternative internal combustion engines or gas turbines after filtration of the unburnt particles.

CHP is considered one of the main alternatives to traditional systems as regards energy conservation and resource management. The main objective in the application of cogeneration systems resides in the generation of energy for buildings. It is the main application at the small scale of this type of plant. Small-scale and micro-scale CHP systems are particularly suitable for application in commercial buildings, such as hospitals, schools, small industries, office building blocks, and single or multifamily dwelling houses[83]. However for the time being, this technology presents technical and economic issues that still need further research. The number of commercially available installations are still limited. Table 2.7 lists the main currently available CHP energy conversion technologies.

Table 2.7 – Major energy conversion technologies of biomass-fuelled CHP systems [83]

Primary technology	Secondary technology
Combustion producing steam, hot water	Steam engine Steam turbine Stirling engine Organic Rankine Cycle (ORC)
Gasification producing gaseous fuels	Internal combustion engine Micro-turbine Gas turbine Fuel cell

2.4 Basic concept of Occupational Safety and Health

The work environment is the environment in which it operates, in terms of size and time, the human being (worker) during his working life. More specifically the term workplace covers all places destined to host work activities, located within the company or site that are accessible by the worker as part of their work[84]. As part of this definition, there is the need to define the term worker. It is any person employed by an employer, including trainees and apprentices but excluding domestic servants[85].

"Occupational health deals with all aspects of health and safety in the workplace and has a strong focus on primary prevention of hazards"[86]. The ILO (International Labor Organization) Occupational Health Services Convention[87] defines occupational health services as services entrusted with essentially preventive functions and responsible for advising the employer, the workers and their representatives in the undertaking on the requirements to establish and maintain a safe and healthy working environment which facilitate optimal physical and mental health in relation to work and the adaption of work to the capabilities of workers in the light of their state of physical and mental health.

The employer shall evaluate the risks for the safety and health of workers, inter alia in the choice of work equipment, the used chemical substances or preparation, and the fitting-out of work places. Subsequent to this evaluation and as necessary, the preventive measures and the working and production methods implemented by the employer must assure an improvement in the level of protection afforded to workers with regard safety and health and be integrated into all the activities of the undertaking and/or establishment and at all hierarchical levels[85].

Risk is the actual exposure of something of human value to a hazard and it is often measured as the product and loss[88]. It can be also defined as the combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence (the damage).

Hazard is commonly defined as the potential to cause harm. More in general , it is a property or situation that in particular circumstances could lead to harm[89].

In the context of Occupational Safety and Health (OS&H) the damage is manifested in the form of temporary or permanent, or recognized as such, significant degradation of the physical, psychological or of social wellbeing worker condition. Generally the damage in the workplace can be expressed as an injury or occupational disease. The term injury includes any accidents that happen for "violent causes during work" from which can derive the worker's death, permanent disability or temporary total disability for more than three days. An occupational disease is a disease whose cause acts slowly and progressively on the organism (diluted cause and not violent and concentrated in time cause). The cause must be traced back to the work activity.

To guarantee the safety of the workers, the population and the environment is necessary to identify all the potential hazard and proceed to analyze the risk. Risk analysis consists in the process of identification of the most suitable exposure model and application of the analysis techniques in order to assess the risk.

2.5 Occupational Safety and Health of forest energy chain

2.5.1 Forest yards and the Occupational Safety and Health legislation

Forestry activities can be distinguished[90] into strictly forestry activities and forestry activities so defined for the environment where they take place. The second are usually borne by other components of the forest system (soil, civil infrastructure).

Forestry activities are considered among the most hazardous activities[91,92]. ILO inserts them in the "hard work category"[93]. At European level, the incidents in agriculture, hunting and forestry operations have higher frequency than other sectors [94]. INAIL (Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro) provides data referred for Italy on the accidents in the forestry sector, aggregated with the agricultural sector[95]. According to occupational accidents reports gathered from a number of selected ILO member states, there are 14 fatal occupational accidents in forestry, logging and related service every one hundred thousand workers[96].

Motorized-manual timber cutting-harvesting operations, such as cutting, felling, limbing, debranching, debarking, cross-cutting, classification, extraction, loading and transporting are among the most difficult and labor-intensive types of physical work[97]. Risks related to forestry are primarily linked to the work environment, which often involves unpredictable factors in comparison with other work. The main hazard factors found in these jobs are: soil and meteorological conditions (high or low temperatures, rain, snow, ice or wind), use of machinery and equipment, heavy loads handling, physical agents (noise and vibration), presence of wood dust and exhaust gases[98]. The variables associated with the risk of accidents or injuries are a high workload, machine-paced work or no breaks at work, lack of worker training, lack of lockout/tagout program and workers inexperience[99]. These factors can increase mental stress, muscle load and locomotor apparatus stress causing musculoskeletal diseases[97] and accidents. In general the major number of accidents occurs during the tree felling and processing phases[98,100].

The increase in the level of mechanization contributed to reduce both the magnitude and frequency of accidents and the occupational diseases[101]. However the high mechanization cannot always be applied both for technical and management reasons (lot size, slope of the ground, etc.). Although in recent years machines for the felling also usable in uneven ground[102] are spreading, there are still limitations to their use, mainly linked to the risks arising from the work environment. In such situations the extraction with tractors and cable yarder is still preferred.

Analyzing the European safety legislation[103], forestry does not appear explicitly in the construction site activities.

In Italy[84], forest activities are considered construction sites exclusively when they involves building or civil engineering works. Forestry in the strict sense is not included in this definition, even though it is clearly distinct by forest yard peculiarities, as the variability and the transformation of the working environment in which it is carried out. Despite the considered activities do not formally fall within the scope of the legislation for construction site (Title IV of D.lgs. 81/08[84]), minimum rules must be followed. In this sense, the revision of Risk Assessment Document (DVR) when there are significant variations of the work environment responds to a safety need. This document must be adapted site for site (or at least for environment type). It is charged to who uses the forest and takes the employer role.

If the wood owner is not the logger itself, logging activities will be subject to contract, in particular in case of public forests where the owner is the municipality or other local government. There is the need, in the public or private contract, to achieve cooperation and coordination between the figures involved in the contract (i.e. enterprises and self-employed workers) in order to organize the overall work and service safety. To handle this, the employer must develop the Interference Risk Unique Assessment Document (DUVRI). This document shows the operating guidelines that must be performed in order to eliminate or, where that is not possible, to minimize the risks. The DUVRI should be adapted according to the work, supplies and service evolution and it should be prepared for forest yards with the same methodology as the Safety and Coordination Plan (PSC) provided for temporary and mobile construction sites. This situation typically occurs when a public body is a forest owner and it entrusts forestry activities to one or more companies.

In particularly critical areas or by choice of the client there is the opportunity to ask the company the Operational Safety Plan (POS) and write up the PSC considered as safety cost.

There is so, on the whole, a complex situation of normative references as regards safety in forest yards. Some Italian regions, through regional preventions plans and guidelines[104], have begun to define the procedures to be followed to minimize and, where possible, to eliminate risks deriving from the forest environment. On the contrary, a procedure defined at national or international level, for proper and safe management of forestry activities still lacks. Companies with PEFC certification, implicitly agree to abide by the national legislation, but, also, in this case a clear reference still lacks.

2.5.2 Heating systems Occupational Safety and Health

During the phase of storage, wood fuels are subject to chemical and biological reactions and decomposition caused by bacteria and fungi. A potential risk for the workers during the timber or chips shift and storage phases is due to the presence of airborne microspores[105] and it should be considered and assessed.

The simple wood deposits are not regulated by mandatory rules but there must be a fire risk assessment.

Chips and pellets storage has to be vented during pneumatic delivery (with an output into a dust sock) to prevent pressurization of the silo but avoid dust blow-out at the same time.

Most fuel stores will be a confined space[106] and therefore potentially hazardous. A confined space is not necessarily a fully enclosed space. Biomass fuel storages, large or small, are hazardous because they are effectively confined spaces connected to a combustion chamber where CO_2 and CO are produced. The design of the storage should seek to minimize the requirement for the worker to enter within it under any circumstances. Any requirement for inside maintenance or repair should be reduced in the design phase to a minimum.

As a generalization, lump wood or chips are very difficult to ignite. However, fine wood dust can cause a risk of explosion in incorrectly designed equipment. In order to comply with the legislation[107] that regulates workplaces in which explosive atmospheres can be created, it is necessary to assess the hazards and design adequate protection and mitigation systems.

The design and management of the thermal systems must be carried out by referring to the international[85] and national[84] regulations for safety in the workplace.

The plants must be considered as an integrated systems whose components must be represented by machines with their own EC label[108] and whose plant networks (electrical and hydraulic) are designed, installed and tested individually by qualified professionals resulting in the declaration of conformity[109].

Boiler hazards exist in the following functional areas[110]:

- Wet side (water or steam);
- Fire side (fire and explosion);
- Flue ducts and chimney.

The most important point which distinguishes biomass from oil or gas is that a biomass boiler cannot be extinguished immediately. Biomass boilers have large thermal inertia caused by fuel burning on the grate and potentially also residual heat stored in the refractory. This present a risk of excess temperature or pressure if the boiler bust be suddenly shut down. This risk can be reduced by including a puffer vessel, an emergency heat dump or cooling loops in the design. The problem tends to be greater with wood chips boilers that are physically much larger than pellets boilers with similar outputs and hence they have a larger thermal inertia. Biomass boilers should never be operated without a suitable pressure relief valve and pressure gauge, either on the boiler or on the connected pipe work.

The combustion of wood biomass fuel involves gasification and production of potentially explosive gas mixtures. Due to the different processes of combustion, biomass boilers cannot be fitted with the same levels of interlocks as gas or oil plant. Occasionally, un-combusted explosive gas mixtures can build up within a biomass boiler combustion chamber and flue, which are subsequently ignited and an explosion can occur. Correct operating procedures minimize this hazard but it cannot be eliminated.

Large chimney systems can present an explosion risk due to the potential build-up of explosive gas. A solution can be an explosion relief for the flues of all non-domestic biomass boilers.

The greatest health and safety risks for the workers which are engaged in the management and maintenance activity of the systems are accidental fires and prolonged exposure to toxic and corrosive chemicals[111].

2.6 Basic concepts of environmental sustainability

The aim of environmental sustainability is the protection of the living environment and the natural environment. The living environment is the space in which the human being lives as a citizen-resident during his whole life. This environment consists of the territory in its entirety, on a local or regional scale[112], and it has within it natural and anthropogenic inhomogeneities. The natural environment is the set of environmental compartments in which the factors that influence the living beings are governed by the course of nature. It is not confined and it is analyzed on large-scale, with regional or global dimensions.

The environmental compartments are often represented as environmental spheres: the atmosphere (the envelope of gas surrounding the Earth), hydrosphere (complex of water present on the Earth's surface), lithosphere (rigid outer casing of the earth) and the biosphere (set of all living beings). These first four spheres constitute the ecosphere. The anthroposphere is the set of human beings and their activities and actions. It belongs with the flora and fauna to the biosphere. It must be considered as a sphere of its own because within it two of the main peculiarities of environmental impact assessments are included: the main sources of pollution are anthropogenic and the human beings are the goal of the protection activities.

The analysis of the anthroposphere should not ignore the natural environment, as it is always involved in the territorial environmental analysis, covering the role of the mean in which the phenomena in question occur.

When exposed to factors that can influence it, an environmental system may respond with a null, reversible or irreversible response. There is a null response when the systems are not influenced. There is a reversible response when there are changes that, once the exposure is removed, disappear and a situation similar to the initial one is again reached. For human beings this response is associated with an annoyance condition. There is an irreversible response when there are permanent harmful alterations in the environmental conditions.

The null and reversible responses correspond to two different environmental conditions of protection: sustainability and compatibility. The environmental compatibility means not generate irreversible damage to the ecosystems under consideration without the protection of their quality. It signifies accepting an impact, i.e. a transformation that influences the different components of the system lowering their quality value. The definition of environmental sustainability is “meeting the resource and services needs of current and future generations without compromising the health of the ecosystems that provide them and more specifically, as a condition of balance, resilience, and interconnectedness that allows human society to satisfy its needs while neither exceeding the capacity of its supporting ecosystems to continue to regenerate the services necessary to meet those needs nor by our actions diminishing biological diversity”[113]. This entails making sure that the rate of pollution and exploitation of natural resources remains within the limits of the absorption capacity of the environment and the possibilities of resources regeneration, as permitted by the cycles of nature.

The damage in environmental sustainability is usually defined as impact. The environmental impact is the effect of an anthropogenic intervention that has caused alterations of individual components of the environment or of an environmental system in its entirety. An impact is the result of interference from an initial source, which through chains of events generate pressures on significant environmental targets. These pressures are potentially capable of altering them.

Hazard factor means a factor (physical, chemical or biotic) with ability to damage the receptor with which it comes in contact. The risk is given by the product of the probability of occurrence of a determined negative event and the magnitude of the damage that could generate. The risk assessment is the quantification or qualification of the overall risk to which the environment is subjected by implementing a defined human action. The risk assessment allows to determine whether the identified impacts are significant or not for the system involved. The acceptability consists in determining a threshold below which it is no longer acceptable the potential problem or the lowering of the quality induced by the analyzed risk.

The effects resulting from exposure to hazard factors vary in intensity in relation to the quality and quantity of contaminant and the temporal characteristics of the risk factor exposure. By varying these parameters, the alterations that may be induced on the population vary:

- Effects of damage, not reversible or not fully reversible changes,
- Effects of disturbance, temporary changes in the psychophysical condition of the subject,
- Effects of annoyance and discomfort, broadly intended with decreased quality of life and the alteration of the social relations and benefits.

Defined and codified procedures were introduced at European level, to assess the impact on the environment and the quality conditions: environmental impact assessment (EIA) and strategic environmental assessment (SEA). They are used as simulation tools of the interactions between the possible source of emissions and the environment, to assess the environmental compatibility of a project.

EIA is a technical and administrative process for the assessment in the design stage of the impacts generated by anthropogenic activities, to ensure high levels of protection and environmental quality. Through the comparison of the different alternatives, it allows to support the decision process. It is a state and impacts assessment procedure and it is performed before the driver exists. It is suitable for large activities.

According to the legislation[114], the effects of a project on the environment should be assessed in order to take account of concerns to protect the human health, to contribute by means of a better environment to the quality of life, to ensure maintenance of the diversity of species and to maintain the reproductive capacity of the ecosystems as a basic resource for life. The environmental impact assessment shall identify, describe and assess in an appropriate manner the direct and indirect effects of a project on the following factors: human beings, fauna and flora, soil, water, air, climate and the landscape, material assets and the cultural heritage, the interaction between the different factors.

The information to be provided by the developer in accordance shall include at least: a description of the project comprising information on the site, design and size of the project, a description of the measures envisaged in order to avoid, reduce and, if possible, remedy significant adverse effects, the data required to identify and evaluate the main affects which the project is likely to have on the environment, an outline of the main alternatives studied by the developer and an indication of the main reasons for his choice, taking into account the environmental effects, a non-technical summary. The legislation lists the projects that are mandatory subject to an EIA.

The Strategic Environmental Assessment is a procedure for assessing the likely environmental effects of plans and programs to ensure the sustainability of planning and programming choices.

The objective of the SEA is to provide for a high level of protection of the environment and to contribute to the integration of environmental considerations into the preparation and adoption of plans and programmes with a view to promoting sustainable development, by ensuring that an environmental impact assessment is carried out of certain plans and programmes which are likely to have significant effects on the environment[115]. An environmental assessment shall be carried out for all plans and programmes which are prepared for agriculture, forestry, fisheries, energy, industry, transport, waste management, water management, telecommunications, tourism, town and country planning or land use.

2.7 Environmental sustainability of forest energy chain

2.7.1 Forestry environmental impact

Modern forestry must combine two often conflicting objectives: minimizing the damages caused to valuable trees left on side (including the advanced natural regeneration), while maintaining financial efficiency fort the harvesting operations[116]. Under such circumstances, the interventions in the forests should consistently take into account a principle of sustainability and environmental protection in forestry. Therefore, it becomes mandatory to use the best suitable technology for each case. As a result, the logging solution chosen for a specific site must take into account simultaneously the remaining trees in the stand, the soil good conditions for natural regenerations, modification or interference of the water network. In other words, not only economic efficiency, but also environmental sustainability must be considered.

Forestry always involves an impact on forest ecosystems and on the territory in general, at least in the short term. Usually it involves temporary modifications or alterations of the state of the sites. They are solvable with simple enforcement activities, if carried out at the end of the work. However, they, if carried out without suitable working conditions systems, careful planning and staff properly trained, can lead to further impacts whose magnitude, severity and duration can be highly variable[117].

During the phases of timber handling in the forest, soil degradation processes occur, such as compaction, grooving and mixing of the upper layers[118]. These phenomena occur due to the trees dragging and the transition of mechanical means[119]. The factors that may affect the degree of compaction and grooving are the number of passages of vehicles, the weight of the machines, the type of engine, the slope of the terrain, the soil characteristics and its conditions. The soil compaction can lead to change in the physical, chemical and biological properties of the soil, while the grooving may increase the risk of erosion due to the canalization of rainwater. The damage of the vegetation may also be of a certain extent. It can be caused by the machines or by the logs that can damage the superficial roots or hit the base of the stems[120]. The extent of the mechanical damage depends on various factors such as the extraction system, the period of work, the intensity of the cut, the planning of the extraction system and the workers training.

Forestry activities can indirectly reduce other functions of forest ecosystems such as carbon sequestration, soil protection, water regulation, as well as they can result in the removal of wildlife.

Previous studies have analysed the environmental impact caused by forestry operations on the surrounding area, mainly due to the difficulty of reconciling the local conditions with the main harvesting methods[121].

The Italian legislation[122] determines that the regions should plan the management and development of the forestry sector through the drafting of forest plans that take into account the multifunctional role of the forest and that meet the strategic objectives and the international, EU and national steerings. The actions to be taken by the regions through the forest plans should consider the six criteria for sustainable forest management[123] and the quantitative and qualitative indicators related to them[124].

2.7.2 Heating systems environmental impact

Pollutant emissions

An environmentally sustainable use of this energy source depends mainly on a correct exploitation of the forest resources and on the atmospheric pollutants emissions control. Assuming that the timber consumption is suitably regulated by the forest management policies[125], the environmental impact of these systems is almost fully related to pollutant emissions in the atmosphere. These are due to two typologies of sources, at the local and regional scale. The former are due to the release of combustion products from the heating systems, the latter to the release of pollutant from vehicles transporting the wood.

The emissions into the atmosphere from a wood combustion system contain mainly CO_2, H_2O, O_2, N_2 and a part of pollutants, minimal when there is complete combustion. With ideal combustion conditions, the fuel the completely oxidized, and the combustion products are mainly CO_2, H_2O, with slight traces of NO_X, SO_2, and some other compounds, depending on the chemical composition of the wood its eventual contamination (by ash, sulfur and nitrogen oxides of sulfur and trace elements such as Cu, Pb, Zn and Cd[74]). The use of wood biomass to replace fossil fuels contributes to reduce the total CO_2 emissions on a global scale[126]. In case of incomplete combustion, in addition to a greater percentage of carbon there are also emissions of particulate matter (PM)[127,128] and volatile organic compounds (VOCs). Other very harmful for the human health and the environment compounds, such as hydrochloric acid, dioxins and furans, may form in the event that the timber is contaminated by chlorine and in particular operating conditions of the heat generator. Numerous studies show that the combustion of biomass as a fuel in small installations, especially in case of incomplete combustion, is a significant source of PM[129] and gaseous emissions, such as VOCs[130], polycyclic aromatic hydrocarbons (PAHs)[131], CO, CO_2, NO_X and SO_X.

The influence of the fuel characteristics on the quantity and composition of the emissions has been the subject of several studies[132,133]. In general, in addition to the type of timber used, the emissions depend on the size of the used material and its moisture. The solid nature of the fuel and its resulting lack of uniformity can result in local conditions of oxygen deficiency or low temperature in the combustion chamber. The ignition phase and the low-load functioning are particularly critical for the emission of unburned substances, due to the low temperature in the combustion chamber. For this reason, the biomass boiler is connected to an accumulation tank, in order to minimize fluctuations due to variations in user requests.

Several studies analyze the actual influence of these systems on air quality[134,135], mainly focusing on the concentrations of PM, due to its well-known health-effects[136,137]. The suitability of the adoption of these systems has therefore to be carefully evaluated in regions where atmospheric PM concentrations are significant. This is the case of the Po Valley and of all neighbouring alpine valleys[138].

EU legislation sets limits for the atmospheric emission. They are based on the size of the plants The systems subjects of the present research are inserted both in the definition of small[139] (<1 MW) than medium[140] (1-50 MW).

Regarding medium combustion systems legislation[140] sets the following limits:

Table 2.8 – Solid fuel combustion (1-50 MW) EU limit values[140]

Pollutant	**Existing plants (1-5 MW) limit values [mg/Nm^3]**	**Existing plants (5-50 MW) limit values [mg/Nm^3]**	**New plants limit values [mg/Nm^3]**
SO_2	200	200	200
NO_X	650	650	300
Dust	50	30	20

Italian legislation[3] sets the following limits for the emission values:

Table 2.9 – Solid fuel combustion plants Italian limit values[3]

	Nominal heat output			
	0.15 - 3 MW [mg/Nm^3]	**3 – 6 MW [mg/Nm^3]**	**6- 20 W [mg/Nm^3]**	**>20MW [mg/Nm^3]**
Total dust	100	30	30	30
COT			30	20, 10[1]
CO	350	300	250, 150[1]	200, 150[1]
NO_2	500	500	400, 300[1]	400, 200[1]
SO_2	200	200	200	200

[1] average daily values

Solid and liquid waste

The waste produced by wood energy conversion systems can be both liquid and solid (ashes). Ashes are usually distinguished according to their volumic mass and their consequent ability to accumulate at the bottom of the combustion chamber or to move away from the same room exploiting the flow of the combustion fumes. The bottom ashes are collected below the grate of the combustion chamber, while the fly or volatile ash are recovered in the fumes treatment section.

The fly ash density is 0.8-0.9 t/m^3. Generally the metals present in the biomass is concentrated in this type of ash. The majority of the bottom ash has such a density (~1.3 t/m^3) that cannot be removed with the flue gas as the fly ash. They contain most of the macro nutrients for the trees (CaO, MgO, K_2O, P_2O_5, Na_2O). The nitrogenous compounds are not present because the nitrogen is released in the form of gas during the combustion.

The amount of ash produced depends on the type of biomass, the technology involved in the energy conversion and the reachable efficiency.

The elements that typically compose the ashes are Si, Ca, K, P, Mn, Fe, Zn, Na and B. These elements are in the form of oxides, silicates and nitrates. The ashes are strongly basic (pH ~ 12). The chemical composition of the ash varies accordingly to the combustion temperature. The content of some metals seems to increase proportionally at the temperature. Instead K, Na and Zn concentrations are inversely proportional. Carbon content and correspondly the ashes amount decrease with the temperature increasing. The environmental most dangerous metals (Pb, Cd and Zn) finish in the fly ash. Contrarily Co, Ni, Cr and V built up in the bottom ash.

Table 2.10 - Average concentrations of plant nutrients in usable ash mixtures depending on the biofuel used[141]

	CaO	MgO	K_2O	Na_2O	P_2O_5
Bark	42.2	6.5	5.1	0.8	1.7
Wood chips	44.7	4.8	6.7	0.6	3.6

The presence of heavy metals in the ash can have negative effects because of their possible percolation in the underground and the surface waters. Heavy metals are mainly present in the fly ash, nevertheless they cannot be excluded in bottom ash[142].

Ashes deriving from biomass combustion are classified as "non-hazardous waste" within the meaning of the Italian legislation[3]. The law establishes various possibilities for recovery of "ashes from the burning of biomass and the like" with simplified procedures. In particular they can be used to produce cement conglomerates, in cement or heavy clay industry, to produce compost or fertilizer and in environmental recoveries. If these options are not possible the ashes must be landfilled. The direct reuse of the ash in agricultural or forest areas is allowed in several European countries, but with limitations as regards the presence of heavy metals. The Italian legislation does not foresee the direct spreading. In order to use in this way the biomass ashes, they must be classified as a by-product[143].

EU legislation[144] allows the use in agriculture of wood ash as fertilizer. Ashes have to derives from not chemically treated after felling wood.

The re-integration of ashes in the land closes the cycle of biomass and it maintains practically unchanged the relative content of nutrients. It requires, however, a series of measures to not trigger counterproductive phenomena for the soil structure and its general chemical-physical balance. The percentage of heavy metals in the bottom ash is generally within the limits of acceptability. They provide, however, a smaller amount of nutrients. A mixture in appropriate proportions of bottom and fly ash can be useful to provide the right amount of nutrients respecting the limits for the concentration of heavy metals [145]. To prevent the accumulation of heavy metals in the soil, the allocation of part of the fly ash in landfills or for other uses may be necessary[38].

Several factors contribute to increasing the need to regulate the ash spreading on the soils:

- The increase in the solid biofuels use also in systems of large size and the consequent growth of ash production;

- The current approach on waste management requires, whenever possible, the recovery of materials and energy and it imposes the landfilling of residual materials as the last available operation;
- The spreading on soils constitute a solution for the recovery of materials which is compatible with the requirements of environmental protection and it is already used in some countries allowing a closure of biomass circle.

The liquid waste coming from the gasification plants have different compositions depending on the characteristics of the heating system. Depending on the composition must be disposed according to the provision by law[3].

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Chapter 3

Method description

The premise of this study is that the consumption of forest biomass to produce thermal energy is an ameliorative use regarding the consummation of resources and it is sustainable from the point of view of the emissions. This is because being a form of renewable energy determines a positive balance regarding the CO_2 emissions, as has already been described previously. The objective of the analysis is to validate the proposed solution with regard to the sustainability of the whole supply chain, its compatibility with respect to the territory in which it is implemented and the cumulative impacts that might occur with an implementation on a larger scale. To achieve this objective, the starting point will be the small scale analysis to check the OS&H and environmental impact assessment of the individual phases of the industry. It will come following an overall assessment of the cumulative impacts of the whole chain on a larger territory.

The analysis is therefore addressed to two different entities: the individual forestry enterprises and plants managers and the local authorities. The firsts need a methodology that allows them to determine the best design choices from the points of view of OS&H and environmental sustainability. Local authorities instead should be able to verify that an effective implementation of the local wood biomass supply chain does not result in an overall impact on the environment both regarding the depletion of forest available resources and the emissions resulting from the biomass combustion.

The carried-out study has, as previously mentioned, a dual purpose:

- analyze the forest-wood-energy chain from the points of view of OS&H and environmental impact to assess the risks for the workers and the environment by identifying the best technologies and the most suitable operating procedures;
- identify a methodology for expeditious analysis, suitable to be applied to small business activities and plants.

The phases of the supply chain have very different characteristics. Some stages have a temporary placement as they have no fixed location on the territory (i.e. forest yards and transport phase), while others are stationary (i.e. fuel wood terminal and energy conversion system). To facilitate the analysis a simplified supply chain was identified, not taking into account for each phase all available technological alternatives. As energy conversion systems pellets and chips combustion boiler have been privileged, suitable for widespread distribution on the territory.

3.1 Research subject

In Figure 3.1 there is the simplified schematic chain that has been the research subject of the present thesis.

The starting point of the analysis is the forest. The trees to be felled have to be identified and counted. The cut has to be done in order to not damage the surrounding trees. Once the tree has been cut down, they are processed. After this phase, there is a ramification of the supply chain. The logs are transported to a collecting point (i.e. the fuel wood terminal). From there the best quality timber goes to the sawmill. However this phase can offer as by-products wood waste that can also be used to produce energy and so this phase is included in description of the chain though it will not be analysed. The wood by-products are usually earmarked to the process of pelletizing.

The rest of the timber not intended for the woodworking is used for energy purposes. The most sustainable solution is wood chipping. Treetops and branches, for their high moisture, are usually chipped right after the felling and directly transported at the energy conversion systems to avoid their decomposition during the storage period. Logs and chips are transported to the fuel wood terminal. The logs are usually dried to improve their characteristics thorough a storage period. Once dried they are chipped. After, the chips are transported to the heat generator and they are stored in a storage room before being burned to produce heat. The size of the hypnotized heat generators is assumed to be compatible with an implementation for small size (few buildings) district heating systems.

The methodology described below will be applied in particular to the forest yards, to the fuel wood terminal and to the heat generators.

As regards the transport phase, for which the evaluation of OS&H and environmental impact is more established, however, it will be taken into account in the further analysis. The transport phase, indeed, cannot be neglected in the cumulative impact on the territory assessment, in the hypothesis of widespread installation of the described design choices. This is because even assuming the maximum reduction of this phase, the displacement of the amounts of timber that are needed to ensure the functioning of the systems may not be negligible in the overall assessment of the impact on a territory.

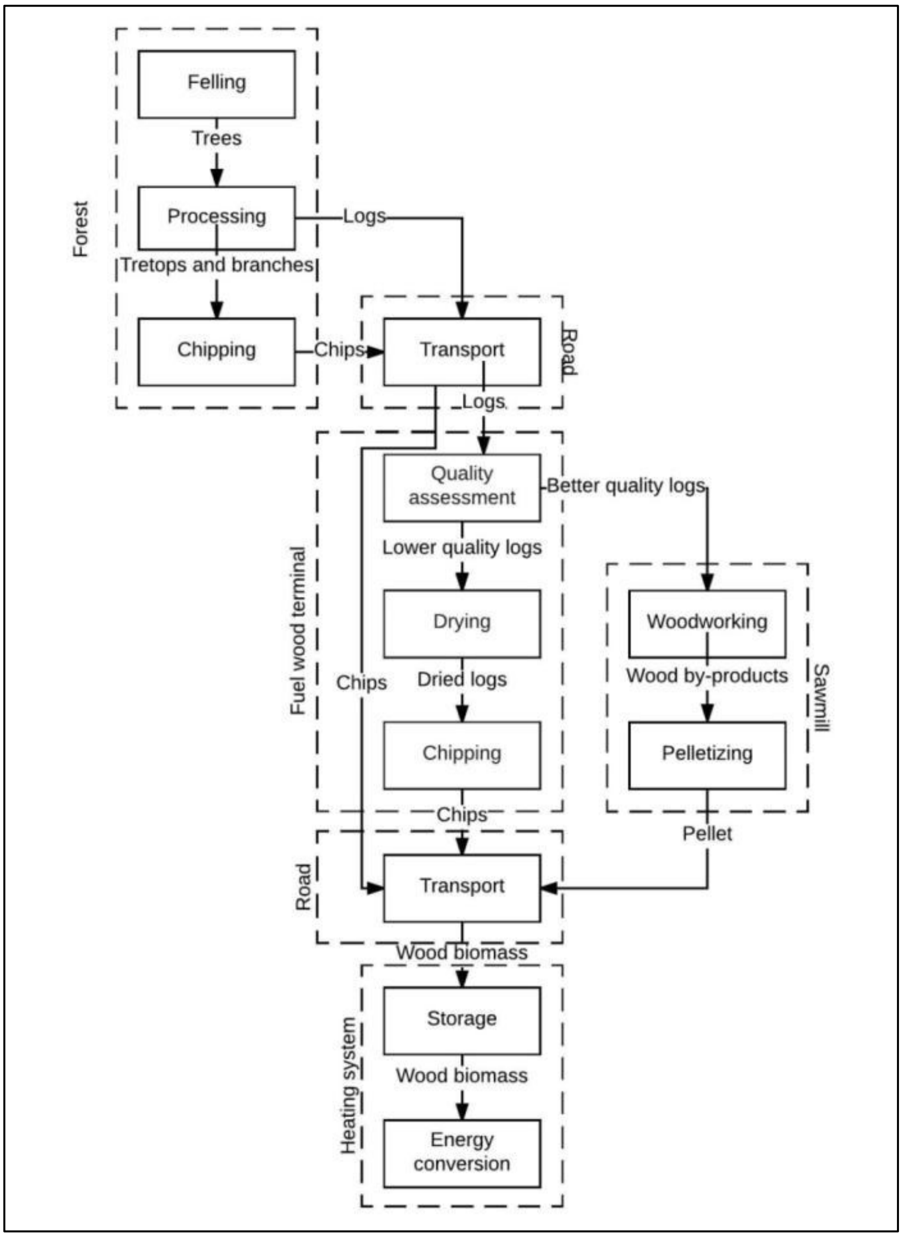

Figure 3.1 - Forest-wood-energy chain

3.2 Identification of the hazard factors sources

In the first stage of the analysis, which was also conducted through the observation of real case studies, the need has arisen for a methodology that would allow the description in detail of the research subjects. The different stages of the supply chain, while taking into account the characteristics that make univocal each case study, are often schematized in some standards work phases that can be found in every analyzed case. Starting from this initial schematization, for each phases of the forest energy chain, sub-phases and elementary processes have been identified. This next schematization is closely linked to the operational choices identified for each case. When there is the need to assess the suitability of a procedural choice, one virtual scenario to be analyzed, or more, are identified. The virtual scenarios and/or the actual plants, if the design is more set, corresponding to the carried out activities shall be described in detail.

Once each task or process of the forest energy chain has been defined in the detail, for each of them all the features and components of the activity that could cause a risk for the workers or the environment have to be identified. They are identified as sources of hazard.

To simplify the further analysis the sources of hazard have been classified for homogeneous groups. For each identified elementary process the main sources of hazard have been divided into used machineries, materials, work environment and organization. The terms machinery includes all that enter in the definition of machine according the legislation[108] (machine, plants and equipment). Inside the definition materials, everything with which workers can come into contact during the individual activity and that should be considered for the purposes of risk assessment is included. To ease the identification of the materials, they are in divided into raw materials, complementary materials, waste and products. The work organization is divided into general organization, in which reference is made to the whole working sub-phase, and to the operative condition, in which the single elementary process is described. To assess the environmental impact is important to divide the work environment into macro, the area involved in the whole activity, and micro, the area involved in each individual work phase. Figure 3.2 describes the classification identified for the analysis.

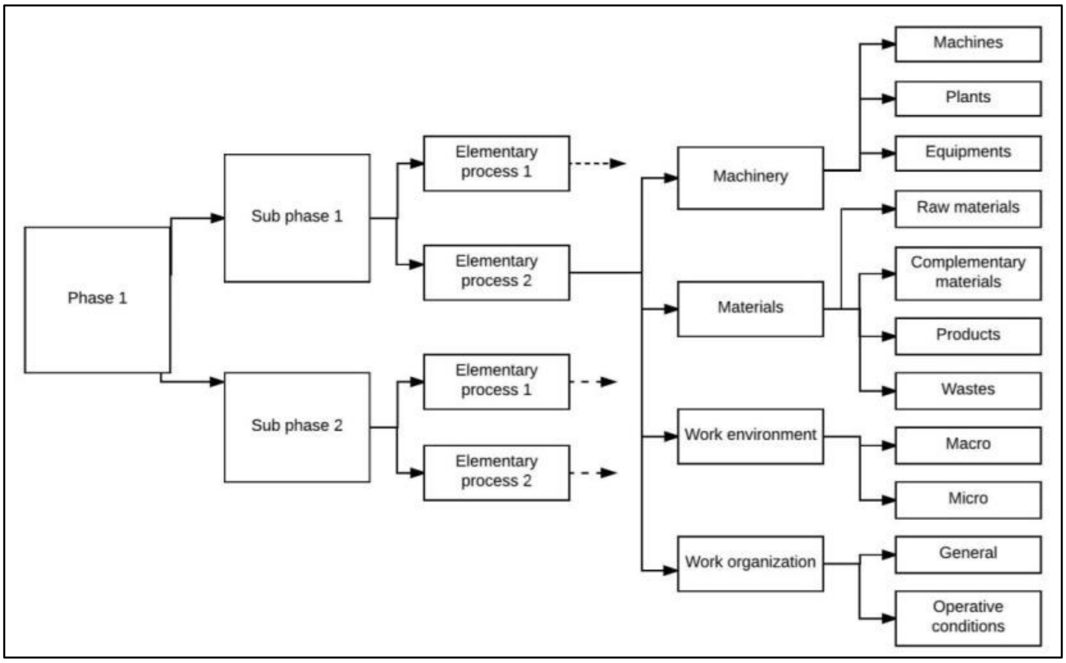

Figure 3.2 – Scheme of the analytical method

This subdivision of the hazard sources allows an exhaustive identification of everything that may create a risk for the workers or the environment.

Starting from this scheme, the analysis ramifies in the two sector of the analysis: the OS&H analysis and the environmental impact assessment and the sustainable management. The previous table is however fundamental to maintain an overview of the whole problem.

Regarding the environmental impact assessment, this methodology is provided for activities and process for which there are not law obligations. Regarding the OS&H the methodology is developed to provide an evaluation tool from which can start all the assessment prescribed by law.

3.3 Occupational safety and health

All the sources of hazard that are identified in the previous phase of analysis can result potentially in a risk for the health and safety of the workers. Therefore every single source of hazard should be analyzed, assuming for each of them the main operating scenarios to observe theirs interferences with the workers.

On this basis, all factors of hazard that may result from the interaction between the workers and the analyzed sources of hazard should be identified. The identification of all the hazard factors is not easy because different aspects have to be taken into account. Once each of them have been identified, the deviations and the damages associated with them have to be determined. In this assessment, not only the immediate risk for the safety of workers (i.e. accidents) but also the risks that can lead to long term health issues (i.e. occupational diseases) must be considered.

After determining all the risks, the technical interventions and the operational procedures to put in place to minimize them should be identified. The aim of the interventions that are implemented is to reach the minimum level of risk. Once implemented all possible measures, a residual risk can remains. To ensure the safety of workers, the collective (CPE) and personal protective equipment (PPE) must then be guaranteed.

For each source of hazard that is identified above and considering the described classification, the related hazard factors, the potential damages associated with them, the technical interventions to be put in place, the procedures to be followed to minimize the risk, the CPE and the PPE to adopt are therefore identified (Figure 3.3).

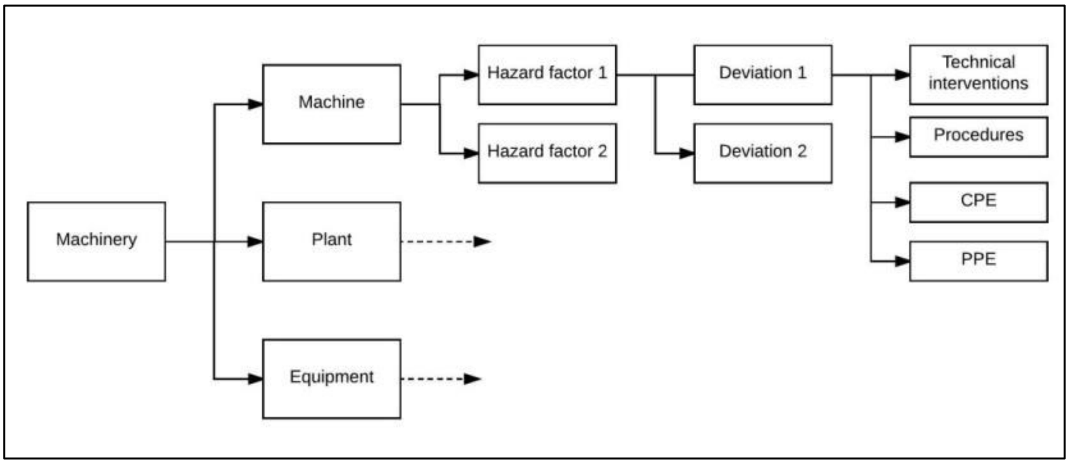

Figure 3.3 – Description of the method for the analysis of occupational safety

In the interest of a proper risk assessment, each source of hazard must be analyzed in detail by referring to the concerning legislation, the technical regulations and the available documentation. Therefore, in determining the hazard factors and the procedures to be followed regarding the machines used is important to refer to the machine documentation (declaration of conformity and the use and maintenance manual)[108] and the technical safety legislation when existing. The analysis of the materials used should refer to the product labeling[146] and the safety data sheet[147], whether it is a chemical substance.

The applied methodology made possible the analysis and the management of the whole plant or activity in all its complexity, which is necessary for an effective Prevention Through Design[148]. The virtual scenarios which have been identified are analyzed and if the risk is not considered acceptable the work activity or the plant is modified and if necessary redesigned. In this way moreover detailed sheet containing the procedures to minimize the risks and the CPE and PPE to give to the workers and available for each person involved in the management of the work activity.

This analysis scheme determine the correct Hazard Identification in standard operating conditions considering mainly the regular productive cycle. Regarding Risk Analysis[149] and Risk Assessmment[150], the occurrence probability, the damage magnitude and the contact factor can be quantified for each individual elementary processes by applying appropriate and dedicated methodology when necessary and required by law, as the Job Safety Analysis (JSA). Therefore the risk associated with the elementary processes, can always be obtained in standard operating conditions.

3.4 Environmental impact assessment

To assess the impact on the surrounding environment that each hazard source may have, the described methodology for the OS&H was hereinafter modified and implemented in order to allow the identification of all the factors which can induce a change in the environment conditions of quality or an impact on the territory introducing the criteria of the DPSIR method. The DPSIR (Driver – Pressure – State – Impact - Response) framework, developed by the European Environmental Agency[151], has been widely adopted in the study of environmental problems. Through a classification of environmental indicators, it simplifies the impact assessment that a project may have on the surrounding area.

DPSIR is a complex analysis framework that can be summarized as follows[152,153]:

- The Driving forces are processes and anthropogenic activities able to cause pressures;
- The Pressures are direct stresses, deriving from the anthropogenic system and affecting the natural environment, i.e. pollutant release;
- The State reflects the environmental conditions of natural systems;
- The Impact is the measure of the effects due to changes in the state of environmental system;
- The Response is the evaluation of actions oriented to solve environmental problems in terms of management strategies.

Used mainly in environmental impact assessment[154] for certain public and private projects, its criterion of analysis may be also suitable and applied in analogy to assess the impacts related to smaller size project. The DPSIR framework has already been used in some studies to assess the sustainability of forest management practices[155,156].

The divisions in phases, sub-phases and elementary processes was maintained from the previous phase of analysis. The drivers correspond with the previously identified hazard sources and the same division is maintained. Indeed each sources of hazard previously identified has the same potentiality to determine an impact on the territory. The work environment, in this phase of analysis, must be assessed not only as a possible source of hazard but also to determine the sphere of influence of each individual elementary process but also of the whole work activity or process.

Each identified driver can determine pressures on the external environment which could potentially induce a modification or an impact on the territory. The pressures are defined maintaining the division in elementary processes previously identified. This simplifies the characterization of the pressures, but complicates the assessment of the cumulative effects. Indeed it makes difficult an overview of the whole issue. For this reason the cumulative impacts given by the interference of different sources of pressures will be analyzed more in detail in a specific chapter.

The surrounding environment is examined in two different perspectives. The first was as an ex-ante state, i.e. the initial conditions of the environment that must be protected and maintained. The second relates to the characteristics of the environment that may affect the work activities and the design choices. Some features may determine the a priori exclusion of some possible design choices. The evolution of some of these parameters should, however, be considered to evaluate the alteration of the environmental state. Therefore they fall also in the first category. The environmental status must be defined by indicators that allow by their observation through time to determine its possible alterations. The indicators are divided according to the environmental sphere of influence (hydrosphere, biosphere, lithosphere, atmosphere and anthroposphere).

Environmental indicators must be assessed both during the activities (i.e. forest yards, fuel wood terminal or energy conversion) and at their conclusion (in case of forest yards when the environment have to be returned to the initial conditions). To simplify the analysis an example set of standard indicators has been identified. According to the different phases of the forest energy chain and the features of each case study, the most suitable indicators should be identified among the defined set and when necessary other indicators can be added (Table 3.1).

Table 3.1 – Example of a set of indicators defined for the description of the environmental state

Hydrosphere		**Biosphere**		**Lithosphere**	**Atmosphere**	**Anthroposphere**		
Surface waters	**Ground waters**	**Flora**	**Fauna**			**People**	**Landscape**	**Economy**
Hydrological and hydrogeological features		Relative wealth of habitat		Prone to flood danger areas	Significant meteorological data	Resident population	Public green	Existing businesses
Hydrographic network		Biodiversity index		Erodibility	Climatic conditions	Population density	Change in overall landscape quality	Wastes (disposal cost)
Delimitation and description of the basin		Presence of protected natural areas		Geomorphological features	Stationary stations monitoring air quality	Existing road infrastructure	Presence of SCI or SPA	Resource use
Surface water circulation		Biotope presence		Altitude	Hydrological balance	Urbanized area	Nature of the settlement	
Surface water and rainwater circulation		Real vegetables /potential vegetables	Presence of dangerous species	Slope	PM concentration	Cultivated area	Urbanized area	
Chemical - composition		Natural vegetation	Main species	Length of the slope	NO_X concentration	Traffic flows		
Gradient surface flow		Dominant height		Soil use	Noise level	Nature of the settlement		
Flood risk		Relative distance of vegetation from near natural population		Soil surface coverage	Noise emission level	Administrative framework on the ability to maintain and on the health of forests ecosystems		
Physical - composition		Defoliation class distribution		Regime of soil moisture	PM10 exceedances daily limits	Density of forest roads		
		Structural diversification		Permeability	PM10 annual average	Characteristics of forest flows		
		Cut extensions		Waste (final destination)		Nearby sensitive receptors		
		Forest surface				Supply chain size		
						Acoustic class in line with the current Acoustics Classification Plan		

This set of indicators have to be adjusted case by case to actually be illustrative of the surrounding environment.

After defining the pressures and the state of the surrounding area, the impacts on the same can be defined. Starting from the pressures for each elementary phase, the impacts are defined by dividing them according to the environmental component of which their effect manifests itself. All types of impact must be considered: direct, indirect and with delayed effects through time. In a design phase the impacts have to be simply qualified, while after the implementation of the activity or the plant they have to be quantified. In some case the qualitative assessment is sufficient to exclude certain design hypothesis. The quantification of the impacts is done by observing the changes that have occurred in the previously identified indicators. This assessment is not simple because for certain indicators there is a general lack of data and measurements. Therefore for them only an qualitative assessment can be done.

The responses to be put in place to reduce the impact on the territory, according to the results, have been defined for individual sources of hazard. The degree of impact on the area determines whether the used machines and the materials and the identified organization of work can be maintained, possibly implementing improvement measures, or if the procedural and technical choices need to be completely reviewed. Based on the measures put in place, preventive or protective, the responses can take action on the drivers, the pressures or the state and directly or indirectly influence the impact.

3.5 Method validation

The method has been developed to be applied in expeditious manner but to allow at the same time a comprehensive assessment of the research subjects. In order to validate the obtained results standard methodologies for separate evaluation of specific aspect of OS&H and environmental sustainability will be applied to different case studies. In fact, as already previously pointed out, the lack of a unified standardized method for the assessment of the different phase of the forest energy chain has determined the need to develop a specific method.

The following methods will therefore be applied in the next chapters in parallel to the described above methodology.

As regards the description and overall assessment of the analyzed system the Failure Mode Effects Analysis (FMEA) was chosen as the comparison methodology among the several different risk analysis methodologies used in the process activities[157]. It has been chosen because given its ability to take into account each individual components of the analyzed system, it should allow to determine if the method in its simplification to allow an easy application can be equally exhaustive. Moreover it starts from an overall description of the system, basic criteria for the choice of the method, and then it goes into the detail of the components. Given the approach bottom-up of the FMEA which will be used in the analysis, starting from the possible failure modes and arriving at theirs causes, the reliability of the results have been considered compatible with an Event Tree Analysis (ETA)[158] with the advantage of a more expeditious analysis.

Regarding the assessment of the occupational safety closely related to the activities undertaken by the workers, the Job Safety Analysis (JSA) will be applied to validate the results. Considering the features of the work activities that are present in the supply chain, it was considered the most appropriate methodology for the risk analysis. This because the analyzed activities are usually done by a single worker, making the JSA the most suitable technique of Hazard Identification. Moreover it has been considered the most suitable to verify if the detail achieved through the application of the method is sufficient for an in-depth analysis.

The validation of the environmental impact assessment will be made by carrying out the measurements for the hazard factors that will be considered most significant.

The methodologies identified for the validation are described below.

3.5.1 Failure mode effects analysis

The FMEA is a technique of Hazard Identification[159] mainly applied to the process industries.

The FMEA is a tool that is used to identify potential failures in products and processes before the problem occurs, to assess the risks, and to develop strategies to eliminate them[160]. Failure refers to a function, a component or a process that does not work as it was designed.

The analysis is aimed at identifying the relationships between the individual failure scenarios and the propagation of the deviations to other involved machines. The main types of FMEA are[159]:

- System FMEA. It is used to analyze systems and subsystems in the early concept and design stage.
- Design FMEA. It is used to analyze products before they are released to manufacturing.
- Process FMEA. It is used to analyze manufacturing and assembly process.
- Service FMEA. It is used to analyze services before they reach the customer.

FMEA allows to determine three basic criteria to assess the problem[161]: severity, occurrence and detection. To each of them a value ranging from 1 to 10 is assigned (Table 3.2). The product of these three parameters, the Risk Priority Number (RPN), is used to prioritize the improvement actions. Once this action are implemented, the RPN should be recalculated to evaluate the efficiency of the undertaken actions.

Table 3.2 – Criteria to assign value to effect, occurrence and detection[161]

Severity	Rank	Occurrence	Rank	Detection	Rank
No effect	1	Almost never	1	Almost certain	1
Very slight effect	2	Remote	2	Very high	2
Slight effect	3	Very slight	3	High	3
Minor effect	4	Slight	4	Moderately high	4
Moderate effect	5	Low	5	Medium	5
Significant effect	6	Medium	6	Low	6
Major effect	7	Moderately high	7	Slight	7
Extreme effect	8	High	8	Very slight	8
Serious effect	9	Very high	9	Remote	9
Hazardous effect	10	Almost certain	10	Almost impossible	10

The realization of the FMEA requires the cooperation of a multidisciplinary expert team to have a thorough understanding of all aspects that may affect the operation of the system. For this during the study and the application of the methodology, different subjects with specific expertise have been consulted.

A variant of the FMEA is the Failure Mode Effects and Criticalities Analysis (FMECA), which takes into consideration also the criticality of each failure mode, or the degree of damage that a failure can cause respect to the others.

3.5.2 Job safety analysis (JSA)

In the application of Job Safety Analysis, the attention is concentrated on the job tasks performed by a person or group[162]. It focuses on the relationship between the worker, the task, the tools and the work environment[163].

The analysis is based on the simplifying assumption that there is a only one worker in the area concerned. The analysis is based on a list of the elementary processes into which a work activity can be broken down. A detailed analysis is made of the operations performed by each employee and each complex operation is broken down into elementary activities. Each elementary operation is associated with the duration allowing to create a time/operations diagram.

Each elementary operation is analyzed in order to determine the factors of hazard which are present in it. Once they have been identified, based on the diagram time/operations the contact factor can be determined.

Once the hazard factors have been determined, the risks and damage that may result from them and their interference with the activity of the worker can be identified.

Assuming to implement all the technical and procedural actions necessary to minimize the risk, the residual risk that is associated with each task is determined by multiplying the contact factor for the magnitude of the damage.

3.5.3 Measurement of emissions

The preliminary assessment carried out found that the potentially most significant impacts to the environment arising from the supply chain and the heating systems under analysis are the atmospheric emissions, in particular particulate matter, and the noise.

<u>Methodology to measure emission at the chimney</u>

Italian law does not exist for the definition of the measurement methodology of the emissions from biomass generators. The measuring instrument used is developed with reference to the German legislation[164]. The correction depending from the measurement uncertainty was determined going in analogy to the regulations for NO_X[165].

<u>Methodology to assess the airborne particulate PM_{10} concentration</u>

PM_{10} is thus defined in the legislation[166]: "PM_{10} shall means particulate matter which passes through a size-selective inlet as defined in the reference method for the sampling and measurement of PM_{10}, EN 12341, with a 50% efficiency cut-off at 10 µm aerodynamic diameter";

The limit values for the living environment are the following (Table 3.3):

Table 3.3 – PM_{10} limit values for the ambient air[166]

	Averaging period	Limit value
PM_{10}	One day	50 µg/m³, not to be exceeded more than 35 times a calendar year
	Calendar year	40 µg/m³

These values are, however, to be taken only as indicative as they are the concentration limits at the receptor of damage. As regards the present work, the methodology described hereinafter was used for measuring the concentration of particulate matter at the emissive sources. In order to assess how a source of emissions could influence a territory a long period of samplings should be programmed in order to observe the modification in the quality of the air. The aim of the measurement which have been done in the present work is only to assess the verify the pressures on the territory given by the sources. An assessment of the impact should take into account different factors and to valutate it a model for the dispersion of pollutant has been chosen (see chapter 8).

PM_{10} measurements will be carried out with continuity by applying in analogy the acquisition methodology of the standard for the determination of the airborne particulate mass concentration[167]. The methodology provides the passage of ambient air through a sampling head at a known and constant flow provided with dimensional selector. The fraction of particulate matter which is to be measured is collected on a filter for a nominal period of 24 h. The particulate mass is determined by weighing the filter in constant specific conditions before and after the sampling.

The results of the measurements are given in µg/ m^3, where the volume of air is calculated at the environmental conditions in correspondence of the sampling head inlet.

The concentration is determined as the difference in mass between the sampled filter and the non-sampled filter, divided by the aspirated volume, calculated as the flow multiplied for the sampling time.

$$c = \frac{m_l - m_u}{\varphi_a \cdot t}$$

Where c = concentration (µg/m^3);

m_l = mass of the sampled filter(µg)

m_u = mass of the non-sampled filter (µg)

φ_a = flow at the environmental conditions (m^3/h)

t = sampling time (h)

As it is expressed by the legislation[166], the assessment of the measures uncertainty should be based on the approach described in the “Guide to the expression of uncertainty in measurement”[168]. The uncertainty shall be calculated for the limit value of particulate air pollution. In agreement with the elements of legislation, the uncertainty is calculated for individual measures. In this case the measures correspond to a period of 24 h. By implementing these simplifying assumptions the relative uncertainty is therefore equal to 3,8%.

<u>Methodology to assess the acoustic impact</u>

In Italia, the Framework Law[169] regulates the criteria, indicators, responsibilities, controls, deadlines and reference penalties to check and mitigate the territories noise pollution. It has been issued in advance of the Community legislation[170].

Since its entry into force a series of executive decrees and regional laws have been issued to complete the regulatory framework. Particularly[171], the limits of the noise sources have been defined for classes that are defined by the acoustic zoning. For each class the input, output and quality day and night limits are set in the acoustic territorial zoning which is defined by each municipality.

The measurements were made in accordance with the procedures defined by legislation[172]. The instrumentation used for sound level measurements conforms to the standards[173–175].

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Section 2: Application of the method

Chapter 4

Materials

Hereinafter the case studies in which the methodology has been applied will be described. The different stages of the supply chain were analyzed in order to show the changes that need to be put in place to adapt the methodology to different characteristics and work environment.

4.1 Forest yards

Forestry consists in the activities that are carried out in the woods before the timber is transported to the subsequent processing stages and energy use.

In this study the analyzed systems have their ideal location in mountain valleys or territories. In these areas the timber presents is able to ensure the wood supply to the boilers or heating systems. These territories are, however, often characterized by a fragmentation of forest lots due to both the lack of regularity of forest land, often punctuated by zones turned to pasture, and the diversification of forest owners. This means that tasks are entrusted to small businesses. For them, to ensure compliance with the safety criteria and the use of best available technologies is more difficult. Furthermore, to be harvested parcels are often difficult to reach and they have critical morphological characteristics. The not optimal features of the surrounding environment influence heavily the safety conditions, greatly constraining the available procedures to follow. The work environment also presents a great morphological and climate variability, and this entails a further difficulty in the proper task management. The work has therefore to be carefully planned, in order to identify the most suitable procedures to guarantee the environmental sustainability and the OS&H.

The activities carried out in woodland, regardless of the individual sites peculiarities, can be traced back to the following work phases[104]: analysis of the work environment (cognitive inspection), the site preparation, felling, processing (limbing and sawing), concentration, extraction, activities at the landing (chipping if carried out on site and debarking) and loading on means of transport.

These activities are generally defined deforestation. They can be performed either as part of measures to promote the conservation and cultural improvement of forest stands, both in operations more narrowly targeted to the collection of timber at the end of the crop cycle. According to a proper and sustainable forest management the harvesting of the trees must be conducted according the silvicultural technical specifications and in compliance with numerous regulatory requirements, so as to ensure the regeneration of the stands after cutting in a natural way or by planting and reforestation. Each work phase has a high number of technological alternatives with which they can be carried out. The equipment used in each of these phases depends heavily from the work environment in which one operates and the characteristics of the plants to be cut[176]. Also the economic factor influences greatly the choice of the suitable technology. The amount of timber to be harvested often is the main parameter that determines whether the use of a specific equipment is economically feasible or not[177].

In Table 4.1, together with a short description of the working phase, the main technological alternatives and the work sub-phases have been listed.

Table 4.1 – Main working phases of the forestry

Working phases	Description of the activity	Main technological alternatives	Working sub phases
Preliminary survey	The preliminary survey, carried out by the employer before the work, is used to identify the characteristics that may influence the selection of techniques, procedures and equipment that will be used in the course of forestry activities.		Observation of the work area Observation of the external environment Observation surrounding activities and infrastructure
Yard preparation	The employer shall prepare the yard. Sufficiently large areas must be identified to maneuver the vehicles, for equipment temporary storage and for timber's stacking.		Identification of the perimeter Placement of yard signage Workers information, education and training Endowment of machines, tools, plants and PPE
Felling	Felling refers to the tree cutting off and their knockdown. Before the felling, an examination of the plant is done to evaluate the appropriate procedures and equipment. If the plant, during the felling, remains entangled with other, it must be landed in the shortest possible time.	Manual Motorized.	Choosing the fall direction Identifying escape route, forbidden zone and danger zone Cutting of the stem
Processing	The processing includes all the various working phases after tree felling and knockdown.	Manual Motorized.	Delimbing Cross cutting Debarking
Concentration	The concentration is the material handling stage from the felling point to the striproad. During this phase each piece follows its own path, oriented along the lines of maximum incline, slipping by gravity or being pulled. This step is the most expensive, both in terms of direct costs both of wood and timber damage. It should be shortened and simplified, limiting the covered distance.	Manual Agricultural tractor with winch	Identifying concentration technology Identifying the concentration point Timber handling Timber movement
Extraction	The extraction occurs along paths specially equipped, the striproads, through which the material is brought up to the log yard, the landing, truck loading point. The striproads can be permanent or temporary. The distances of extraction are normally on the order of hundreds of meters.	Tractor with winch; Tractor with grabble; Tractor with trailer; Tractor with trailer and crane; Cable crane; Helicopter.	Identifying extraction technology Locating points for the vehicles arrival Timber handling Timber movement
Activity at the landing	The work phases, which cannot be carried out on felling point for reasons related to their mechanization, take place at the landing.		Chipping Debarking Loading timber and chips

The forest yards usually occupy variable size portions of the territory which can have not optimal characteristics to execute the work activities, both from an orographic and a vegetational point of view.

The choice is therefore strongly influenced by different aspects and often conflicting aspects. Frequently the most appropriate for the characteristics of the work environment technical or procedural choice is not the best from a workers' safety point of view. It is therefore necessary, as already said, an analysis method that facilitates the identification of the procedures to minimize the risks.

Perform forestry in small size and difficult to access forest lots causes difficulty in the management. To analyze it real case have been identified and examined. For this reason, during the PhD project a period of external activity was carried out in a company that operates in the forestry sector, the cooperative "La Foresta". The examined forest sites were chosen to be illustrative of the context of the short supply chain. The heat generators that have to be supplied are therefore small, placed in an alpine valley area at a short distance from the point of harvesting and extraction. Compliance with the criteria of environmental sustainability is guaranteed by the PEFC certification of the company that performed the activities. Despite the certification, the company itself has expressed the need for a methodology to assess its activities. This company operates in the Alpine valleys of western Piedmont. The examined harvesting activities were conducted in the spring and summer of 2014.

Each of the examined sites shall be considered a separate case, having each of them its own and univocal characteristics. The identification of the most appropriate technology and procedures is often solely relied on the experience of the company that carries out the work and that choice is more critical if the financial resources are limited.

In particular, the methodology has been applied in two different forest yards. They were chosen because the operations that were done during the felling and extraction were illustrative of the different activities that can be carried out within the forest yards. They are located in a Northwestern Italy alpine valley (Figure 4.1) in the municipalities of Mattie and Almese.

The maps present in this and in the following chapters have been produced by the author using as basis an ortophoto developed by Regione Piemonte[178].

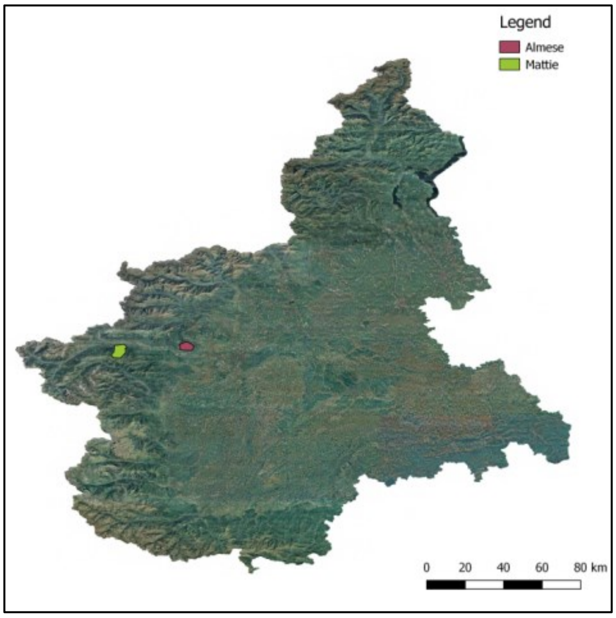

Figure 4.1 – Location of the forest yards

The first examined case study was the thinning of a wooded lot (called "Pera Pluc") located on the territory of the municipality of Almese, on the left bank in the Lower Susa Valley. It is located at an altitude of between 570 and 620 MASL and it has an extension of about 2.25 ha. (Figure 4.2). It is located in an area where there are reforestation of *Pinus nigra*, mainly, and *Pinus sylvestris*.

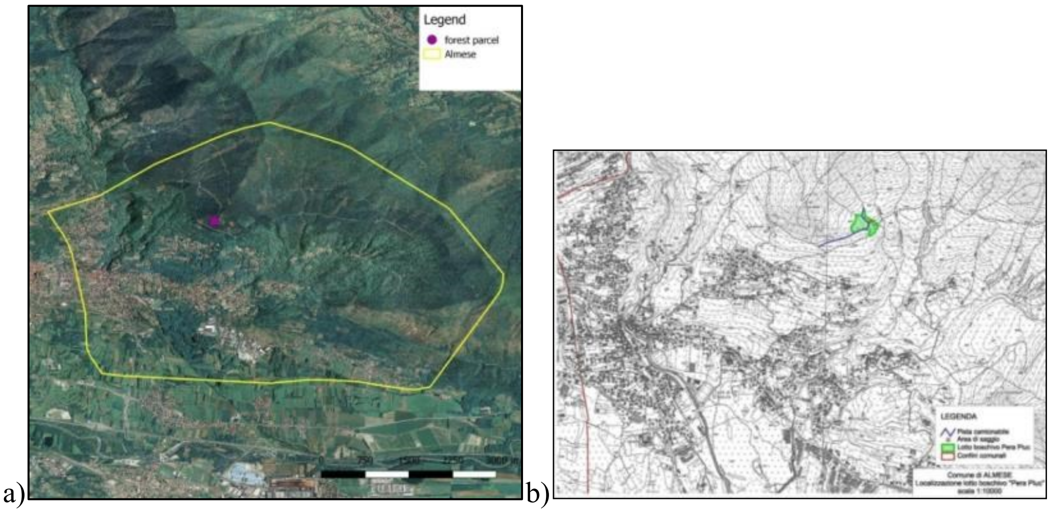

Figure 4.2 - Location (a) and extension (b) of the "Pera Pluc" wood lot

The wooded lot is accessible via two forest tracks: one that runs at the foot of the lot and the other running through the lot. Both are unpaved, but with characteristics that allow the access of all the required on site forest machines.

The activities were carried out by three operators for a period of about two months in the 2014 spring-summer.

The lot has a not excessive slope and the distances to be covered between the stump and the accessible by forestry machines points are short. The choice of the most appropriate operating procedures to be used has been made, also, according to these characteristics. The felling, processing and handling operations have not been carried out sequentially. The forest lot has been divided into similar sized areas and the aforementioned processes were carried out area by area to facilitate the movement of vehicles. The work area, being slightly inclined, is suitable for the harvester use (Figure 4.3). It is a machine with a felling and processing head. The machine through the two forest tracks access, manage to access a large portion of the wooded lot. In areas where access is not possible the timber was moved through a forestry winch. The timber was concentrated and stacked according to the characteristics and the subsequent use. Chipping of treetops and branches was made at the landing.

Figure 4.3 - Harvester

The cutting operations of a wooded lot (called “Chatelard”) that is located on the territory of the municipality of Mattie, placed on the orographic right in the Lower Susa Valley, were the second case study. It is located at an altitude of between 970 and 1120 MASL and it has an extension of about 4.08 ha. (Figure 4.4). It is located in an aged coppice where there are mainly *Fagus sylvatica*, *Castanea sativa* and hardwood mixed.

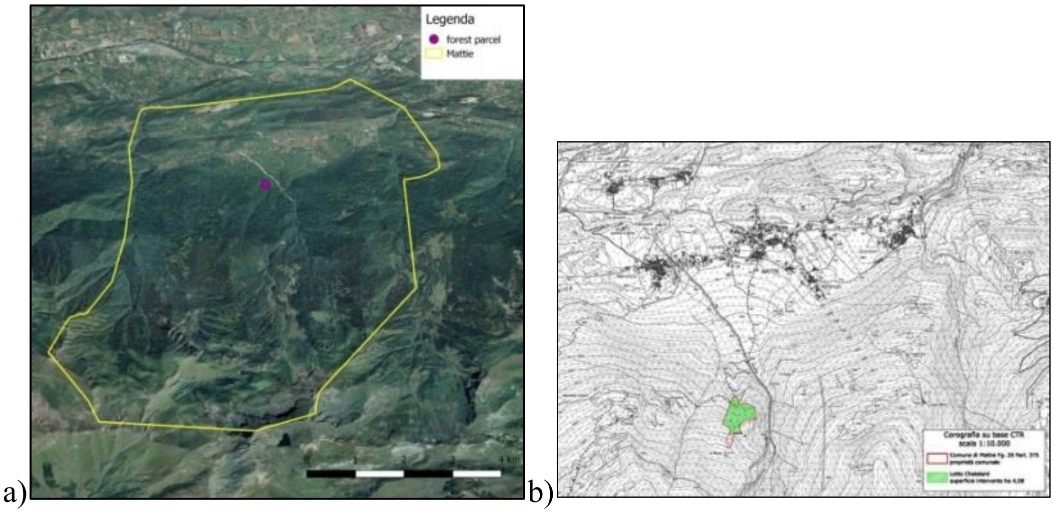

Figure 4.4 – Location (a) and extension (b) of the “Chatelard” wood lot

The forest yard is accessible through a lateral deviation of the provincial road 207 which then continues into a not paved road passing at the base of the wooded lot.

The phase of the material handling was carried out in July-August 2014, while the phase of felling had already been carried out previously in March-April 2014.

The wooded lot has a high slope as it has a vertical drop of about 200 m between the highest and the lowest point. Furthermore, the access of the means of transport is limited at the only stretch of road that passes at the base of the lot.

The first operation was the felling of all the tress to be harvested. The processing was done plant by plant before the starting of the extraction. Given the conformation of the lot, the extraction was carried out using a traditional cable crane (Figure 4.5).

Figure 4.5 – Cable crane

The timber was moved down to the base of the lot where the access of traditional means of transport is possible. The timber was concentrated, using a tracked excavator with hydraulic shears.

4.2 Fuel wood terminal

The characteristics of the supply chain and the fuel needs of heat generators, influences the correct design of the fuel wood terminal. Its main function is the storage of the timber. It must be realized so as to ensure a constant supply of wood fuel to heating systems regardless of seasonal fluctuations. Its proper sizing depends on this function. Other activities that can be carried out in the square, mainly quality assessment and processing, depend on the characteristics of the analyzed supply chain.

The location of the fuel wood terminal depends on its size and the maximization of the efficiency of the transport phase. Therefore it depends on the position of the woods and the heating systems, but also on the used means of transport and therefore the amount and type of timber to be transported and the characteristics of the road infrastructures.

In the present analysis the functions to which the fuel wood terminal is intended are mainly the timber storage, drying and chipping before to be send at the heating systems. The material that comes is first subjected to a quality assessment. Timber suitable for woodworking is sent directly to the sawmill, while the lower quality timber is intended for energy purposes. The second is then dried and chipped.

The drying is natural, therefor the material is stored for a period that depends on the initial moisture and the type of timber. The chipping is done before sending to heat generators since the storage of wood chips is not recommended for long periods because a degradation process of the chips can start.

The treetops and branches are usually already chipped at the forest yards. This chips are stored for a as short as possible period of time before being sent to the heat generators. Given their poor quality, they can only be sent to plants equipped with the appropriate emission control systems.

The main stages of work taking place in this stage of the supply chain are therefore as follows:

- Discharge of the timber and/or wood chips;
- Quality assessment;
- Timber for energy purposes identification;
- Sending of the better quality timber at the sawmill;
- Timber storage in a suitable location for drying;
- Storage of wood chips for a short period if necessary;
- Periodic checks of the drying process;
- Timber movement in the vicinity of the chipper;
- Wood chipping;
- Loading of wood chips on transportation.

4.3 Heating systems

The PhD projects focused mainly on wood chips boilers. This solution is the most suitable both as regards the possibility through the chipping to use an higher percentage of felled plants, and for the possibility of such plants to be used for low energy requirements.

The analyzed heat generators are nearby the described above forest yards. In particular they are located in the municipalities of San Giorio di Susa, Almese and Mattie in the northwestern Piedmont (Figure 4.6). The figure also shows the power of the installed boilers. All the examined systems are designed to ensure the thermal requirements of small complex of buildings.

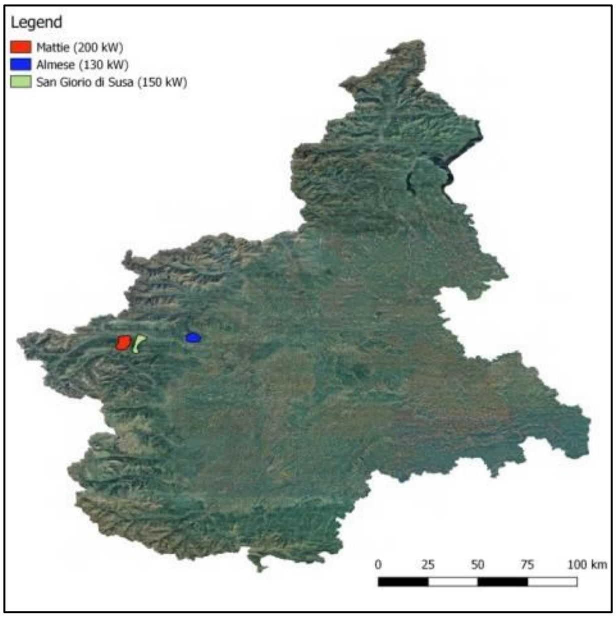

Figure 4.6 – Location of the examined boilers

The examined systems were generally composed by:

Figure 4.7 – Example of analyzed chips boiler

- Stoker grate chips boiler with an average power between 130 and 200 kW. The size of the boiler has been assessed in order to be compatible with their implementation to supply little complex of the buildings through district heating systems. The supply of hot water to the different buildings is beyond the scope of this research.

- A water storage tank (i.e. a puffer) of sufficient capacity to ensure supply of the building to be heated (Figure 4.8). It is connected to the boiler through a three-way valve, useful to absorb the abrupt power changes given by the not regular combustion. In this type of system the installation of this component is very recommended as it increases its efficiency in no small measure. In stationary operation the temperature inside the puffer is about 75 °C.

Figure 4.8 – Puffer

- Two fan coil connected to the puffer to disperse the excess power when the operating temperature has been reached.
- A fuel extraction screw driven by an engine. Depending on the thermal load to be supplied the rotation and pause between two rotations time is automatically altered, in order to have a more or less frequent and/or heavy load.
- A chips storage tank with a capacity such as to ensure sufficient operating time according to the plant requirement (Figure 4.9). Handling systems are

generally present to avoid the formation of so-called "bridges", which can block the fuel loading.

Figure 4.9 – Chips storage tank

- Network of pipes and pumps with temperature and flow rate sensors.

An example of scheme of the analyzed system is shown in Appendix 1.

The activities that characterize this stage of the supply chain can be divided into process activities, that relate to the functioning of the system, and management and maintenance activities that require the presence of workers. The process steps that take place within the plant are generally: chips supply system, chips boiler, smoke and/or air purification line, combustion waste collection system, water heating and building heating.

The plant management foresees the presence of workers only as regards the step of storing the fuel in the chips storage tank. As regards maintenance, it will be distinguished in the subsequent analyzes in ordinary and extraordinary maintenance.

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Chapter 5

Application of the method to standard activities

Below some results will be shown as an example of application of the methodology to case studies belonging to different phase of the wood energy chain. The terms standard means activities which, as regards the used technologies and procedures, are well-known and spread among the companies working in the forest energy field. The results obtained have allowed to determine what operational steps were the most critical with regard to the OS&H and the impact on the environment. The technical interventions and operational procedures to put in place to reduce these issues have also been determined.

The obtained results allowed to identify the changes to be applied to the method. They were necessary in order to allow its application to different for characteristics, size and location research subjects.

Part of the work that has been described in this chapter has been addressed briefly in some publications[179,180]. They were written during the doctoral period.

5.1 Forest yards

Observing case by case the characteristics of the place where the examined forestry activities are carried out, the sector operators identify the technologies and procedures deemed most suitable. The method of analysis was applied in a first step by referring to these operational and procedural choices. The examination of the results allowed to determine whether these choices were also appropriate from the points of view of environmental sustainability and OS&H, i.e. whether the impacts on the environment and the risks for the workers were minimal. If so, the technical and procedural measures to be put in place to minimize the residual risks have been identified. If not, the choices made were revalued and the most suitable alternatives have been identified.

In the first stage of the study the hazard sources have been identified. The forest yards, especially in recent years, are characterized by an high mechanization that involves all the different work phases. Therefore the most significant hazard sources are the machines that are used for the felling and the handling of timber.

In Table 5.1 and Table 5.2 the sources of hazard for two different phases of the forest yard have been identified. The results show that in both the case studies the most significant hazard sources are the machines which are used in the site.

Sources of hazard for the phase of timber handling with yarder

Sub Phases	Elementary processes	Machinery	Materials				Work environment	Work organization	
			Raw materials	Complementary materials	Waste	Product		General	Operative conditions
Handling with yarder	**Timber docking**	Yarder	Trunks, branches	Diesel fuel, steel ropes	▨	▨	Forest	2 workers	1 worker docks the tree to the rope, 1 worker starts the winch
	Timber lifting				▨	▨			1 worker starts the winch, 1 worker directs the tree movements
	Timber handling				▨	▨			
	Timber lowering				▨	▨			
	Timber unhooking				▨	▨	Staple	1 worker	1 worker unhooks the tree
Stacking through crawler excavator	**Timber lifting**	Crawler excavator with hydraulic shears		Diesel fuel	▨	▨			1 worker steers the excavator
	Timber handling				▨	▨			
	Stacking				▨	Timber piles			

zard for the phase of timber limbing and cutting with harvester

Sub Phases	Elementary processes	Machinery	Materials				Work environment	Work organization	
			Raw materials	Complementary materials	Waste	Products		General	Operative conditions
Felling	**Plant gripping**	Harvester	Tree	Diesel fuel	Sawdust, leafage				1 worker steer the harvester
	Cutting					Landed log			
Limbing and cutting	**Timber lifting**		Log				Processing area	1 worker	
	Limbing					Limbed log, branches			
	Cutting					Cut logs			
	Log deposit					Timber piles			

5.1.1 Occupational risk analysis

Once the sources of hazard have been identified, they were individually analyzed to determine the factors which can determine a situation of hazard for the workers. Each machine used in the forestry has characteristic factors of hazard that determine the need to adopt certain technical interventions and operating procedures to ensure safe conditions (what is safe at the landing might it may not be safe in an inclined slope). Table 5.3 and Table 5.4 show the analysis that has been applied to the harvester and the cable crane. They are among the most hazardous machine that are used in a forest yard and they were considered representative of the analysis that has been done. However it is important to observe how the high mechanization imply a safer operative place for the workers compared to for example the use of chainsaw.

Both analyzed machines are characterized by the presence of factors of hazard such as the falling from a height of material and moving mechanical parts. They are among the factors of hazard related to the use of machinery which may pose a higher risk for the workers. This depends on both the magnitude of the damage which may result and the contact factor. Other hazard factors resulting from the used machines which may pose a significant risk for the health of the workers are noise and the production of sawdust and dust during the cutting activities. In this cause the presence of this factors of hazard may determine the appearance of occupational diseases for the workers.

Table 5.3 – Occupational risk identification of the harvester

Machinery	Hazard factor	Possible associated deviations and damages	Technical interventions	Procedures	CPE	PPE
Harvester	Awkward postures	Muscoloskeletal and articular damages		Take appropriate postures Adopt the correct operating procedures		
	Dust and sawdust	Eyes and airways irritation		Maintain safety distances		Eyes protection
	Sharp blades	Contusions, wounds	Verify the presence of the hot surface protection systems	Adopt the correct operating procedures		Gloves Safety shoes
	Moving mechanical part	Contusions, fractures wounds	Verify the presence of the protection systems	Perform maintenance and overhaul following the instructions in the manual		Gloves Fitting clothing
	Projection of splinters	Wounds to the face and eyes				Eyes protection
	Loss of control	Contusions, fractures, wounds, injuries	Installation of anti-tipping devices	Move the machine along the lines of maximum slope to prevent tipping; Adopt correct operating procedures Observe the predetermined yard viability		
	Material fall from a height	Contusions, fractures, wounds, crushing injuries, injuries to internal organs		Maintain safety distances Adopt the correct operating procedures Ensure the stability of the load		Safety helmet Gloves Safety shoes
	Entanglement and dragging	Fractures, wounds and injuries from crushing	Verify the presence of the hot surface protection systems	Maintain safety distances		Fitting clothing Safety shoes Gloves
	Flammable liquids	Burns		Do not smoke Do not use open flames Adopt the correct operating procedures for refueling		
	Hot surfaces	Burns from contact	Verify the presence of the hot surface protection systems	Adopt the correct operating procedures		Gloves Protective clothing
	Noise	Hypoacusis, physiological disorders, interferences with verbal communication		Perform maintenance and overhaul following the instructions in the manual Reduce the exposure time by appropriate work organization		Ear protection

Table 5.4 – Occupational risk identification of the cable crane

Machinery	Hazard factor	Possible associated deviations and damages	Technical interventions	Procedures	CPE	PPE
Cable crane	Material fall from a height	Contusions, fractures, wounds, crushing injuries, injuries to internal organs	Ensure the stability of the load	Maintain safety distances Adopt the correct operating procedures		Safety helmet Gloves Safety shoes
	Work at height			Adopt the correct operating procedures	Devices to prevent falls from height	Safety helmet Gloves Safety shoes Fall protection harnesses
	Moving mechanical parts	Contusions, fractures, wounds	Verify the presence of the protection systems	Perform maintenance and overhaul following the instructions in the manual		Gloves Fitting clothing
	Flammable liquids	Burns		Do not smoke Do not use open flames Adopt the correct operating procedures for refueling		
	Hot surfaces	Burns from contact	Verify the presence of the hot surfaces protection systems	Adopt the correct operating procedures		Gloves Protective clothing
	Noise	Hypoacusis, physiological disorders, interferences with verbal communication		Perform maintenance and overhaul following the instructions in the manual Reduce the exposure time by appropriate work organization		Ear protection
	Vibrations to hands and arms	Raynaud's disease, neuro-sensory and osteo-articular disorders		Perform maintenance and overhaul following the instructions in the manual Reduce the exposure time by appropriate work organization		Gloves
	Manual handling of loads	Musculoskeletal and articular damages		Take appropriate postures Adopt the correct operating procedures		Gloves Safety shoes
	Awkward postures					

The previously described methodology was applied by way of example to the materials that are involved in the timber handling with cable crane phase (Table 5.5).

Table 5.5 - Occupational risk identification of the materials

Materials	Hazard factor	Possible associated deviations and damages	Technical interventions	Procedures	CPE	PPE
Trunks branches	Unexpected and sudden shift	Contusions, fractures, wounds, crushing injuries		Keep the predetermined positions and safety distances Adopt the correct operating procedures		Safety helmet Safety shoes
	Rolling					Safety shoes
	Whipping	Contusions, wounds		Keep the predetermined positions and safety distances Adopt the correct operating procedures		Safety helmet Gloves Face shield or safety glasses Safety shoes Protective clothing
	Fall and projection	Contusions, wounds, traumatic injuries				Safety helmet Safety shoes
	Manual handling of loads	Musculoskeletal and articular damages		Take appropriate postures Adopt the correct operating procedures		Gloves Safety shoes
	Awkward postures	Muscle and articular pain				
Steel ropes	Damage and breakage	Burns, lacerations and wounds		Carry out regular checks Make a proper handling		Gloves
	Entanglement and dragging	Contusions, fractures, wounds, crushing injuries		Keep the and safety distances		Gloves Fitting clothing
	Manual handling of loads	Musculoskeletal and articular damages		Take appropriate postures Adopt the correct operating procedures		Gloves Safety shoes
	Awkward postures	Musculoskeletal and articular damages		Take appropriate postures Adopt the correct operating procedures		
Diesel fuel	Flammable substance	Burns		Do not smoke Do not use open flames Keep away from heat Adopt the correct operating procedures for refueling		
	Hazardous substance	Damage to the airways		Adopt the correct operating procedures for refueling Protect airways		Protective masks
	Irritating substance	Skin irritations		Adopt the correct operating procedures for refueling		Gloves Protective clothing

The materials with which workers come mostly in contact in forestry activities are trunks and branches (raw materials), fuels (complementary materials) and the necessary for the tree felling and the log processing utensils (complementary materials). Being material with which the workers enter in contact and therefore strictly related of the work activity the interventions that are preferred to minimize the risk are procedural. If the risk cannot be minimized by procedural measures and the use of DPI, the material is directly replaced.

The work environments where the forestry activities take place, specifically the forest and the landing, have their own characteristics compared to conventional workplaces (not provided for and regulated in the norm). The procedures to be put in place must therefore take account of these features and be adapted each time to the specific case (Table 5.6). Being an external environment the hazard factors are closely linked to the environment itself and therefore it is often difficult to intervene with preventive interventions. The only solution is often to implement specific procedures and providing the protection devices. In this case a careful observation of the environment before the starting of the activities is very important to identify the presence of hazards for the health and safety of workers.

Table 5.6 – Occupational risk identification of the work environment

Work environment	Hazard factor	Possible associated deviations and damages	Technical interventions	Procedures	CPE	PPE
Wood	High temperatures	Dehydration, thermal stress		Take adequate food and drink Suspend work if appropriate		Breathable clothing
	Weathering	Colds, in the event of lightning, burns and electric shock		Ensure the availability of temporary shelters Take adequate food and drink Suspend work if appropriate		Protective clothing
	Vipers	Poisoning				Gloves Safety shoes Protective clothing
	Wild animals	Transmission of diseases		Make the necessary vaccinations		Gloves Safety shoes Protective clothing
	Insects	Local reaction, anaphylactic shock, skin, eye and respiratory tract irritation		Make the necessary vaccinations Use specific repellents		Gloves Safety shoes Protective clothing
	Shrubs and brambles	Contusions, injuries, infections		Make tetanus vaccination		Gloves Safety shoes
	Trunks and rocks rolling	Contusions, fractures, wounds, traumatic injuries		Adopt the correct operating procedures		Safety helmet Safety shoes
	Slips and falls	Contusions, distortions, fractures, musculotendinous injuries, wounds		Adopt the correct operating procedures		Safety shoes
	Instability of the slope	Injuries		In the event of excessive rain, suspend the processing Adopt the correct operating procedures		
Staple	Investment	Contusions, fractures, injuries		Maintain safety distances Adopt the correct operating procedures Observe the yard mobility		

In the analyzed cases the organization of work requires that in the forest yards three workers are present simultaneously. The working procedures must have been previously determined and each worker must have its own task (Table 5.7) and its paramount to avoid the interferences between the different activities. The workers must be informed, educated and trained before the starting of the activities.

Table 5.7 - Occupational risk identification of the work organization

Work organization	**Hazard factor**	**Possible associated deviations and damages**	**Technical interventions**	**Procedures**	**CPE**	**PPE**
3 workers	Failure to comply with the work organization	Interference with other processes, incorrect load's handling		Observe established breaks and the forecast work rotation Respect the timetable imposed by the employer Adequately informed, instructed and trained workers		
	Work-related stress	Stress, psychological disorders				

Once all the sources of hazard were assessed, the analysis must determine whether the technical interventions, the operational procedures and the CPE are sufficient to ensure the health and safety of workers, i.e. if the safety and health of the workers is guaranteed. According to the identified risk, the most suitable techniques of Risk Analysis and Assessment have to be applied. If this is not possible the technical choices need to be reviewed and the critical work phase must be modified. In this way, a real Prevention Through Design is done because OS&H is already considered at the design stage.

The case studies and the application of the method are shown in detail in a specific document[181].

5.1.2 Environmental impact assessment

The evaluation of the environmental impacts was done, as it has been described above, with a modified and implemented version of the DPSIR method.

The drivers coincide with the identified previously sources of hazard. In this part of the analysis it is important to pay particular attention to the work environment and work organization. The work environment must be divided into macro and micro in order to identify areas of impact and action. The large-scale workplace is defined by the area of influence. It is evident that it can be much more wide of the area where the activities are strictly carried out. The fact that the forestry activities are carried out in non-anthropic environments must also be taken into account for their greater sensitivity to the action of the human beings.

As regards the general organization of work, the influence that processes can have depends on their duration, and, consequently, on the number of workers. The repetitiveness of different processes must also be considered.

To each identified driver the pressures that it can induce on the surrounding environment are associated. They, like the drivers, are defined according to each elementary processes and distinguished according to their origin. This simplifies the characterization of the pressures, but it makes it difficult to assess the cumulative effects that are related to the whole work phase. Table 5.8 shows the pressures that derive from the phase of felling, cutting and limbing with machines (Table 5.2). As in Occupational Safety and Health analysis, the most significant pressures for the environment derive from the machines used. In this case is important to observe how the difference between the duration of the activities changes according to the used equipment and so the duration of the emissions of the different pressure. The duration of the same process according to the chosen technology can influence the consequent impact of the territory.

Table 5.8 – Pressures for the felling, limbing and cutting sub phases

Sub Phases	Elementary processes	Machinery	Materials				Work environment		Work organization	
			Raw materials	Complementary materials	Waste	Products	Macro	Mcro	General	Operative conditions
Felling	**Plant gripping**	CO, HC, NO_X, PM, noise	Removal of organic matter, removing roots, failure to absorb CO_2	Fuel leaks, spills during refueling	Sawdust	▨	Soil compaction, alteration of the landscape	▨	Transit of means of transport	▨
	Cutting					Removal of organic matter		Alteration of landscape		▨
Limbing and cutting	**Timber lifting**				▨	▨		▨		▨
	Limbing				Sawdust	▨		▨		▨
	Cutting					▨		▨		▨
	Log deposit				▨	▨		▨		▨

In the examination of the surrounding environment it is important to maintain a distinction made between ex ante state and working area according to the parameters that must be taken into consideration. This distinction is reflected in the characterization of the environmental state. In the characterization of the state there are features which are important because they influence the work activity and the technological choices while others are important because they represent characteristics of the environment to be protected. Some parameters can cover both the aspects.

In Table 5.9 a distinction is made between the environmental indicators to be protected (blue), those that are useful to characterize the lot for work purposes (white) and those included in both categories (light blue). The indicators are diversified according to the different environmental components to which they refer: hydrosphere, biosphere, lithosphere, atmosphere and anthroposphere.

This table is a representation of the environment and therefore it is destined to evolve during the work to make explicit the impacts on the environment. Environmental indicators must therefore be assessed both during the activities and to their conclusion. It is obvious that the assessment of the environment must be carried out by experts of forestry. The parameters listed in the table are only examples. They should be adjusted case by case to actually be illustrative of the surrounding environment.

To simplify the assessment of the actual state of the environment, the impacts are classified according to the environmental component on which their effect is expressed (Table 5.10). Regarding the analyzed activities the most significant impacts can be found on the atmosphere. This is due to the high level of mechanization of the work activities. According to the identified impacts and the environmental components on which they act, the indicators previously identified should be analyzed again in order to quantify the aspects. The analysis shown in this table has be only qualitative for lack of data which can allow a characterization of the state of the environment before and after of the activities.

Table 5.9 – Environmental state of the lot and the surrounding area

Hydrosphere		Biosphere		Lithosphere	Atmosphere	Anthroposphere		
Surface waters	**Ground waters**	**Flora**	**Fauna**			**People**	**Landscape**	**Economy**
Hydrological and hydrogeological features		Relative wealth of habitat		Prone to flood danger areas	Significant meteorological data	Resident population	Public green	Existing businesses
Hydrographic network		Biodiversity index		Erodibility	Climatic conditions	Population density	Change in overall landscape quality	
Delimitation and description of the basin		Presence of protected natural areas		Geomorphological features	Stationary stations monitoring air quality	Existing road infrastructure	Presence of SCI or SPA	
Surface water circulation		Biotope presence		Altitude	Hydrological balance	Urbanized area		
Surface water and rainwater circulation		Real vegetables /potential vegetables	Presence of dangerous species	Slope	PM concentration	Cultivated area		
Chemical - composition		Natural vegetation	Main species	Length of the slope	NO_X concentration	Traffic flows		
Gradient surface flow		Dominant height		Soil use	Noise level	Nature of the settlement		
Flood risk		Relative distance of vegetation from near natural population		Soil surface coverage		Administrative framework on the ability to maintain and on the health of forests ecosystems		
Physical - composition		Defoliation class distribution		Regime of soil moisture		Density of forest roads		
		Structural diversification		Permeability		Characteristics of forest flows		
		Cut extensions						
		Forest surface						

Table 5.10 – Impacts for the felling, limbing and cutting sub phases

Sub phases	**Elementary processes**	**Hydrosphere**		**Biosphere**		**Lithosphere**	**Atmosphere**	**Antroposphere**		
		Surface waters	**Ground waters**	**Flora**	**Fauna**			**People**	**Landscape**	**Economy**
Felling	**Plant gripping**	▨	▨	Flora removing, ecosystem change	Wildlife disturbance	Soil compaction	Alteration of air quality	Annoyance and disturbance for noise	▨	▨
	Cutting	▨	▨				Alteration of air quality, dustiness		Alteration of the landscape	▨
Limbing and cutting	**Timber lifting**	▨	▨				Alteration of air quality		▨	▨
	Limbing	▨	▨						▨	▨
	Cutting	▨	▨						▨	▨
	Log deposit	▨	▨						▨	▨

The described methodology allows an analysis in detail of the single operational phases, but in order to determine the responses to be implemented to reduce the impact on the territory, an overview of the activity analyzed is necessary. Therefore the responses to be put in place have been identified according the sub phase of reference. By way of example some operational procedures to be put in place to reduce the impact of the single operating phase are shown in Table 5.11.

Table 5.11 - Responses for the felling, limbing and cutting sub phases

Sub phases	Technical intervention	Operative procedures
Felling		Program the felling so as to avoid the machine transits in the same area when not necessary Program the felling in order to reduce the annoyance for the population
Limbing and cutting		

Often the best response to reduce the impact on the surrounding area is the identification of technological and procedural alternatives at the initially considered choice. In this case, the analysis has to be redone according to the new design choice. Given the high number of factors that come into consideration in the assessment of the alternative, it must be examined on a case by case basis.

Often then there is a contrast between the safeguard of the safety and health of the workers and the reduction of the environmental impact. As stated previously, the use of machines for forestry activities entails less risk to workers, but a greater impact on the environment. For this reason it has been shown as an example the phase of felling and processing with machines, being one of the operational decisions with the greatest impact on the territory.

5.2 Fuel wood terminal

The fuel wood terminals are characterized by the simultaneous presence of different activities that may pose a high risk of interference and then an additional hazard factor for the safety of workers. Therefore, the sources of hazard (Table 5.12) must be defined and evaluated with special attention in particular as regards the work environment and the work organization so as to avoid creating hazardous situations for the workers and interferences between the different activities. Given the characteristics of small dimension of the plants considered the impact on the environment of this activities is limited.

Table 5.12 – Sources of hazard for the fuel wood terminal

Sub phases	**Elementary processes**	**Machinery**	**Materials**				**Work environment**		**Work organization**	
			Raw materials	**Complementary materials**	**Waste**	**Product**	**Macro**	**Micro**	**General**	**Operative conditions**
Quality assessment	Discharge of the timber and/or wood chips	Transport means with forestry pliers	Timber	Diesel fuel			Area for charge and discharge	Area for mechanical parts moving and	Separate the working area and avoid the presence of workers with different task in the same area	1 workers steers the machine
	Quality assessment							Area for timber storage		1 expert checks the timber quality
	Sending of the better quality timber at the	Transport means with forestry pliers		Diesel fuel		Logs destined at		Area for mechanical parts moving and operator position		1 workers steers the machine
Timber storage	Timber storage in a suitable location for	Transport means with forestry pliers					Area for storage			
	Periodic checks of the drying process					Dried timber		Timber piles		1 workers checks periodically the
	Timber loading	Transport means with forestry pliers						Area for mechanical parts moving and		1 workers steers the machine
Chipping	Timber movement in the vicinity of the		Dried timber	Diesel fuel			Area for chipping	Machine movement area		
	Wood chipping	Trasport means with forestry pliers, chipper,			Sawdust	Chips		Area for mechanical parts moving and		
Chips storage	Chips unloading	Hook lift trucks					Area for chips storage	Machine movement area		
	Chips storage							Chips piles		1 workers checks periodically the
Transport	Loading of wood chips on transportation.	Hook lift trucks		Diesel fuel			Area for charge and	Machine movement area		1 workers steers the machine

5.3 Heating systems

The analysis of heat generators has focused mainly on how the methodology should be changed depending on the different characteristics of different phases of the forest energy chain.

The main differences between the forest yards and the heating systems that influence the analysis is the temporary nature of the first compared to the second's stationary and the organization of work. Regarding this second point, the forest yards works provide continuous activity albeit limited to the temporary nature of the work activity itself. The energy production plants, despite their stationary installation features that significantly influence the long-term impacts on the territory, provide for a work activity primarily of management of the plant, mainly related to the supply of fuel, and maintenance. Indeed, they are assumed to be not manned 24 hours on 24. Therefore the workers came in contact with the plant for a limited period of time and consequently the factor of contact is limited. The process phases, related to the operation of the plant itself, and the management and maintenance phases carried out by the workers have been distinguished in the analysis (Table 5.13 and Table 5.14). The former must be judged primarily in terms of environmental sustainability and process safety, while the latter have to be evaluated also from the point of view of OS&H.

Table 5.13 - Hazard sources for the process phases

Process phase	**Elementary processes**	**Machinery**	**Materials**				**Work environment**	
			Raw materials	**Complementary materials**	**Waste**	**Product**	**Macro**	**Micro**
Chips supply system	**Extraction**	Feeding screw	Chips, electric energy		Wood dust		Thermic system	Chips storage
	Supply			Electrical system				Boiler
Chips boiler	**Combustion**	Boiler	Chips, incoming air, electric energy		Combustion waste	Hot water		
Smoke and/or purification line	**Fumes filtrations**	Van	Smokes	Piping, filters	Volatile substances	Filtered fumes		
	Emissions		Filtered fumes	Piping, chimney		Atmospheric emissions		
Combustion waste collection system	**Combustion waste collection system**			Filters, ash tank	Ashes			
Water heating	**Water circulation**	Pump	Cold water	Pipes and valves				Water tank
	Water heating					Hot water		
	Water storage		Hot water					
Building heating	**Water circulation**	Pump		Pipes and valves		Cold water	Building	Building

Table 5.14 – Hazard sources for the fuel storage and maintenance phases

Phases	Sub phases	Elementary processes	Machinery	Materials				Work environment		Work organization	
				Raw materials	Complementary materials	Waste	Product	Macro	Micro	General	Operative condition
Fuel storage	**Truck unloading**	**Truck unloading**	Trucks	Chips		Dust		Square	Square	Unloading/ storage phase	
	Fuel storage	**Fuel storage**					Stored chips		Storage tank		
Maintenance	**Ordinary maintenance**	**Periodic monitoring of the system**	Boiler, pump, van, feeding screw		Maintenance equipment			Thermic system	Thermic system	Frequency established according to the system features	Adequately informed, instructed and trained workers
		Check for correct operation									
		Periodic monitoring of the electric system			Electric system				Electric panel	Frequency established by law	Certified workers
	Extraordinary maintenance	**Assessment failure severity**	Boiler, pump, van, feeding screw		Maintenance equipment				Thermic system	Procedures to assess failure severity	Adequately informed, instructed and trained workers
		Repair								Procedures to repair the failures	

The analysis was developed by maintaining this division, concentrating more on the first table as regards the assessment of environmental impacts and the overall safety of the process, and on the second with regard to OS&H.

The results showed a critical issue related to the presence of wood dust in the chips storage tank that can give rise to risk of formation of explosive atmospheres. This risk is particularly significant with regard to the storage tank and the phase of boiler loading through chips screw conveyor. The explosion protection is based on avoiding the formation of an explosive atmosphere ensuring low concentrations of dust and the formation of possible phenomena of ignition. The screw conveyor must be made of material that avoid the formation of sparks. A periodic cleaning of the tank to limit the dustiness of the environment should therefore be guaranteed. As it can be seen in the figure, in the analyzed plants the presence of dust in the chips tank (Figure 5.1a) and in the loading system is limited (Figure 5.1b). The chips storage tank have to be submitted to an assessment of the risk of fire in order to receive the authorization at the construction.

Figure 5.1 – Chips storage (a) and screw conveyor system (b)

For large deposits (up to 100 t), which therefore fall outside the aim of the present thesis, the absence of potential trigger phenomena must be guaranteed with some particular devices. There should be only electrical devices with a rating of at least IP 54 and the storage tank and other installations lighting must be approved for ATEX Zone 22[182].

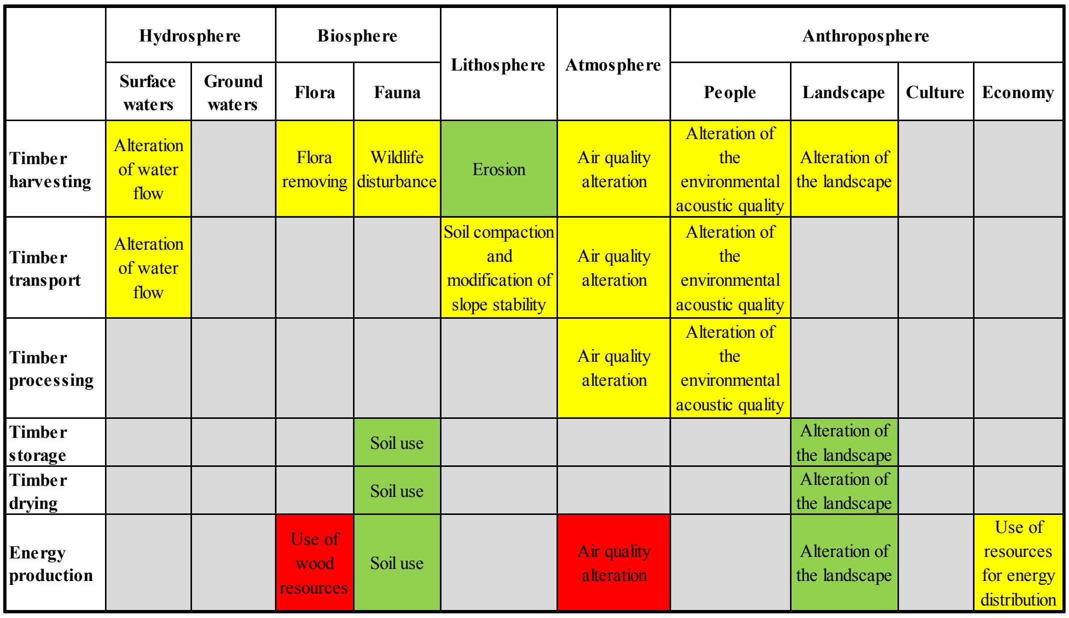
5.4 Cumulative impacts

In order to determine if the method could satisfy all the objectives set at the beginning of the analysis, it has to be applied also to assess the cumulative impacts caused by the whole forest energy chain.

Table 5.15 shows the main impacts for each phase of the supply chain and a assessment of the impacts through “traffic light”. The colors matched with each impact have the following meaning:

- The green impacts are whose for which response have not to be envisaged because the impacts are minimal;
- Yellow and red impacts are differentiated according to the priority of intervention.

Table 5.15 – Main cumulative impacts of the forest energy chain



	Hydrosphere		Biosphere		Lithosphere	Atmosphere	Anthroposphere			
	Surface waters	Ground waters	Flora	Fauna			People	Landscape	Culture	Economy
Timber harvesting	Alteration of water flow		Flora removing	Wildlife disturbance	Erosion	Air quality alteration	Alteration of the environmental acoustic quality	Alteration of the landscape		
Timber transport	Alteration of water flow				Soil compaction and modification of slope stability	Air quality alteration	Alteration of the environmental acoustic quality			
Timber processing						Air quality alteration	Alteration of the environmental acoustic quality			
Timber storage				Soil use				Alteration of the landscape		
Timber drying				Soil use				Alteration of the landscape		
Energy production			Use of wood resources	Soil use		Air quality alteration		Alteration of the landscape		Use of resources for energy distribution

The table allows to observe how a real assessment of the cumulative impacts is difficult through the only application of the method. Only a qualitative determination of the impacts is possible. Wherefore the method has been modified integrating it with further analysis. However the method allows to determine that the most significant impacts are the use of wood resources and the air quality alteration. The further analysis will therefore concentrate on these perspectives.

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Chapter 6

Application of the method to a prototype plant

The method has been afterwards applied on a prototype plant. The aim of this phase of the analysis is to observe how the application of the method previously described can influence and modify the design phase. In this way the implementations can be done before the construction of the plant. Moreover the application of the method can be seen as a starting point in the hypothesis of need of EC labeling[108] in case of marketing of the prototype plant.

6.1 Description of the prototype plant

The analysis was done in correlation with the “ENSESBID” project done in collaboration with the Department of Energy (DENERG) of the Politecnico di Torino and the Cooperative "La Foresta", a company that operates in the field of forest biomass (PEFC certificated). A prototype plant of wood biomass micro generation and of energy-sufficient wood processing was created within this project.

The project involved the construction of an integrated system for drying timber planks and energy recovery of wood by-products.

The designed plant was initially composed by a chips storage silo, a chips supply system to the gasifier and to the boiler, a pyrogasifier, an internal combustion engine, a wood chips boiler, an heat accumulation system, a flue gas line, a system for the collection of the gasification and combustion waste, water-air exchangers and a dryer for wood planks.

The previously described methodology was applied in the phase of plant design and plant implementation[183–185]. The liquid wastes that are produced in the phase of pyrogasification results to be already in the preliminary assessment in very large amounts. Moreover some pollutants, present in them, exceed the limits set by environmental legislation[3]. Proper environmental management of liquid waste would determine the disappearance of the economic feasibility of the entire project. This situation have led to the decision to replace within the plant, as power generation system, the pyrogasifier with the previously planned as backing wood chips boiler.

After putting in place the implementations resulting from the analysis, the plant was built at a preliminary stage in a company that operates in the field of forest-wood-energy. It is located in the province of Turin, in the lower Susa valley in the eastern part of the municipality of Susa, a few hundred meters from the municipal boundary with the municipality of Bussoleno (Figure 6.1).

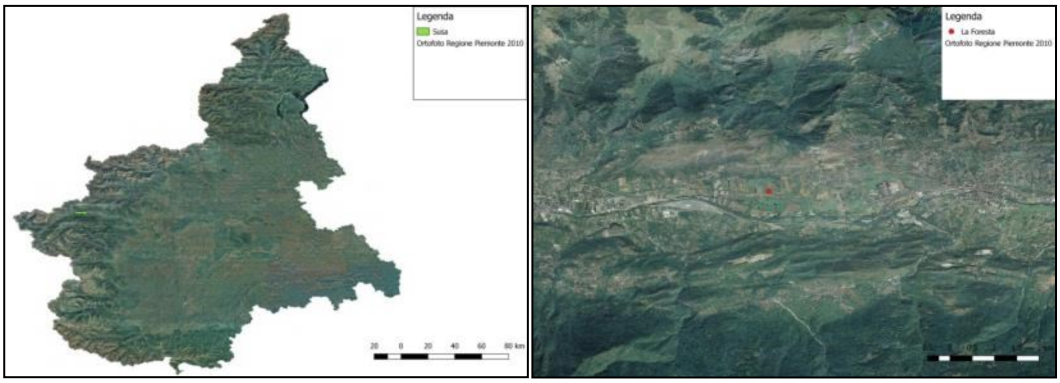

Figure 6.1 – Location of the analyzed plant

The final system consists of the following parts:

- container "boiler" (pellets/chips supply, water heating, hot water storage, water supply, water transport, fumes and ashes discharge),
- container "dryer" (water transport and timber drying),
- warehouse "La Foresta" (chips drying).

As can be observed compared to the initial scheme, within the system a phase of drying the wood chips has also been inserted. This is because in order to enhance energy waste from wood processing by-product, in this way also chips of lesser quality can be used for energy purposes. The main function of the chips drying phase is to add value to the food service industry chips, especially for the smoking of food. It is therefore part of the objective of valorizing the timber by-products. The system has been put in proximity of a wood fuel terminal place. In a following phase of the project the plant will be moved near the end-user in order to use part of heat produced to warm a built up area aside from dry the timber planks.

In Figure 6.2 there is the flow chart of the analyzed system. In the scheme the power supply was not inserted, for simplicity of representation.

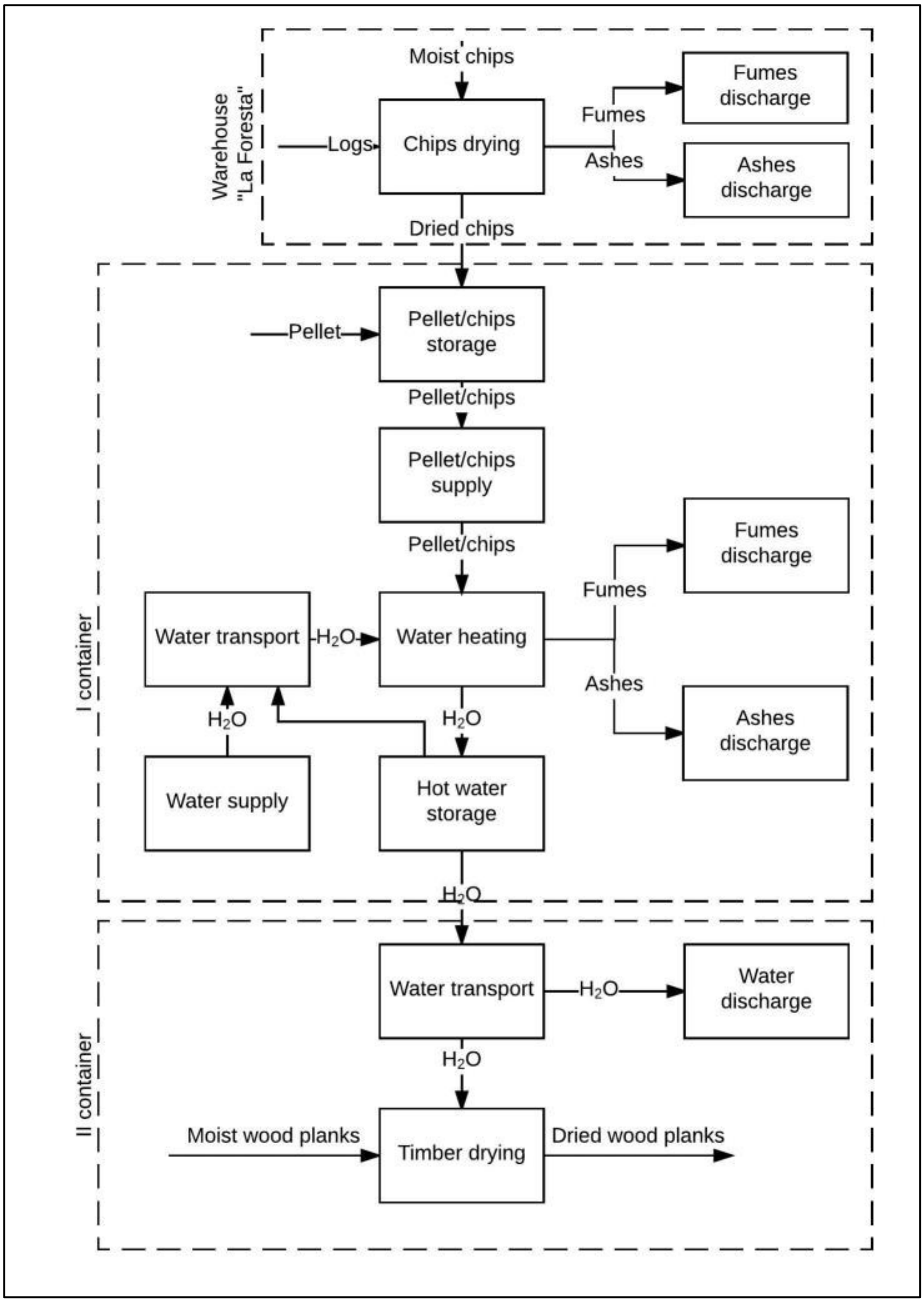

Figure 6.2 – Flow chart of the prototype plant

The wood chips drying takes place in a “tower” dryer. It is a small capacity system for the production of dried wood chips. The drying uses hot air as a heat carrier produced by a heat generator of 80 kW (Figure 6.3), fed with wood logs. It was installed in a separate building from the two containers.

Figure 6.3 – Hot air generator and chips “tower” dryer

The "boiler" container is divided into two parts. In the first there is the storage of wood chips/pellets, while in the second there are the boiler, the puffer, the supply and return pipelines and the electrical system. The connection between the two parts is carried out by a chips screw conveyor. The water is heated by a chips/pellets boiler with a nominal power of 21 kW. In order to be used in the this plant the chips must have certain dimensional characteristics so as not to create problems in the fuel system, that is initially intended for pellets use only. The boiler is equipped of a control unit with assure the maintaining of the optimal parameters of temperature and pressure.

This modification of the boiler has been done within the “AlterPELLET” project developed by the department of the Politecnico di Torino DENERG, the cooperative “La Foresta”, Rossetto Legnami and HERZ.

The timber drying happens in a small containerized plant. It consists of a insulated drying chamber coated by about 7 cm of thick extruded polystyrene that contains the timber to be dried (Figure 6.4).

Figure 6.4 – Timber plank dryer

The system employs hot water as a heat carrier at a lower of 95 °C temperature. The management of the dryer occurs through an electronic system (PLC) that monitors the quantity and temperature of inlet water, power and direction of the fans, quantity of air input / output, in order to avoid a too fast drying (which would produce internal tensions, breakage, cracking and warping of the wood).

6.2 Application of the methodology to the prototype pant

Table 6.1 shows the sources of hazard that have been identified in the study of the prototype plant. In this phase of the analysis only the main process phases have been identified and the process has not been divided into elementary phases.

Table 6.1 – Sources of hazard for the prototype plant

Process phases	Machinery	Materials				Work environment		Work organization	
		Raw materials	Complementary materials	Waste	Product	Macro	Micro	General	Operative conditions
Chips drying	Hot air generator, chips "tower" dryer	Firewood, wet chips	Electrical system	Atmospheric emissions, ashes, wood dust	Dried chips	"La Foresta" shed		Drying cycle duration	1 worker load periodically the hot air generator
Pellet/ chips storage	Transport means	Pellet/ chips		Wood dust		I container	Chip storage silo	Periodic pellet storage	1 worker steers the transport mean and he unloads the pellet
Pellet/chips supply	Pellet/chips screw conveyor	Pellet/ chips, electric energy	Electrical system					Drying cycle duration 20 days	Optimized operation thanks to the presence of the storage tank
Water heating	Boiler, pressure sensor, temperature sensor, control unit	Pellet/ chips, incoming air, electric energy		Combustion waste	Hot water		Boiler		
Hot water storage	Pressure sensors, temperature sensor, pumping system	Hot water	Water piping, water tank		Hot water (T < 90°C)		Puffer		
Water supply		Water	Hydraulic system						
Water transport			Water piping				Piping		
Water discharge			Discharge collector funnels, valves, water piping		Water				
Fumes discharge	Temperature sensor	Smokes	Filters		Atmospheric emissions		Chimney		
Ashes discharge	Tipping grid		Filters, ash tank		Ashes		Boiler		
Timber drying	4 fans, 8 wood hygrometer, 2 air hygrometer, temperature sensors, PLC, water spryers	Hot water, cold air, electric energy, moist planks (moisture 80%)	Electrical system, water piping	Atmospheric emissions	Dried planks (moisture 10%), hot air	II container	Whole environment		
System maintenance	Hot air generator, chips tower dryer, boiler, sensors, pellet screw conveyor, fans, pumping system		Filter, valves, water piping			Whole system	Boiler, pellet storage, II container	Periodic maintenance	Workers follow the maintenance procedure

The most significant sources of hazard are also in this case the used machinery. While making reference to the following for the specific application of the FMEA to the system, Table 6.2 shows the simplified correlation matrix of the system only reporting the macro-system components. Already at this early stage, a comprehensive assessment of the system with the application of the FMEA proves to be very complex.

Table 6.2 – Correlation matrix of the prototype plant main functions

	Components													**Interfaces**				
Components & interfaces / **Functions**	Chips tower dryer	Pellet/chips storage	Pellet/chips supply	Boiler	Water tank	Piping	Pressure sensor	Temperature sensor	Fumes chimney	Ash bin	Fans	Wood hygrometer	Air hygrometers	Power supply	Water supply	Fuel supply	Atmosphere	Landfill
Chips drying	Y													Y		Y	Y	Y
Pellet/chips storage		Y	Y	Y														
Pellet/chips supply		Y	Y	Y										Y		Y		
Water heating		Y	Y	Y	Y		Y	Y	Y	Y				Y				
Hot water storage				Y	Y	Y	Y	Y						Y	Y			
Water supply				Y	Y	Y	Y							Y	Y			
Water transport				Y	Y	Y	Y	Y						Y				
Water discharge					Y	Y								Y				
Fumes discharge				Y				Y	Y					Y			Y	
Ashes discharge				Y						Y				Y				Y
Timber drying						Y					Y	Y	Y	Y		Y		

6.2.1 Occupational risk analysis

Table 6.3 shows the risk analysis relating to the machinery in the prototype plant. The methodology, as mentioned earlier, has been applied both in the design phase and in phase of the assessment of the build system. Therefore the possible technical interventions have already been taken into account: these include the replacement of pyrogasification with a pellets/chips boiler. The table shows the assessment of the plant in place and therefore only the procedures to be adopted to minimize risk and the PPE to provide workers are reported, leaving out the column of the technical interventions, which have already been applied.

Table 6.3 – Occupational risk identification of the prototype plant machinery

Machinery	**Hazard factors**	**Possible associated deviations and damages**	**Procedures**	**PPE**
Means of transport	Tipping	Contusions, fractures, wounds, crushing injuries	Moving of the vehicle according to the identified path	
Chips/ pellet screw conveyor	Moving mechanical parts	Entanglement of clothes, hands or arms crushing	Perform maintenance and overhaul following the instructions in the manual Check the presence of the protection systems Maintain safety distances Do not stand within range of the machine	Protective helmet Suitable work clothing Gloves
	Splinters projection	Wounds to face or eyes		Visor
	Dust and sawdust	Eye and airways irritation	Maintain safety distances	
		Explosion	Check the conformity to the machine installation manual	
			Observe the operating parameters	
Boiler	High temperature	Explosion	Check the conformity to the machine installation manual	
			Observe the operating parameters	
Tank	Hot surfaces	Burns from contact	Verify the presence of the hot surfaces protection systems	Protective clothing
Pumping system			Adopt the correct operating procedures	Gloves
Hot air generator	Hot surfaces	Burns from contact	Verify the presence of the hot surfaces protection systems Adopt the correct operating procedures	Protective clothing Gloves
	High temperature	Explosion	Check the conformity to the machine installation manual	
			Observe the operating parameters	
Chips tower dryer	Hot surfaces	Burns from contact	Verify the presence of the hot surfaces protection systems Adopt the correct operating procedures	Protective clothing Gloves
	Dust and sawdust	Eye and airways irritation	Maintain safety distances	Visor
		Explosion	Check the conformity to the machine installation manual	
			Observe the operating parameters	
Fans	Moving mechanical parts	Entanglement of clothes, hands or arms crushing	Perform maintenance and overhaul following the instructions in the manual Check the presence of the protection systems Maintain safety distances Do not stand within range of the machine	Protective helmet Suitable work clothing Gloves
	Wood dust	Explosion	Control the temperature and moisture values	
	Noise	Hearing loss, physiological disorders, interference with verbal communications.	Perform maintenance and overhaul following the instructions in the manual Reduce the exposure time through proper work organization	Ear protectors

Regarding the machinery analysis, it is important to observe how the single part of the plant are machine according the legislation[108], they have to have to follow the principle given by the EC labeling. Therefore for the risk analysis of the single machine reference is made to the machine documentation.

The materials with which the workers may come into contact mainly concern the tank and dryer loading activities and the maintenance operations. The factors of hazard that are associated with them can therefore pose a limited, as regards the factor of contact, risk for the workers (Table 6.4).

Table 6.4 – Occupational risk identification of prototype plant materials

Materials	Hazard factors	Possible associated deviations and damages	Procedures	PPE
Chips/pellet	Material fall from a height	Contusions, fractures, wounds, crushing injuries	Maintain safety distances Adopt the correct operating procedures Ensure the load stability	Gloves Protective helmet Safety shoes
	Dust and sawdust	Eye and airways irritation	Maintain safety distances	Visor
Electric system	Parts in voltage	Direct contact	Check the presence of the attestation of conformity Maintenance and overhaul must be performed by qualified staff and at plant shutdown Periodically check the function of the GFCI Segregate the parts under voltage through insulating screens	Gloves Safety shoes
		Indirect contact		
		Electric arc		
		Ignition of fire		
		Ignition of explosion		
	Blackout	Growing of the temperature and decreasing of the humidity without ventilation	Opening of the air inlets and outlets if there is a power cut	
Water piping	Hot surfaces	Burns from contact	Verify the presence of the hot surfaces protection systems Adopt the correct operating procedures	Gloves Protective clothing
Planks	Material fall from a height	Contusions, fractures, wounds, injuries	Maintain safety distances Adopt the correct operating procedures Ensure the load stability	Gloves Protective helmet Safety shoes

The process takes place in closed environments so leaving out the working activities strictly related to the same process, which as mentioned earlier are limited, the hazard factors that may pose a risk for the workers operating near the plant are not detectable (Table 6.5).

Table 6.5 - Occupational risk identification of the prototype plant work environment

Work environment	Hazard factors	Possible associated deviations and damages	Procedures	PPE
Storage silo	Material fall from above	Contusions, fractures, wounds, crushing injuries	Maintain safety distances Adopt the correct operating procedures Ensure the load stability	Gloves Protective helmet Safety shoes
	Dust and sawdust	Eye and airways irritation	Maintain safety distances	Visor
Boiler room	Parts in voltage	Direct contact	Check the presence of the attestation of conformity	Gloves Safety shoes
		Indirect contact	Maintenance and overhaul must be performed by qualified staff and at plant shutdown	
		Electric arc	Periodically check the function of the GFCI	
		Ignition of fire	Segregate the parts under voltage through insulating screens	
		Ignition of explosion		
	Hot surfaces	Burns from contact	Verify the presence of the hot surfaces protection systems Adopt the correct operating procedures	Gloves Protective clothing
Dryer	Hot surfaces	Burns from contact	Verify the presence of the hot surfaces protection systems Adopt the correct operating procedures	Protective clothing Gloves
	High temperatures	Thermal stress for workers	Make the filling and emptying only at plant shutdown and after an appropriate time	
	High temperatures (>90 °C)	Formation of explosive atmospheres	Shutdown of the drying process	
	High temperatures (>75 °C) and low humidity (<65%)	Formation of explosive atmospheres	Control the temperature and the humidity of the container through the PLC. If necessary shutdown of the process	
			Open the air inlets and outlets and activation of the water sprayer	
	Moving mechanical parts	Entanglement of clothes, hands or arms crushing	Perform maintenance and loading following the instructions in the manual Check the presence of the protection systems Maintain safety distances Do not stand within range of the machine Entry the dryer only at plant shutdown	Protective helmet Suitable work clothing Gloves
	Dust and sawdust	Eye and airways irritation	Perform maintenance and overhaul following the instructions in the manual	Visor
		Explosion	Control temperature and air humidity of the container through the PLC	

The organization of work depends on the duration and the number of drying cycles carried out (Table 6.6). As for the activity itself the activities must not interfere with other activities in the vicinity.

Table 6.6 - Occupational risk identification of the prototype plant work organization

Work organization	**Hazard factors**	**Possible associated deviations and damages**	**Procedures**	**PPE**
Loading of the hot air generator	Handling of loads	Contusions, fractures, wounds, crushing injuries	Introduce breaks during the work activity Adopt the correct operating procedures	Gloves Protective helmet Safety shoes
	Ripetitive movements	Musculoskeletal damages	Introduce breaks during the work activity Adopt the correct operating procedures	
	Dust and sawdust	Eye and airways irritation	Maintain safety distances	Visor
Loading of the storage tank	Moving vehicles	Investment, fractures	Avoid the approach of other workers during operations Delimit the transit routes of the vehicles	
	Handling of loads	Contusions, fractures, wounds, crushing injuries	Introduce breaks during the work activity Adopt the correct operating procedures	Gloves Protective helmet Safety shoes
	Ripetitive movements	Musculoskeletal damages	Introduce breaks during the work activity Adopt the correct operating procedures	
	Dust and sawdust	Eye and airways irritation	Maintain safety distances	Visor
Filling and emptying of the dryer	Moving vehicles	Investment, fractures	Avoid the approach of other workers during operations Delimit the transit routes of the vehicles	
	Handling of loads	Contusions, fractures, wounds, crushing injuries	Maintain safety distances Adopt the correct operating procedures Ensure the load stability Carry out the handling operations by forklift and not manually.	Gloves Protective helmet Safety shoes
Maintenance operation	Parts in voltage	Direct contact	Check the presence of the attestation of conformity	Gloves Safety shoes
		Indirect contact	Maintenance and overhaul must be performed by qualified staff and at plant shutdown	
		Electric arc	Periodically check the function of the GFCI	
		Ignition of fire	Segregate the parts under voltage through insulating screens	
		Ignition of explosion		
	High temperatures	Thermal stress for workers	Make the maintenance operation only at plant shutdown and after an appropriate time	

In summary with regard to process safety, plant management has been examined for the purposes of compliance with the Italian and European regulations for safety in the workplace. The plant is an integrated system whose components are represented by machines with their own EC labeling and by plant networks (electrical and hydraulic) that are designed, installed and tested individually by licensed professionals resulting in the declaration of plant compliance.

A significant critical issues emerged from the presence of wood dust that can cause the formation of explosive atmospheres. The evaluation has shown that such a factor of hazard is present mainly in two process phases: the power supply system of the boiler and the timber plank drying system.

As regards the supply to the boiler, in the majority of commercial proposals, the power system is included in the system “boiler" meant as a machine for the purposes of legislation[108]. Therefore this risk lies in the risk assessment that is carried out by the producer. As for the drying system, at atmospheric pressure, the purpose of the function implies the presence within the dryer of the entire amount of water that is extracted from the timber. Since the temperatures during the drying process are (in analogy to other plants of the sector) normally lower than 70 - 80 °C, the percentage of moisture present should be sufficient for inerting the environment. For this reason the system of control of the dryer is equipped with suitable sensor to control the temperature of the environment and the humidity of air and wood. The PLC have to constantly assess all the parameters in order to detect the arising of risk. If the temperature is too high the system has to be shut down.

As for the loading of the dryers and maintenance operations, applying a proper Prevention Through Design and adopting the necessary technical interventions already in the planning stage, the adoption of the correct procedures guarantees the safety of workers. The most significant risks are given by the handling of the means of transport, therefore this activity has to be suitably planned. The interferences with other activity have to be eliminated. The loading phase will be analyzed in more detail through the validation of the method with application of the Job Safety Analysis.

6.2.2 Environmental impact assessment

The starting point of the prototype plant environmental impact assessment is Table 6.3, where there are the source of hazard or rather the drivers. Starting from the drivers the induced on the surrounding environment pressures were identified (Table 6.7).

Table 6.7 – Pressures on the environment deriving from the prototype plant

Process phases	**Machinery**	**Materials**				**Work environment**		**Work organization**	
		Raw materials	**Complementary materials**	**Waste**	**Product**	**Macro**	**Micro**	**General**	**Operative conditions**
Chips drying	CO, NO_X particulate matter	Wood biomass	Use of electric energy		Dried chips				
Pellet/ chips storage	Dust, sawdust			Wood dust emission		Alteration of the landscape			
Pellet/ chips supply		Wood biomass	Use of electric energy						
Water heating	CO,HC, NO_X particulate matter, noise	Water use							
Hot water storage									
Water supply		Water use	Use of electric energy						
Water transport									
Water discharge									
Fumes discharge					Particulate matter, NO_X				
Ashes discharge					Ashes production				
Timber drying	Noise, sawdust	Timber							

The environmental impacts arising from the plant depend on the system setup features and, obviously, on the characteristics of the environmental where it is installed. Table 6.8 shows the main indicators that were identified to describe the state of the environment on which the plant was installed. They have been identified in order to allow an exhaustive description of the area and of the receptors present in them. In the identification of the necessary indicators the induced pressures are taken into account to make sure not to neglect aspects required in the characterization of the environment.

To quantify the indicators a reference area assuming a radius of influence as regards the direct impacts of 2 km has been identified (Figure 6.5). Clearly, the highlighted area is as illustrative only of the most significant impacts. Especially as regards the impacts on the atmosphere and the waste landfilling the area of influence turns out to be much greater.

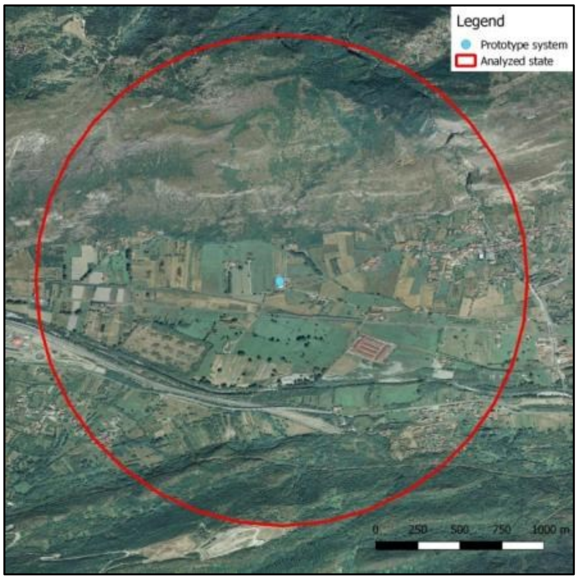

Figure 6.5 – Area of influence of the prototype plant

In the territory where the plant is installed there are not sensitive receptors and the number of residential buildings is very limited. In addition, the territory has low characteristics of naturalness and there are no rivers. Table 6.9 describes the state where the plant is installed through the quantification of the identified indicators.

Table 6.8 – Indicators describing the state of the surrounding environment

Hydrosphere		Biosphere		Lithosphere	Atmosphere	Anthroposphere			
Surface waters	Ground waters	Flora	Fauna			People	Landscape	Culture	Economy
Hydrological and hydrogeological features		Presence of protected natural areas		Prone to flood danger areas	Meteorological data	Resident population	Public green		Existing business
Hydrographic network		Biotope presence		Erodibility	Stations monitoring air quality	Population density	Change in landscape quality		
Delimitation and description of the basin		Forest surface		Slope	PM_{10} exceedances daily limits	Existing road infrastructure	Presence of SCI or SPA		
Surface water circulation				Altitude	PM_{10} annual average	Urbanized area			
Flood risk				Soil use		Nature of the settlement			
				Soil surface coverage		Acoustic class in line with the Acoustics Classification Plan			
				Geomorphological features		Supply distance			
				Waste (final destination)		Nearby sensitive receptors			

Table 6.9 – State description[183–185]

Hydrosphere		Biosphere		Lithosphere	Atmosphere	Anthroposphere			
Surface waters	Ground waters	Flora	Fauna			People	Landscape	Culture	Economy
Average flow: 17.3 m^3/s Rivers chemical status: good Ecological status: sufficient	Acquifers chemical status: good	Parco Naturale Orsiera Rocciavrè		No	Average annual precipitation: 802.2 mm Average temperature: 12.3 °C Average wind speed: 1.41 m/s Average umidity:73.67%	500	Parco Naturale Orsiera Rocciavrè		Farms
Shallow aquifer at times fed and drained by the river Dora Riparia		Xerothermic areas Rocciamelone		No	Susa-Repubblica (ARPA Piemonte)	71 inhabitants/km^2	Agricultural areas		
Dora Riparia basin		0.15 km^2		0.007	11 year exceedances daily limits	SS 25	Susa valley xerothermic oases - Chianocco Orrido		
						E70	Orsiera Rocciavrè		
						SP 24	Rocciamelone		
Dora Riparia and his				460 m.a.m.s.l.	17.69 µg/m^3	0.12 km^2			
No				n.d.		Agricultural areas			
				Flood deposits		III			
				Flood deposits		2.5 km			
				Landfill		Primary school			

According to the pressures and the identified indicators, the impacts on the surrounding environment were determined (Table 6.10). The actual quantification of impacts is postponed to a later stage of assessment as the factors to consider are numerous. A real determination of the impacts caused by the plant on the surrounding territory have to take into account different factors, such as the other sources present and the time necessary for the impact to manifest itself. In this phase of the analysis, the assessment of the impact is therefore only qualitative. In this context a "traffic light" assessment of the environmental state changes according to the pressure identified can be done.

The most significant impacts are the alteration of the air quality and the modifications in the noise level, and consequent annoyance for the people living nearby. However the size of this impact deriving from a plant with small dimensions as whose considered can be assumed minimal. With regard to the alteration of the landscape, it is closely connected to the area in which the plant is placed and to its natural characteristics. The area surrounding the plant is destined for agricultural purposes is installed so has limited natural characteristics. Given also in this case the small features of the system considered, the alteration of the landscape is to be considered minimum.

A qualitative assessment however is not sufficient in case of implementation of different plants in the same territory. There is in this case therefore the need of an assessment through modeling of the cumulative impacts. This is particularly significant in the evaluation of the atmospheric emissions, given their peculiarity and their capacity to significantly influence the air quality. To validate this hypothesis an application of a model for the dispersion of pollutant has been assumed and analyzed in the following chapters.

Table 6.10 - Impacts on the environment deriving from the prototype plant

Process phase	Hydrosphere		Biosphere		Lithosphere	Atmosphere	Antroposphere			
	Surface waters	Ground waters	Flora	Fauna			People	Landscape	Culture	Economy
Chips drying			Use of resources		Soil use, landfill	Air quality alteration		Alteration of the landscape		Ash disposal, electric energy use
Pellet/ chips storage					Sol use		Noise annoyance			
Pellet/ chips supply						Dustiness				Electric energy use
Water heating	Use of resources (minimal)				Soil use	Air quality alteration				
Hot water storage										
Water supply			Use of resources							
Water transport										Ash disposal
Fumes discharge								Alteration of the territory (see chapter 8)		
Ashes discharge					Soil use, landfill			Alteration of the landscape		
Timber drying			Use of resources		Soil use	Air quality alteration	Noise annoyance			Electric energy use

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Section 3: Validation of the method

Chapter 7

Validation of the method

The methodology that is described in the previous chapters has been developed in order to allow an expeditious assessment of case studies belonging to different phases of the forest energy chain. Moreover it can be applied directly by the system managers. At the same time, however, there is the need for this methodology although simplified, to be exhaustive, and to identify all the possible issues. There is therefore the need to validate the method in order to understand if it is complete and allows to analyze all the aspect which are significant regarding the aim of the research.

It was therefore decided to apply to the same case studies both the developed methodology and standardized methods. In particular for the different points of view that are covered by the methodology, the Failure Mode Effects Analysis, the Job Safety Analysis and direct measurements of significant emissions will be used to assess the prototype plant that has been described in the previously chapter. They have been considered well suited in order to exemplify the different peculiarities of the research scope. Different methodologies have been identified given the difficulty to find a single methodology that can be exhaustive regarding the completeness of aspects considered. The comparison of the considered features and the obtained results thus enabled to validate the method.

As a starting point, the Failure Mode Effects Analysis was identified as a standardized method to validate the results obtained. FMEA as previously described identifies for each component of the system the possible failure modes, the effects and causes of failure and the control measures to be implemented. FMEA has been chosen to be applied to the prototype plant in the preference to the FMECA. This because the quantitative approach of the FMECA needed data on the reliability of each components, data not always available in the case of a prototype plant. Moreover given the need of the system to be implemented in the design phase, the FMEA is most suitable for a repetition of the analysis different times.

The FMEA structure needs to take into account all the components of the system in respect of the functions that are affected by them. For this reason often the starting point of the FMEA is a correlation matrix that highlights the relationships between system components and the functions that the analyzed system must fulfill.

Table 7.1 shows a simplified correlation matrix for the forest energy chain (the components of the system are reported only for categories).

Table 7.1 – Correlation matrix for forest energy chain

	Components							Interfaces			
Components & interfaces / **Macro functions**	Felling machines	Extraction machines	Processing machines	Vehicles for the transport	Heating system	Chips/pellet supply system	Dryer	Forest	Road	Fuel wood terminal site	Heating system site
Timber felling	Y	Y						Y	Y		
Timber transport	Y	Y	Y	Y	Y			Y	Y	Y	Y
Timber processing	Y	Y	Y	Y	Y			Y	Y	Y	Y
Timber storage			Y	Y	Y	Y	Y			Y	Y
Timber drying							Y	Y		Y	
Energy production			Y		Y	Y	Y				Y

As can be seen in the table the factors to be examined are very numerous. The application of FMEA is thus very costly in terms of time, especially if different technological alternatives must be assessed. This involves an additional difficulty since, in particular as regards the forest yards, for their characteristics of small size and different locations that significantly differentiate the possible technological alternatives, there is often the need to quickly evaluate different scenarios in order to choose the most suitable case for case.

The correlation matrix can be identified and compared with part of the table of the sources of hazard (Table 7.2) that are defined through the application of the methodology.

Table 7.2 – Hazard source for the forest energy chain considered in the FMEA

Macro functions	Machinery	Materials	Work environment	Work organization
Timber felling	Felling machines		Forest	
Timber transport	Extraction machines, vehicles for the transport		Forest, road	
Timber processing	Processing machines		Forest, fuel wood terminal	
Timber storage	Chips/pellet supply system			
Timber drying	Dryer		Fuel wood terminal	
Energy production	Heating system		Heating system site	

The table shows how the materials and the organization of work are not taken into account in the FMEA. Also the work environment is considered only for the influence that it can have on the work activity, completely excluding the impact on the surrounding territory. Furthermore although the standard application of the FMEA proves to be very suitable for the analysis of process safety of a plant, it takes into account only to a lesser extent the safety of workers.

Therefore, given its complexity, the application of the FMEA at the whole forest energy chain is difficult. Moreover, the obtained information and the data that are available for the subsequent analysis are incomplete especially regarding the environmental aspect.

The FMEA, however, has the advantage of taking into account all the component of the system. It was therefore decided to adopt it to analyze the research subjects as a whole and determine whether the results obtained from the application of simplified methodology were complete from the regarding the considered components. To complete the analysis concerning the OS&H, the Job Safety Analysis was adopted to analyze in the specific the activity of the workers. To determine the accuracy of the assumptions about the environmental pressures, measurements at the source for the most significant emissions have been carried out.

7.1 Application of the FMEA to the prototype plant

The FMEA was applied only to the part of the plant concerning to the production of thermal energy and the drying of the timber (Figure 7.1). Besides the function covered in the FMEA, the scheme includes also the boiler control unit and the PLC given their importance in the management of the process. The heat generator and the tower dryer are therefore excluded. This is because these are machines according the legislation[108], the relative risk analysis is already part of the accompanying documentation.

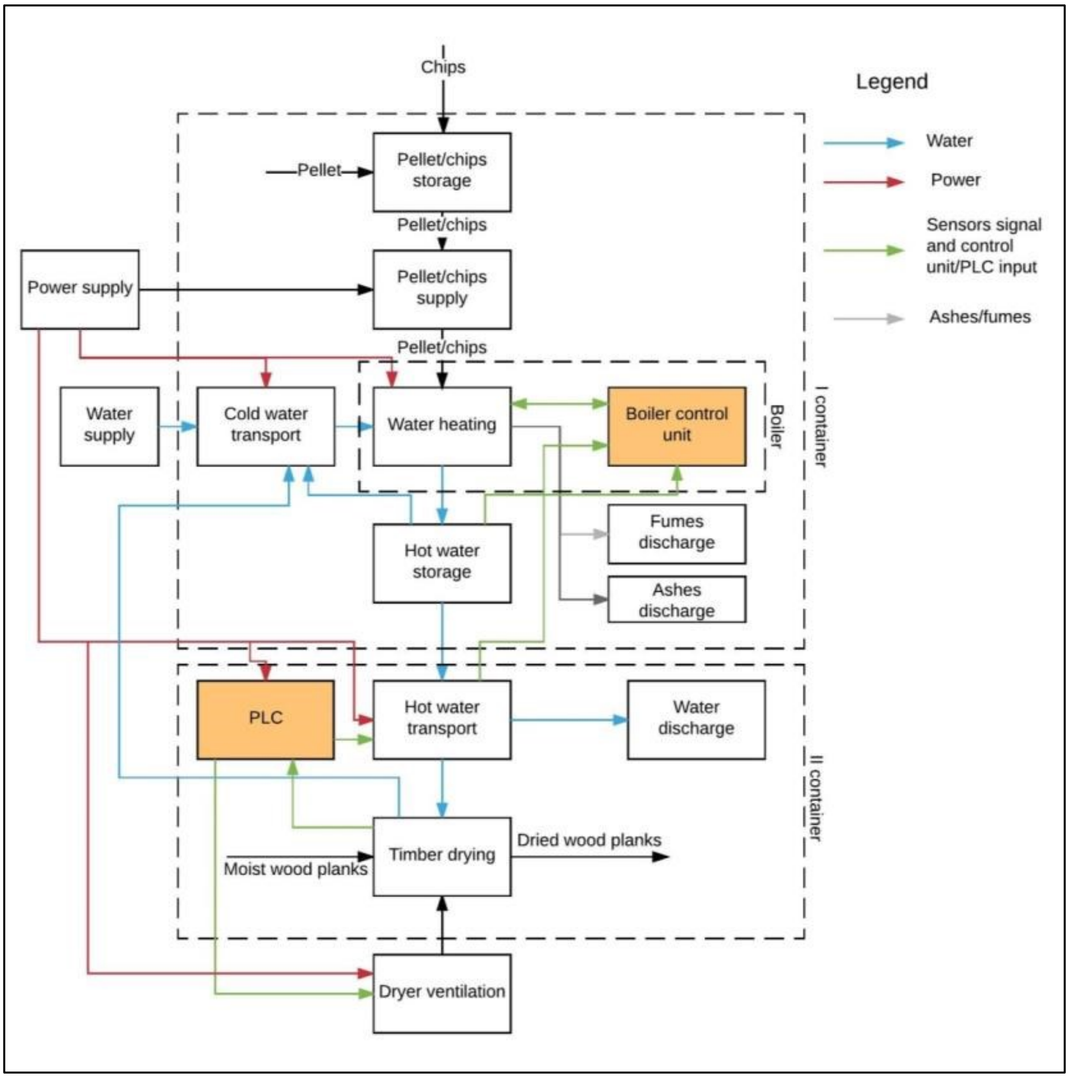

Figure 7.1 - Part of the plant to which the FMEA was applied

In the table below there is the correlation matrix between the functions covered by the system and its different components and interfaces with the external environment (Table 7.3). As it can be seen despite having the plant smaller dimensions, the analysis using the FMEA is onerous from the point of view of the features to be analyzed.

Table 7.3 – Correlation matrix of the prototype plant – Correlation matrix of the prototype plant

	Components																																									Interfaces					
Components & interfaces / Functions	Boiler	Boiler control unit	System control unit	Water storage to flood the screw conveyor	Ashes screw conveyor	Chips/pellet storage	Chips Screw conveyor	Boiler temperature sensor	Fumes chimney	Water tank	Optical-acoustic alarm	Water feeding manifold	Water return manifold	Ball valves	Seal	Three-way solenoid valve	Three-way temperature valve	Pressure gauge	Thermometer	Non-return valve	Expansion tank	Maximum manostat	Minimum manostat	Safety diaphragm valve	Thermic discharge valve	Y-filter	Discharge collector funnel	Lambda sensor	Water tank temperature sensors	Pipes temperature sensor	Boiler recirculating pump	Recirculating pump	Floating air outlet	Hydrodynamic proportional dispenser	Fans	Air termometer	Wood hygrometer	Hot air chimneys	Air inlets	Water sprayer	Air hygrometers	Pipe brackets on the container walls	Power supply	Water supply	Fuel supply	Atmospheric emissions	Ashes disposal
Water heating	Y	Y		Y		Y	Y	Y	Y					Y			Y	Y	Y						Y				Y		Y												Y		Y		
Hot water transport	Y	Y	Y							Y	Y	Y	Y	Y	Y	Y	Y	Y	Y			Y	Y	Y		Y			Y	Y	Y	Y										Y	Y				
Hot water storage	Y	Y	Y							Y			Y			Y	Y										Y		Y	Y	Y	Y	Y										Y				
Cold water transport	Y	Y	Y							Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y			Y		Y			Y	Y	Y	Y										Y	Y				
Fumes discharge	Y	Y							Y																			Y														Y	Y		Y	Y	
Water supply														Y	Y			Y		Y														Y								Y	Y	Y			
Ashes discharge	Y				Y																																						Y				Y
Fuel supply	Y	Y				Y	Y																		Y																		Y				
Timber drying	Y		Y											Y	Y			Y	Y											Y		Y			Y		Y				Y	Y	Y				
Dryer ventilation			Y																Y													Y			Y	Y	Y	Y	Y	Y	Y		Y				

The failure modes have been determined considering how for each function, a deviation of the functioning of each component could cause to not guarantee the function. The identification of the deviation of the process functioning from the suitable parameters has been done thanks to the information given by the designer and the managers. This deviation has been identified as a failure mode. Given the prototype characteristics of the system analyzed, in the identification of the failure modes reference has to be done with similar systems when possible. When not possible hypothesis have been done and they are analyzed in order to determine their feasibility. The severity has been determined considering how the failure mode can influence the system and its functioning. The occurrence has been determined considering when possible similar failure mode in existing systems and when not possible making hypothesis according the characteristic of the system.

The failure modes considered are a total of 235, and the effects of such failures are totally 458. For each of them the RPN value was calculated and then determine the most significant risks to which action is needed have been determined. “Traffic light” colors have been applied to the values obtained for each criteria in order to facilitate their assessment (Table 7.4). In awarding the “traffic light” colors to the three criteria, the criteria of occurrence and severity were considered most critical for the safety.

Table 7.4 - Seriousness assessment of the three criteria

Occurrence	Severity	Detection
1	1	1
2	2	2
3	3	3
4	4	4
5	5	5
6	6	6
7	7	7
8	8	8
9	9	9
10	10	10

In order to determine the required interventions a “traffic light” assessment has been done also for the RPN. It has been considered a threshold of intervention a value of RPN higher than 120 (red) and a threshold of interventions a value higher than 80 (yellow). However when possible, interventions have been programmed also in case of smaller value of RPN. In this way a thorough improvement of the system has been done.

According to the obtained results, interventions have been assumed in order to reduce the risk for each failure mode and its effect.

Table 7.5 shows by way of example an example of FMEA application to part of the components of the process phase of dryer ventilation. The application of FMEA to the whole system is shown in Appendix 2.

Table 7.5 – Example of FMEA application at the dryer ventilation process phase

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Dryer ventilation	Fans	Not correct dryer ventilation	Fans failure	5	Not correct dryer ventilation	6	PLC	3	90	Programmed maintenance	3	6	3	54
			System control unit failure	4	Not correct dryer ventilation	6	PLC	3	72	Programmed maintenance	3	6	3	54
	Air thermometers	Failure to send the signal	Cable wear	5	Not correct dryer ventilation	6	PLC	3	90	No info available	3	6	3	54
			Sensor failure	4	Not correct dryer ventilation	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
		Temperature higher than 90 °C	Excessive water heating	4	Risk of formation of explosive atmosphere	9	PLC	3	108	System shutdown	4	8	3	96
		Temperature higher than 85 °C	Excessive water heating	4	Risk of formation of explosive atmosphere if humidity lower than 70 %	9	PLC	3	108	Controll of the settings	3	8	3	72
	Air hygrometers	Failure to send the signal	Cable wear	5	Not correct dryer ventilation	6	PLC	3	90	No info available	3	6	3	54
			Sensor failure	4	Not correct dryer ventilation	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
		Air humidity lower than 65 %	Not correct ventilation	5	Risk of formation of explosive atmosphere	9	PLC	3	135	System shutdown	5	8	3	120
			Water sprayer failure	5	Risk of formation of explosive atmosphere	9	PLC	3	135	System shutdown	5	8	3	120
		Air humidity lower than 70 %	Not correct ventilation	5	Risk of formation of explosive atmosphere if temperature higher than 85 °C	9	PLC	3	135	Controll of the settings	5	8	3	120
			Water sprayer failure	5	Risk of formation of explosive atmosphere if temperature higher than 85 °C	9	PLC	3	135	Controll of the settings. Programmed maintenance	3	8	3	72
		Air humidity lower than 80%	Not correct ventilation	5	Too low humidity	7	PLC	3	105	Closing air inlets	3	7	3	63
			Water sprayer failure	5	Too low humidity	7	PLC	3	105	Programmed maintenance	3	7	3	63
		Not correct choice of sensor	Not correct design	4	Not correct dryer ventilation	6	Control of the design	3	72	System reliability analysis	3	6	3	54
	Air inlets	Excessive air imput	Not correct regulation of the inlets	5	Too lower humidity	7	PLC	3	105	Programmed maintenance	3	7	3	63
		Low air imput	Not correct regulation of the inlets	5	Too hig humidity	7	PLC	3	105	Programmed maintenance	3	7	3	63
	Wood hygrometers	Failure to send the signal	Cable wear	5	Not correct dryer ventilation	6	PLC	3	90	No info available	3	6	3	54
			Sensor failure	4	Not correct dryer ventilation	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
		Low wood moinsture	Excessive drying	5	Too lower humidity	7	PLC	3	105	Closing air inlets	3	7	3	63
		Not correct choice of sensor	Not correct design	4	Not correct dryer ventilation	6	Control of the design	3	72	System reliability analysis	3	6	3	54
	Hot air chimney	Not correct air emission	Clogged filters	6	Not correct dryer ventilation	6	PLC	3	108	Periodic filter substitution	4	6	3	72
			Not correct design	6	Not correct dryer ventilation	6	Control of the design	3	108	No info available	6	6	3	108

Figure 7.2 shows the obtained result for the RPN value before and after the implementation of the recommended interventions.

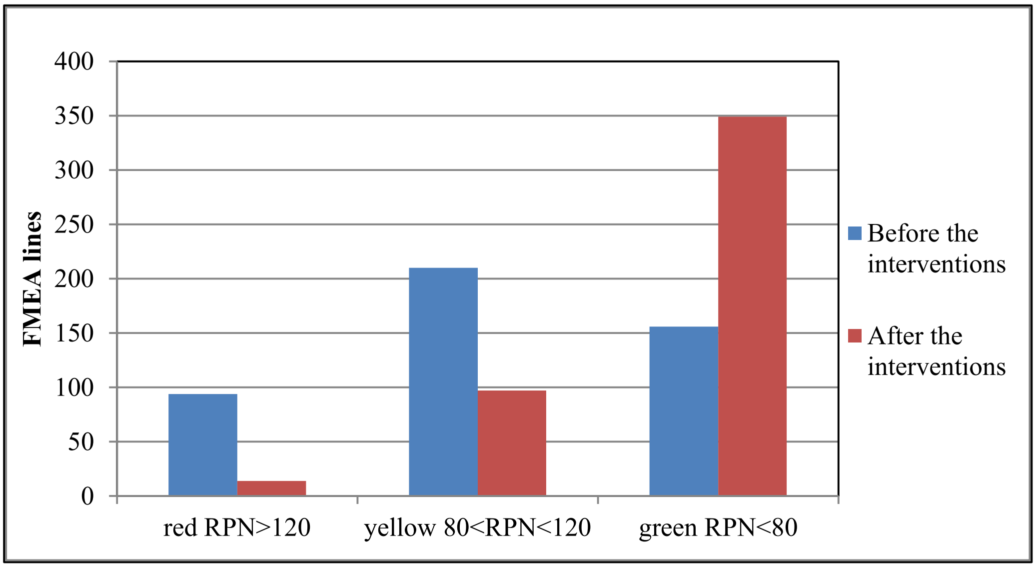

Figure 7.2 – RPN value before and after the interventions

In the application of the FMEA how for 50 effects of failure it has not been possible implement interventions to reduce the RPN value or the availability of the interventions have to be assessed (uninterruptible backup).

It must however emphasize that although it was possible to determine an intervention order to minimize risks and identify many of intervention actions, FMEA is, however, very costly in terms of time and expertise. These problems make difficult, therefore, an application on large scale of such methodology.

The results of the FMEA are consistent with the result obtained through the application of the methodology. Although the FMEA is most exhaustive from the point of view of the aspects considered, the most significant risks have been identified and managed also by the methodology.

The FMEA allows to determine the seriousness of the hazard and to prioritize the interventions, while the method give the same priority to all the technical interventions. The FMEA is most efficient regarding this aspect but the method is most expeditious regarding a complete assessment of the whole system.

7.2 Job Safety Analysis

The Job Safety Analysis will be applied to the wood chips storage tank and dryer loading work activities. They are the only activities, excluding the maintenance activities, with the presence of workers during the course of the process.

The risk analysis will be carried out by determining the residual risk. Therefore it will be assumed that all possible technical and procedural measures to minimize the risk have already been put in place. The probability of occurrence will then be assumed equal to one. Moreover the work activities are assumed to be done by workers with a suitable information, formation and training.

The work will be initially decomposed into elementary steps and for each step the time allocated to that operation compared to the daily 8-hour shift will be determined. For each elementary operation the factors of hazard and risks associated with them will be identified. The factor of contact will be determined by summing the time devoted to each operation with which it may be associated this hazard factor. For each risk the possible associated deviations and damages will be identified and the expressed as working days lost magnitude will be defined. The residual risk is calculated by multiplying the extent of damage (ED) for the contact factor (FC).

7.2.1 Loading activities of the wood chips storage tank

The storage of wood chips loading work phase was divided into the following elementary processes:

- Opening of the tank bulkhead;
- Loading the chips on the loader;
- Moving the loader;
- Approaching the loader at the tank;
- Emptying the chips in the tank;
- Closing the tank bulkhead.

The loader was assumed with EC labeling and therefore with the proper documentation. The bulkhead of the storage tank is assumed to be provided of suitable devices to prevent squeezing and crushing while closing.

For an assessment of the total duration of the individual operations the following data have been taken into account:

- Volume of wood chips in the tank: 2 m^3
- Loadable volume on the tractor shovel: 0.25 m^3
- Required travels to complete the loading of the tank: 8
- Duration of the chips loading on the vehicle phase: 30 sec

- Duration of the chips discharge in the tank phase: 1 min
- Duration of the vehicle moving phase: 3 min
- Duration of the wood chips tank bulkhead opening: 1 min
- Duration of the wood chips tank bulkhead closing: 1 min

It is evident that this work organization cannot be followed in the hypothesis of issues which can cause the not respect of the time/operation schedule. The most probable deviations from the program can happen in case of chips fall from the loader. In this case the worker have to recover the lost load with the use of a shovel. In a thorough risk analysis also the deviations from the standard activities has to be considered.

Figure 7.3 shows the distribution of the dedicated to each elementary operation time over the whole working day in the hypothesis of absence of deviations from the standard activities.

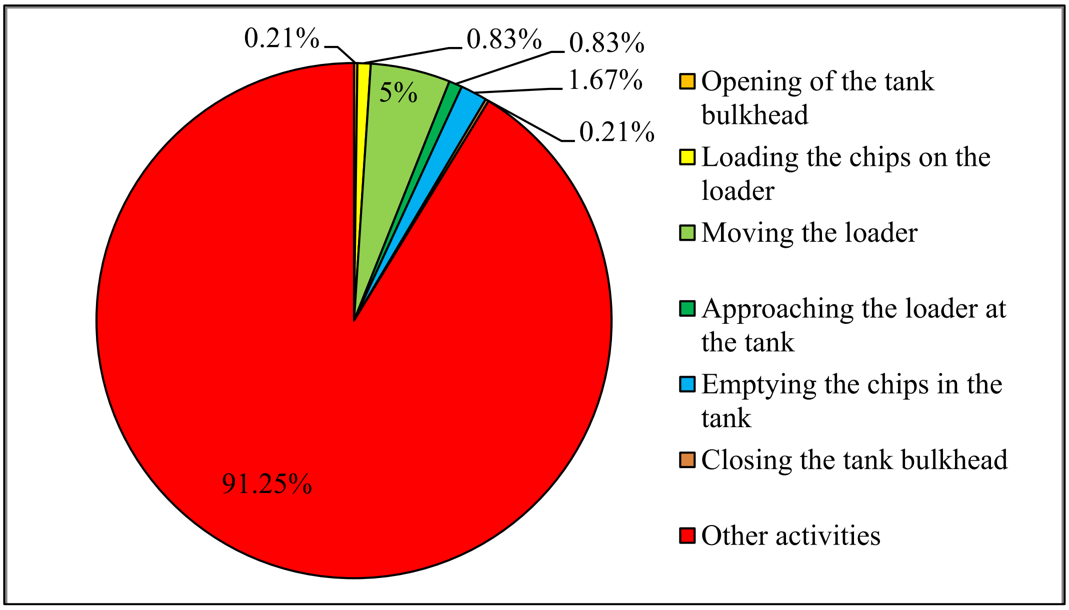

Figure 7.3 – Daily time/operations graph for the chips tank loading activities

In the hypothesis of fall of the load the time/operations graphs could have a modification with the introduction of the phase of manual loading of the chips on the loader.

For each standard elementary phase the hazard factors and their associated risks were identified (Table 7.6).

Table 7.6 - Risk identification for storage tank loading operation

Elementary processes	Interference	Hazard factors	Risk
Opening of the tank bulkhead	Worker/chips/storage tank	Chips	Biological agents (insects)
Loading the chips on the loader	Vehicle/man/chips	Chips pile	Slips of the chips pile Tipping of the vehicle
Moving the loader	Vehicle/man	Moving vehicle	Transit of people on the path of the vehicle
Approaching the loader at the tank	Worker/chips/storage tank	Moving vehicle	Transit of persons on the path of the vehicle
Emptying the chips in the tank	Worker/chips/storage tank Chips	Chips	Tipping of the vehicle Slips of the chips pile
Closing the tank bulkhead	Worker/chips/storage tank	Chips	Biological agents (insects)

Below the risk analysis and the calculation of the residual risk resulting from the application of JSA for each identified hazard factor (Table 7.7).

Table 7.7- Risk analysis of the storage tank loading operation

Risk	Possible associated deviations and damages	ED	CF	Technical intervention	Procedural intervention	Residual risk
Biological agents (insects)	Insect bites - allergic reaction	1 day	0.2%+0.2%= 0.4%		Avoid the direct contat with the chips	1*0.4=0.4
Slips of the chips pile	Burying - Bruises and wounds	7 days	0.8%+1.7%= 2.5%		Avoid the approach of other workers during operations	7*2.5=17.5
Tipping of the vehicle	Wounds and fractures	30 days	0.8%+1.7%= 2.5%		Avoid the approach of other workers during operations	30*2.5=75
Transit of persons on the path of the vehicle	Investment - Fractures	40 days	5%+0.8%= 5.8%		Avoid the approach of other workers during operations Delimit the transit routes of the vehicles	40*5.8=233.2

As can be seen in the table, the most significant risk for the workers is the transit of people along the path of vehicles. Therefore the vehicles transit routes must be properly marked and bordered.

In the hypothesis of deviations of the activities the risk due to the presence of biological agent grows because of the contact with the chips during the phase of chips loading. Moreover an additional risk due to the manual handling of loads have to be considered.

7.2.2 Loading and unloading activities of the dryer

The dryer loading and unloading activities were divided into the following elementary phases:

- Loading the timber on the forklift;
- Moving the forklift;
- Unloading the timber inside the dryer;
- Starting the drying cycle;
- Stopping the drying cycle;
- Loading the timber on the forklift;
- Moving the forklift;
- Unloading the timber inside the dryer.

The loader was assumed with EC labeling and therefore with the proper documentation. Meanwhile also the electric system and the PLC is assumed to be suitably designed and constructed with the necessary documentation.

For an assessment of the total duration of the individual operations the following data have been taken into account:

- Volume of timber plank in the dryer: 7 m^3
- Loadable volume on the forklift: 0.5 m^3
- Required travels to complete the loading of the dryer: 14
- Duration of the timber planks loading on the vehicle phase: 1 min
- Duration of the vehicle moving phase: 5 min
- Duration of the planks unloading in the dryer phase: 1 min

Figure 7.4 shows the distribution of the dedicated to each elementary operation time over the whole working day.

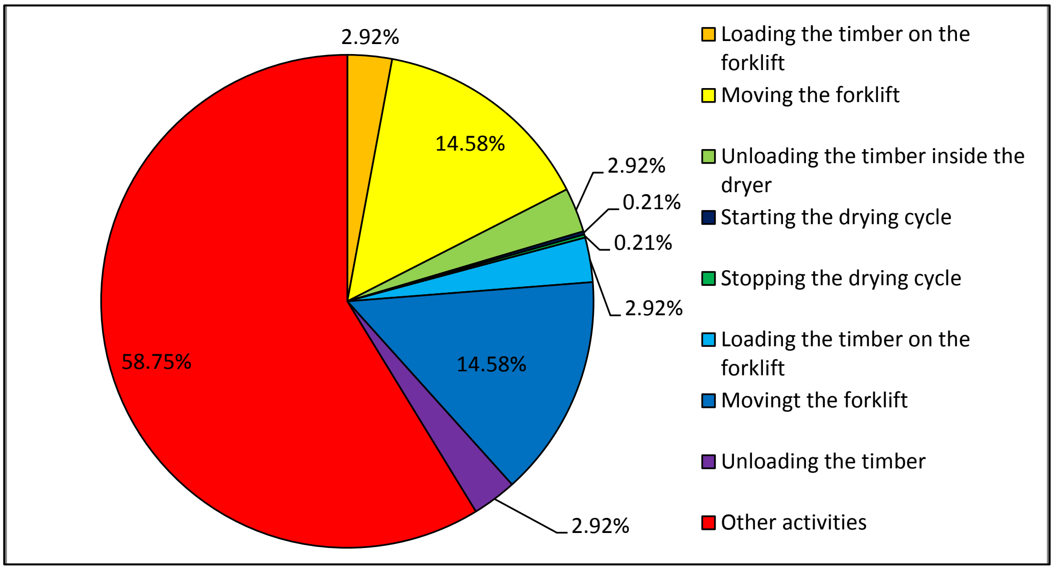

Figure 7.4 - Daily time/operations graph for the dryer loading and unloading activities

For each elementary phase the hazard factors and their associated risks were identified (Table 7.8).

Table 7.8 - Risk identification for dryer loading operation

Elementary processes	Interference	Hazard factors	Risk
Loading the timber on the forklift	Worker/timber/forklift	Timber	Falling material from above Incorrect manual handling of loads Repetitive movements
Moving the forklift	Worker/timber/forklift	Forklift Timber	Falling material from above Transit of persons on the path of the vehicle
Unloading the timber inside the dryer	Worker/timber/forklift/dryer	Timber	Falling material from above Incorrect manual handling of loads Repetitive movements
Starting the drying cycle	Worker/dryer	Dryer	Contact with parts in voltage
Stopping the drying cycle	Worker/dryer	Dryer	Contact with parts in voltage
Loading the timber on the forklift	Worker/timber/forklift	Timber	Falling material from above Incorrect manual handling of loads Repetitive movements
Moving the forklift	Worker/timber/forklift	Forklift Timber	Falling material from above Transit of persons on the path of the vehicle
Unloading the timber	Worker/timber/forklift/	Timber	Falling material from above Incorrect manual handling of loads Repetitive movements

Below the risk analysis and the calculation of the residual risk resulting from the application of JSA for each identified hazard factor (Table 7.9).

Table 7.9 - Risk analysis of the storage tank loading operation

Risk	**Possible associated deviations and damages**	**ED**	**CF**	**Technical intervention**	**Procedural intervention**	**Residual risk**
Falling material from above	Bruises and wounds	7 days	2.9%+14.6%+2.9%+2.9%+14.6%+2.9%= 40.8%		Avoid the approach of other workers during the operations	7*40.8=286
Incorrect manual handling of loads	Musculoskeletal damages	10 days	2.9%+2.9%+2.9%+2.9%= 11.7%		Handle loads correctly.	10*11.7=116.8
Repetitive movements	Musculoskeletal damages	10 days	2.9%+2.9%+2.9%+2.9%= 11.7%		Handle loads correctly. Breaks during the working activity	10*11.68=117
Transit of persons on the path of the vehicle	Investment - Fractures	40 days	14.6%+14.6%= 29.2%		Avoid the approach of other workers during the operations Delimit the transit routes of the vehicles	40*29.2=1166
Contact with parts in voltage	Electrocution	10 days	0.2%+0.2%= 0.4%	Single out parts in voltage		10*0.42=4.2

Also in this work phase, the most significant risk for the workers is the transit of people along the path of vehicles. This is mainly due to the greater contact factor than the other elementary phases.

The results obtained with the application of the JSA are consistent with the results of the application of the methodology. The method has allowed the identification of the same hazard factors. Even without the assessment of the risk, the methodology allows to identify the most significant risks and implement the necessary procedures and interventions.

The only criticality is that the method does not allow to prioritize the interventions. However a through risk assessment requires that all the available interventions has to be done to minimize the risk and the method allows to comply with this objective.

7.3 Measurements of the emissions

The pressures on the environment that have been considered the most significant are particulate matter emissions and noise. Campaign of measurements to quantify these emissions have therefore been carried out. In particular as regards the PM the measurements were carried out both in the chimney that external near the source. The noise emissions were also measured near the source.

7.3.1 Measurements of the atmospheric emissions at the chimney

The measurements of the chimney emissions were carried out using the measurement device for total dust TESTO 380-2 LL. 4 tests were carried out in continuous operation for a period of 15 min and for each of them 180 samplings were carried out. From the 4 tests of chimney emissions there has been an average value of 45.4 mg/Nm^3 (Figure 7.5).

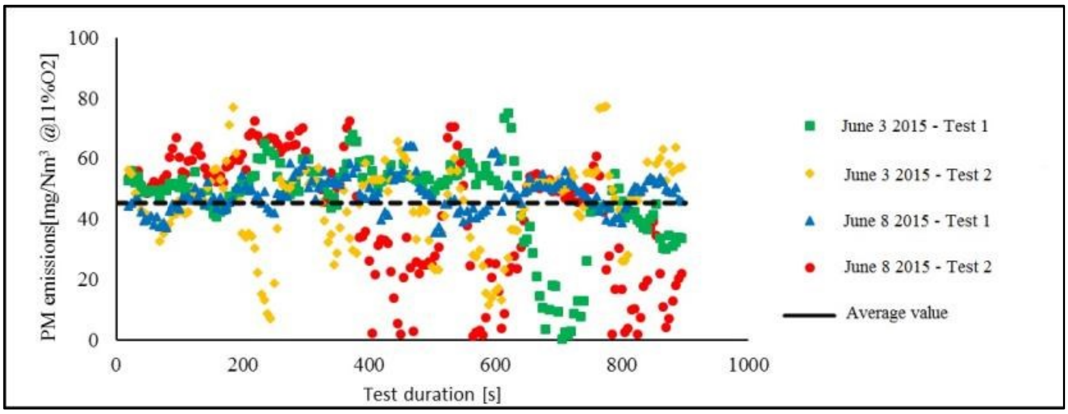

Figure 7.5 - Analysis of pollutant concentration in the flue gas

7.3.2 Monitoring of PM$_{10}$

The carried out monitoring was aimed at the characterization of the prototype plant object of study as an emissive source relative to particulate matter.

The measurement campaign goes from 13/03/2016 to the 4/07/2016.

During the execution of the measures on site the following instruments were used (Figure 7.6):

- Sequential sampler Zambelli model EXPLORER PLUS with pump module
- Automatic filters change Zambelli model CONTROLLER 16.
- PM10 sampling heads

- Thermo ventilated cabin
- Personal Computer and data aqusition software Hyper Terminal
- Quartz fiber filters MILLIPORE, diameter 47mm

Figure 7.6 – Strumentation for the sampling of PM_{10} concentration

During the execution of the measures in laboratory the following instruments wew used:

- Weight scale SCALTEC model SBC 21 (±10 μg)
- Weighing room Aquaria srl model Activa Climatic Cabinet
- Tweezers for filters handling
- Filters containers for storage and transport before and after the sampling

The point of sampling, for the purposes of a more correct characterization of the source from the emissive point of view, has been chosen so as to be placed in under wind respect to the source direction (Figure 7.7).

Figure 7.7 – Location of the sampling point

In the period in which the measures took place, the plant was in operation from the 13/06/2016 to the 27/06/2016.

The period in which the measurement campaign has been done was overally characterized by meteorological ideal for the purposes of the source characterization conditions. The meteorological data for this period come from the meteorological station Davis Vantage Pro 2 post at the headquarters of the company "La Foresta" and they are contained in the Appendix 3.

The results of the measurement are the following (Table 7.10):

Table 7.10 - PM_{10} concentration

Measure date	**Dust weight (μg)**	**PM_{10} concentration ($\mu g/m^3$)**	**Measure date**	**Dust weight (μg)**	**PM_{10} concentration ($\mu g/m^3$)**
13-giu-2016	935	54.19*	24-giu-2016	1755	34.79
14-giu-2016	2045	39.59	25-giu-2016	1890	37.48
15-giu-2016	2770	54.63	26-giu-2016	2630	52.04
16-giu-2016	840	16.59	27-giu-2016	1725	31.9
17-giu-2016	350	n.d.	28-giu-2016	3625	67.27
18-giu-2016	770	15.4	29-giu-2016	1915	35.41
19-giu-2016	615	12.27	30-giu-2016	955	17.93
20-giu-2016	890	17.61	01-lug-2016	885	16.64
21-giu-2016	1340	26.51	02-lug-2016	1210	22.57
22-giu-2016	1635	32.45	03-lug-2016	1100	20.23
23-giu-2016	1630	32.45			

The measurement campaign results have an average value which is equal to 30.72 ± 1.17 $\mu g/m^3$ and a variation range that goes from 12.27 to 67.27 $\mu g/m^3$.

The results show an atypical value as the maximum value has been detected the 28/06/2016. In this day the system was not in operation, then the high value found cannot be attributed entirely to the source. The meteorological data showed calm wind conditions this day. This value can then be attributed at least in part to the persistence of the particulate coming from the road in the vicinity of the prototype plant. Besides this outlier, in general it can be observed that in the days of plant switching off the values observed are generally lower. However, the magnitude of the determined values in this period shows the influence on the obtained values of other sources of PM, such as the dirt road in front of the measuring point.

In general under optimal conditions for the measurements, the values obtained are on average lower than the annual limit corresponding to 40$\mu g/m^3$ [166]. The results are compatible with the assessment done afterwards the application of the method. Indeed the emission deriving for this kind of systems are not significant in an assessment case by case but the results confirm the need to assess the cumulative impacts in the hypothesis of different plants in the same territory.

7.3.3 Monitoring for noise impact assessment

In parallel to the measurements of atmospheric emissions into the atmosphere the monitoring for noise impact assessment took place. The monitoring was carried out in the period between 21/06/2016 and 13/07/2016.

The phonometric chain used for the noise monitoring consists of:

- Modular Precision Sound Analyser Bruel & Kjaer, Type 2250 (serial n. 2579708).
- Microphone Bruel & Kjaer, Type 4189 with phonometric extension and windscreen UA-0237
- Software Evaluator Type 7820, Version 4.16.8
- Calibrator Bruel & Kjaer Type 4231 (serial n. 2115263).
- Power supply through a photovoltaic system with solar panel 100 W, control cabin with charge controller 10 A and external backup battery.

The measurements were performed at a fixed location in the vicinity of the dryer along the perimeter of the company (Figure 7.8). The phonometric chain was positioned, as precautionary measure, in a central position but not in the vicinity of the point of maximum emission constituted by the chimneys of the dryer ventilation system.

Figure 7.8 – Positioning of the measuring point relatively to the emission source

The measurements have detected the trend over time of the signal, the weighted equivalent level, the frequency spectrum and other acoustic indicators, such as the maximum "A" weighted level.

In the period in which the measures took place, the plant was in operation from the 13/06/2016 to the 27/06/2016.

For the whole period of monitoring the meteorological conditions have been verified to be in accordance with the provisions of legislation[172]. Therefore the data that are collected in not suitable meteorological conditions have not been considered.

Table 7.11 shows the results of sound level measurements including the total duration of the measures and the considered noise indicators. For a better management of the high-resolution data collected in broadband during the monitoring, the sampling have been separated into two files. Therefore, with the partial A is defined the period between 21/06/2016 and 29/06/2016 and the partial B the period between 29/06/2016 and 13/07/2016. The complete results of the measurements are shown in the Appendix 4.

Table 7.11 – Results of the measurements

Name	Starting time	Time passed	Overload [%]	LAeq [dB]	LAFmax [dB]	LAFmin [dB]
A	21/06/2016 12:11	190:24:42	0	56,3	98,7	36,6
B	29/06/2016 10:36	336:45:54	0	55	105,7	26,7
TOTAL	**21/06/2016 12:11**	**527:10:36**	**0**	**55,5**	**105,7**	**26,7**

The data has been processed in order to obtain the levels, for the entire duration of monitoring, concerning day and night time, as required by legislation are subsequently carried out. The results include the assessments of the meteorological conditions which have been detected during the measurement period. Table 7.12 shows the synthesis of the results.

Table 7.12 – Overall results of the measurements

Name	Starting time	Time passed	Overload [%]	LAeq [dB]	LAFmax [dB]	LAFmin [dB]
Day	21/06/2016 12:11	351:10:36	0	55	99,8	31,8
Night	21/06/2016 22:00	174:00:00	0	50,7	105,7	26,7

By processing the data the contributions of the background noise at plant stop and of the environmental noise during system operation have been obtained. In this regard, an estimation of the actual contribution of the system in operation (F) in order to exclude the noise generated from the particulate matter measuring instrument (P), located several dozen meters downstream of the plant, compared to the other widespread background sources (R).

There were three characteristic time intervals:

- 21/07/2016 – 27/07/2016: Environmental noise with plant and PM measuring instrument on (F+P+R);

- 28/07/2016 – 04/07/2016: Environmental noise with plant of, background noise and on (F+P);
- 04/07/2016 – 13/07/2016: Background noise, plant and PM measuring instrument off (R).

As a first approximation, the background noise (R) measured between 4 and 13 July 2016 was considered as representative value of the entire monitoring period.

Therefore, to estimate the contribution of the source, the following procedure has been followed:

- Collection and processing of input data;
- Calculation of the contribution of (Pcalc);
- Calculation of the environmental noise at plant on without the contribution of PM sampling instrument (F+Rcalc)
- Calculation of the plant contribution (F).

The used input data refer to the night period, where there are conditions of increased risk caused by the introduction of the source. Also, this solution allow to reduce the incidence of the overall wind conditions which have been very significant in daytime during the entire measurement. In order to further minimize the variability which can be induced by the occasional gusts of wind, the previously described methodology was applied to the statistical levels L_{95} and L_{90} (Table 7.13).

Table 7.13 – Assessment results of the source contribution during the night

Data	**LA_{eq}**	**L_{95}**	**L_{90}**	**Calculation**	**LA_{eq}**	**L_{95}**	**L_{90}**
Period F-R-P	52,2	47,6	48	P calculated [(R-P)-R]	45,3	40,7	41,8
Period R-P	50,5	42	43,4	F+R calculated [(F+R+P)-(P calc)]	51,2	46,6	46,8
Period R	48,9	36,3	38,1	F calculated [(F+R calc)-(R)]	47,4	46,1	46,2

In order to verify the results, the assessment has been repeated with the collected in the daytime period data (previously not considered) (Table 7.14).

Table 7.14 - Assessment results of the source contribution during the night

Data	**LA_{eq}**	**L_{95}**	**L_{90}**	**Calculation**	**LA_{eq}**	**L_{95}**	**L_{90}**
Period F-R-P	55,6	48	49	P calculated [(R-P)-R]	43,8	36	35
Period R-P	54,6	44	46	F+R calculated [(F+R+P)-(P calc)]	55,3	48	49
Period R	54,2	44	45	F calculated [(F+R calc)-(R)]	48,9	46	47

Following the different necessary approximations - in particular caused by the disturbances in the daytime period attributable to the presence of wind on a daily basis in an extended time period between 12.00 and about 18.00 - there has been a slightly higher contribution of the source in the estimate from daytime input.

The application of statistical estimation levels was aimed to minimize this effect. Although not being comparable with any regulatory limit, the result allows to highlight a minor deviation of the results between nighttime and daytime.

Concluding the emission from the source falls within a range of 45 ± 2 dB (A).

In the analysis of the frequency spectra, finally, impulsive and significant vibrational phenomena, nor a prevalence of low frequencies, have been identified.

The monitoring results show an emissive framework compatible with the emission values of acoustic territorial zoning class III. This class is the most cautionary between the areas of possible installation of this type of system.

The previously described method is validated by the results of noise measurements because knowledge of emissions, which in the case of implementation of the prototype plant for sales shall be known, allows to see if it is compatible with the acoustic classification of the territory. Indeed, it has been identified as an indicator of state to be known to assess the environmental impact.

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Chapter 8

Cumulative impacts

The results obtained make it possible to observe how the described method does not allow a full assessment of the cumulative impacts on the territory. This aspect is very significant in the case of spread of wood biomass heating systems. There would be, indeed, the need to determine the influence that a significant number of these systems could have on an area.

The analysis has shown that, in the environmental impact assessment, the emission of pollutants into the atmosphere is the most significant pressure deriving from the plant. Determining the impact on air quality that such systems may cause, even knowing the emission value, closely related to the plant features, is very difficult. Indeed, factors related to meteorological characteristics and models of pollutants dispersion into the atmosphere must be taken into account. The impact given by a single plant is resulted minimal from the results of the methodology, however the same cannot be assumed in case of application of numerous systems.

An abroad period has been done at the Laboratoire de Mécanique des Fluides et Acoustique of the Ecole Centrale de Lyon. The objective of the this external research was to learn and use a model there developed to determine and analyse phenomena of pollutant dispersions.

As mentioned previously the most significant pollutants that may result from the installation of this type of plants are PM, NO_X and SO_2. In particular according the literature analysis, particulate matter emissions are particularly critical[186]. Several studies analysed the actual influence of these systems on air quality[134,135], mainly focusing on the PM concentrations, given their well-known impact on human health[136,137]. The impact that these systems can have in regions where atmospheric PM concentrations are significant has therefore to be carefully assessed. In Italy, this is the case of the Po Valley and of all neighbouring alpine valleys[138]. These areas present critical air quality conditions which can be further worsened if other pollutants sources are added[187].

The aim of this phase of the study is the assessment of the impacts of a network of wood biomass heating system located within an alpine valley in the north of

Italy. The objective is the assessment of the hypothesis of the progressive replacement of traditional fossil fuel boilers with wood biomass boilers. The effects of emissions scenarios due to a replacement of the entire traditional natural-gas heating system with small to medium size biomass boilers have been analyzed. The analysis focuses on PM and NO_X concentration in air, and it aims to compare the environmental impacts of woodchips boilers, traditional stoves and natural gas boilers.

Part of the work described in this chapter is being published.

8.1 Definition of the emission scenarios

The definition of a realistic emission scenario first requires the estimate of the emissions factors for wood and natural gas which are given in Table 8.1. Particulate matter emissions of natural-gas systems are considered as negligible, as a first approximation[186,188].

Table 8.1 - Emission factors for wood and natural gas[189,190]

FUEL	**Traded forms**	**AGGREGATE EMISSION FACTORS (mg/kWh)**									
		CO_2	N_2O	NO_X	CO	NMVOC	SO_2	PM_{10}	$PM_{2.5}$	PAH	PCB
Wood and similar	**Average value**	3.33E+05	5.04E+01	2.20E+02	1.94E+04	2.29E+03	4.59E+01	1.45E+03	1.44E+03	7.80E-01	2.16E-04
	Wood, chips, spruce			4.58E+02	2.71E+02			1.12E+01			
	Pellet, spruce			2.92E+02	6.14E+01			3.97E+01			
	Log wood, beech			5.23E+02	6.68E+03			3.34E+02			
Natural gas		2.04E+05	3.60E+00	1.25E+02	8.99E+01	1.80E+01		7.19E-01	7.19E-01		

The average value for wood and similar that is present in Table 1 have to be considered as reference averaged values, taking account any kind of technological solution currently adopted in the conception of wood heating systems. These therefore include also traditional systems, such as woodstoves and fireplaces, whose emissions are known to be particularly high[191]. Nevertheless, modern wood chip plants are characterized by lower emission values[192], although not yet comparable with the emissions from natural gas boilers (Table 8.1).

Note that, when considering the impact of wood heating systems, there is also the need to take into account emissions from the transport phase, whose estimate require specific emission factors of Heavy Goods vehicles[193].

Once identified these emission factors, the scenario was designed based on the following hypotheses:

- Substitution of the entire fossil fuels heating network with wood biomass boilers linked to the buildings through a district heating network.
- Heat demand determined by both residential and industrial buildings.
- Emissions due to biomass boilers and to the vehicles supplying wood, only.
- Unlimited availability of timber in the surrounding area.
- The entire building is characterized by a same average energy class.
- Typology of boilers are given by Best Available Technology solutions.

This scenario is based on a simplifying assumption, that of decoupling the sizing of the boilers from the actual availability of wood in the surrounding areas. In view of its effective implementation, a sustainable design of the network requires it to be dimensioned avoiding a depletion of the local forest resources[194].

The chosen sample area is the Municipality of Avigliana located at the entrance of an alpine valley in the North West of Italy. This area covers about 25 km^2 and it is surrounded by woods that can potentially supply the heating network. The emissive scenario is designed assessing separately the thermal needs of the residential, municipal and service buildings and of the buildings used for industrial activities.

To determine the heating requirements of residential buildings, needed to estimate the number of boilers and their power, the consumption of domestic hot water has also been taken into account. A proper evaluation of the distribution of boilers over the territory should take into account the size, the architectural characteristics and the thermal properties of the building[195,196]. Since all these information were not available in the examined case, their spatial distribution is assumed to depend on the density of the resident population defined for homogenous areas.

The heating requirement for the industrial buildings is based on the cubic footage. Considering the thermal needs in the industrial areas here higher power boilers compared to those in residential areas were assumed. One of these higher power boiler will be the one devoted to the drying of the wood for the whole area. It was assumed to put a fuel wood terminal in this area. Given the hypothesis that the wood will be stored and chipped close to this boiler, i.e. that all trucks transporting wood will be directed there. Figure 8.1 shows the location and power of point sources, i.e. the wood biomass boilers and road network considered for calculating the emissions of the transport means

Overall, the heating requirement is assumed to be guaranteed by 76 boilers with powers ranging from 100 to 1500 kW (Figure 8.1). This correspond to a whole power of 44,6 MW, which is consistent with a high-efficiency thermal network, therefore including all technical upgrading to minimize thermal losses[197].

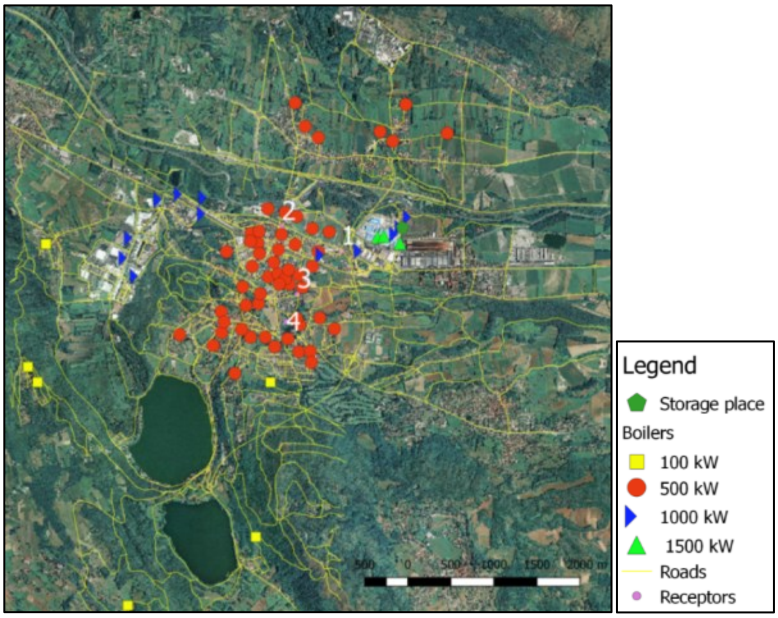

Figure 8.1 - Location and power of point sources, road network, receptors and the storage place

Concerning the modulation of the emissions, full or part load operating boilers were assumed according to the season and the hour of the day. The whole required quantity of wood chips has been determined according to the number, the power and the operating boilers. The traffic flows (vehicle per hour) for the wood transport and their hourly modulation over the whole year were determined by imposing the typologies of trucks and identifying preferential hours for the chips delivery. The domain was divided in areas with a known number of boilers to determine the traffic flow for each section of the road network. Pollutant emissions were subsequently computed based on vehicles typology and flow.

The analysis is performed using the meteorological data for the year 2015. Temperature values during 2015 are rather high compared to long term temperature statistics. These can be however considered as representative of climatic conditions in the next future, as induced by the trends observed in the last decades due to the global warming.

In order to observe how the influence of varying operating conditions can affect air pollutant concentrations, three different scenarios have been analyzed:

1. Scheduled operating conditions for the whole year (with reduced power in summer to supply the hot water);
2. Modulated operating conditions, based on the external temperature, over the whole year (with reduced power in summer to supply the hot water);
3. Modulated operating conditions, based on the external temperature, and compete switch off in the summer, i.e. excluding their use for the supply of hot-water.

In all case the boilers has been modulated at lower loads in the middle of the day and at night. The height of the emission stack is variable from one source to the other and depends on the height of each single building in the domain. As a general rule the stack height was estimated by adding 3 meters to the height of each single building within the domain.

Scenario 1 is the worst regarding the used forest resources. In order to assess the impact on the wood resources of the territory, the necessary amount of timber has been calculated. To calculate the necessary amount of chips in tonnes, the calorific value of dry wood chips was assumed equal to 4kW/kg. Therefore in determining the quantity of timber the weight loss in the timber drying process must be considered. Based on the described assumptions to ensure the functioning of the boilers about 42000 t of wet wood chips in winter and 12000 t in the summer months are needed annually. In total, it is therefore necessary 54000 tons of wet wood chips. Assuming a density equal to 1 t/m^3, 54000 m^3 of timber shall be provided annually.

Assuming to only use the lower-quality timber and an annual forest growth of 6.5 m^3/ha, 84 km^2 of forest should be intended for wood biomass production.

8.2 Atmospheric dispersion modeling

To estimate the air concentration of PM at ground level simulations of atmospheric dispersion have been performed with the model SIRANE[198,199]. It has been developed at the the Laboratoire de Mécanique des Fluides et d'Acoustique of the Ecole Centrale de Lyon by the team AIR. SIRANE is a model conceived to simulate pollutant dispersion emitted from line sources (e.g. traffic emissions) and punctual sources (e.g. chimneys) at a local scale. The model calculates the concentration of pollutants with an hourly time-step over domain whose dimensions can reach 30 km x 30 km. The SIRANE model requires as input the meteorological data, the emissions of pollutants (from punctual, linear and area sources), the pollutants background concentration (measured outside the analyzed domain). SIRANE is a second generation Gaussian model, i.e. it models the air low in the lower atmosphere as a boundary layer, according to Monin-Obukov similarity theory. Pollutant dispersion are parameterized by a Gaussian plume, with transversal and vertical spread parameterized according to local velocity statistics[199]. In the modeling of particulate matter emissions, we have assumed the particles characteristics comparable to those of PM_{10}.

Comparing the different impact of wood chips boilers and traditional heating systems (i.e. wood stoves and natural gas boilers) is the first objective of the analysis. To that purpose the concentration field at ground level obtained with these different heating systems are compared. Regarding chips boilers in this phase of the analysis only the first of the three emission scenarios presented in sect. 7.1 was considered. It is the worst from an emission point of view.

The comparison with wood stoves is presented in Figure 8.2 and Figure 8.3, where the annual average concentration of PM is plotted.

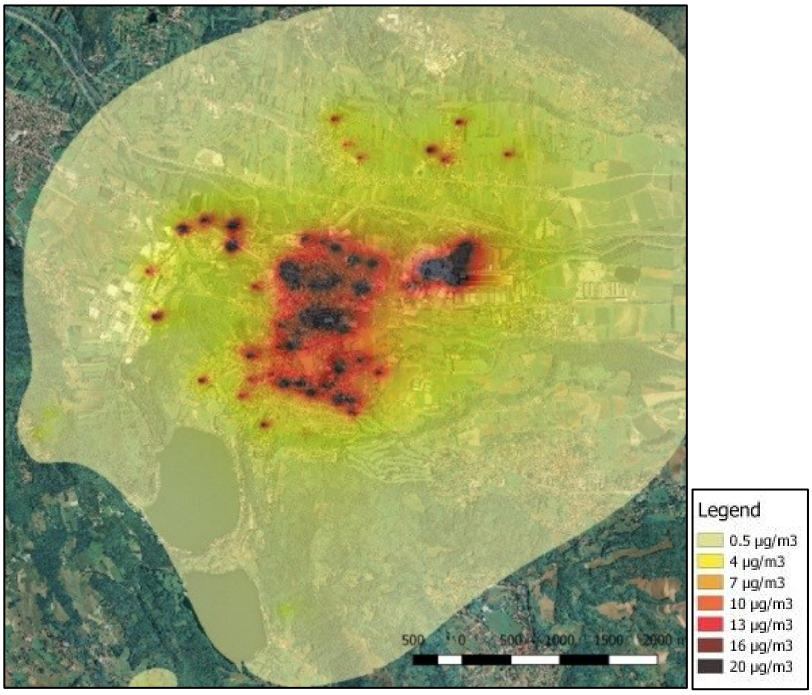

Figure 8.2 - Annual concentration of PM due to emissions of traditional wood stoves

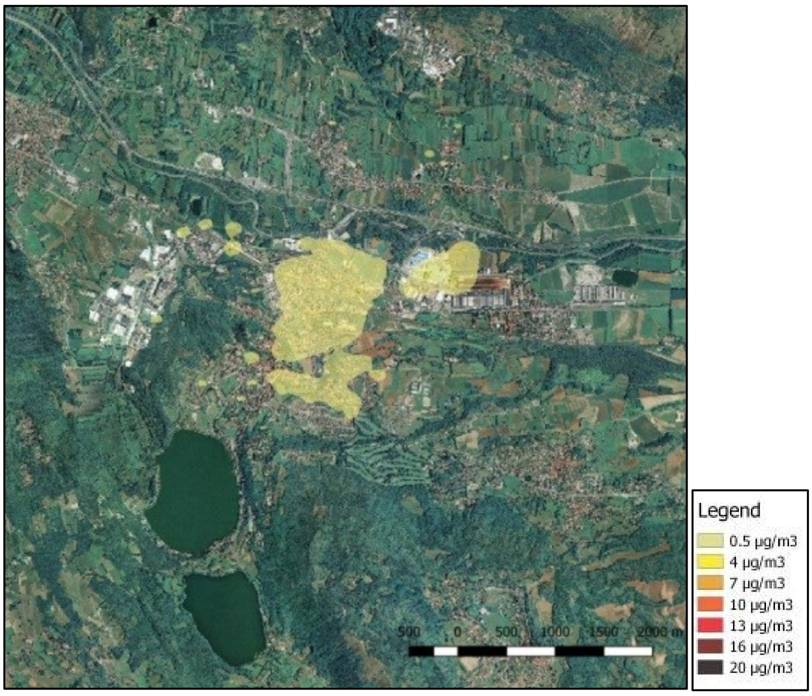

Figure 8.3 - Annual concentration of PM due to emissions of biomass boilers

The differences between the two fields are striking. In case of traditional stoves, PM concentrations exhibit significantly larger with peaks exceeding 20 $\mu g/m^3$ in several part of the domain, and locally reaching 40 $\mu g/m^3$. Therefore, the sole contribution of emission related to traditional stoves (and without taking into account the role of background pollution) would imply exceeding the limiting value for the quality of life (40 $\mu g/m^3$) indicated by the European legislation for PM_{10}[166]. Conversely, in case of wood chips boilers, concentration values are significantly reduced. These are generally in the range 0 - 0.5 $\mu g/m^3$ (Figure 8.3) and hardly exceed 1 $\mu g/m^3$.

The comparison with natural gas boilers is instead based on annual averaged concentrations of NO_X, since their PM emissions can be considered as negligible (Table 8.1). Results are presented in Figure 8.4, and show that the use of wood chips boilers, compared to natural gas ones, induces a relevant increase of ground level concentration with local peaks that exceed 20 $\mu g/m^3$ (Figure 8.4b).

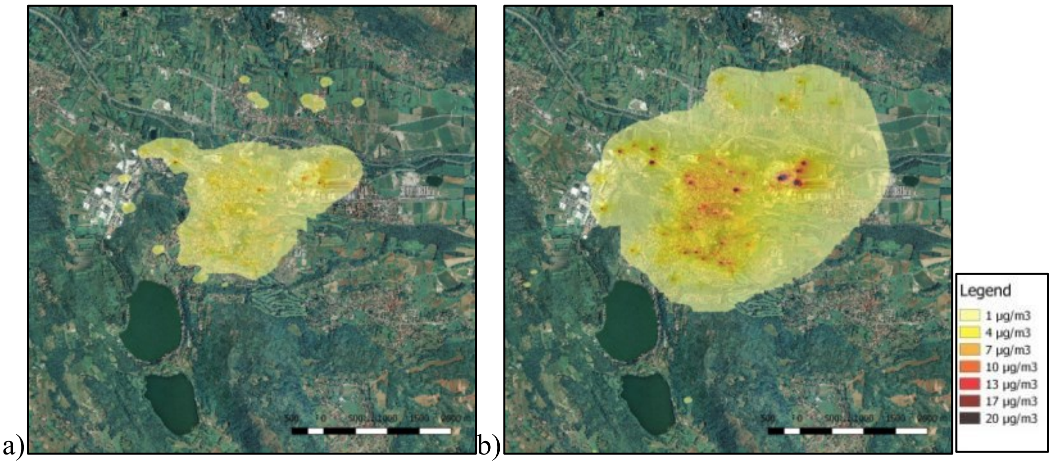

Figure 8.4 - Annual concentration of NO_X from the emissions natural gas boilers (a) and wood biomass boilers (b)

To further characterize the wood chips boilers emission scenario, the emissions from punctual sources, due to boilers emissions, and linear sources, due to traffic related emissions (Figure 8.5a) have been assessed separately. The results show that the contribution of boilers emissions to ground level concentration largely exceed those from traffic (Figure 8.5b). In this latter case concentration values are in the range $5.9\cdot10^{-6}\div0.026$ $\mu g/m^3$, several order of magnitude smaller than those observed considering boilers emissions. The only relevant contribution on local concentration can be detected south of the city centre, around the location where according to the design hypothesis the timber was harvested (at which therefore all heavy goods vehicle trajectories had to converge).

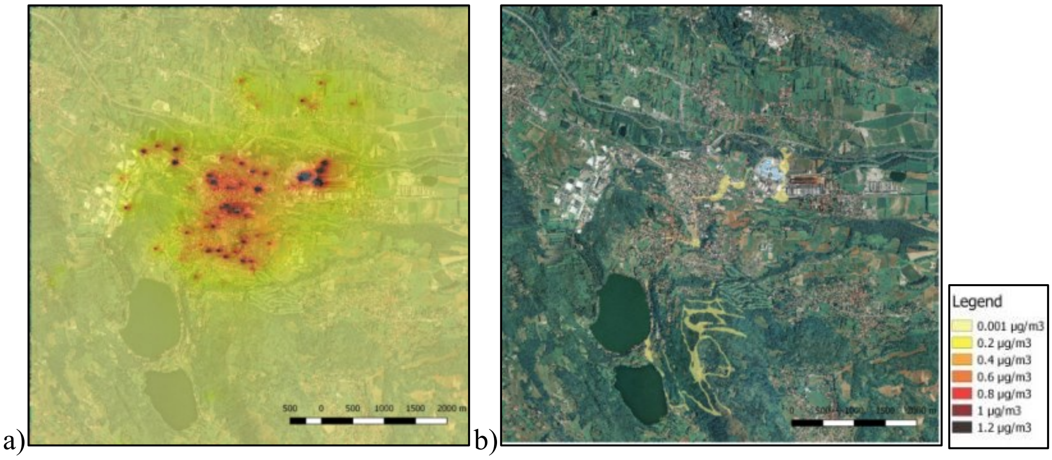

Figure 8.5 – Annual concentration of PM from the emissions of biomass boilers (a) and timber means of transport (b)

Note that, all results presented so fare refer to the Scenario 1, in which emissions are assumed to be constant over the whole year. For a more comprehensive evaluation of the impacts of these heating systems, hereinafter the results referring to the other scenarios will be shown. In these scenarios the emissions data have been modulated according to the measured external temperature and to the hot water supply.

Results show that a modulation of the emissions based on the ambient temperature induces a slight reduction of yearly averaged ground level concentration (see Figure 8.6a and Figure 8.6b). Conversely, a significant improvement of air quality can be obtained by completely switching-off of the boilers during the ‘hot’ months, i.e. from beginning of May to the beginning of October (see Figure 8.6c). This implies that these heating systems have to be coupled with some other renewable energy sources in order to heat water for domestic and industrial uses.

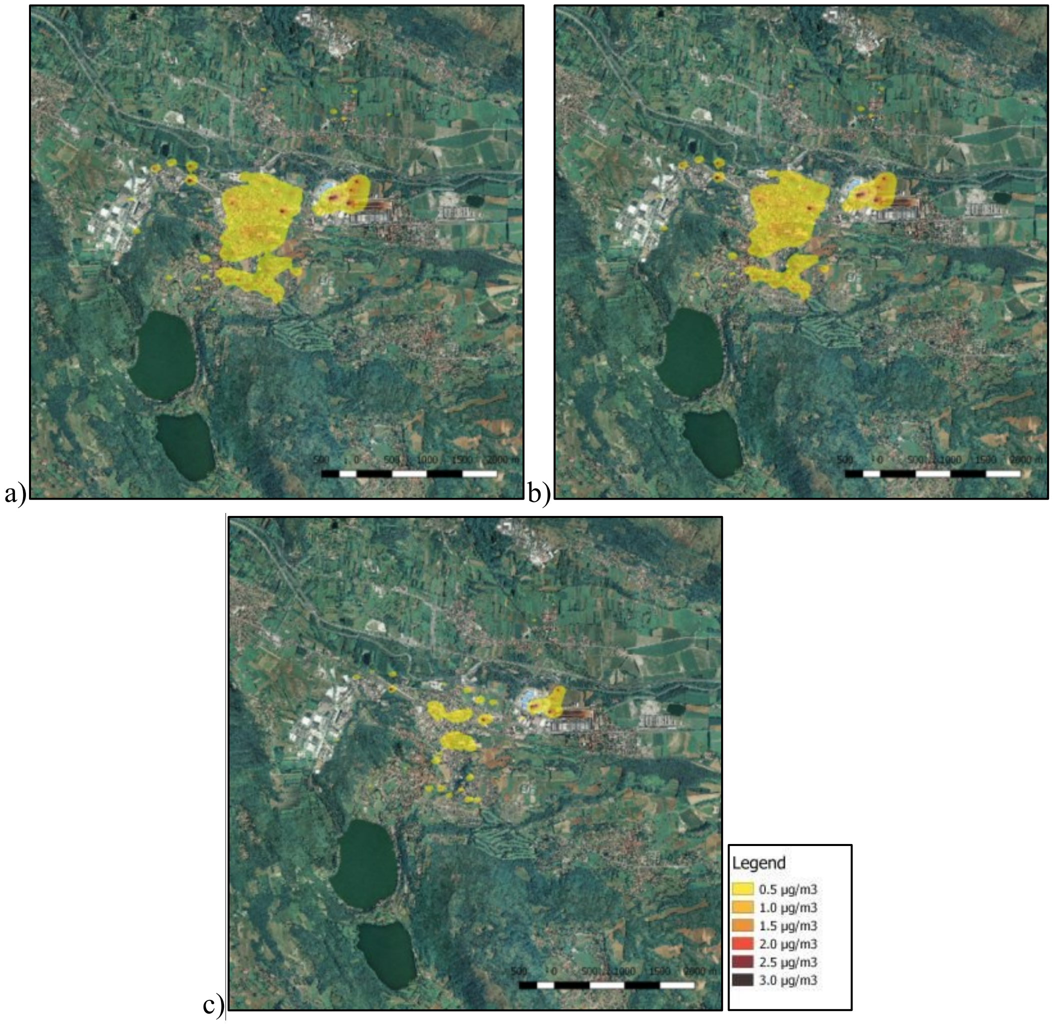

Figure 8.6 - Annual concentration of PM from the emissions of biomass boilers in the three scenarios considered: with scheduled working conditions for the whole year (a), with modulated, according to the external temperature, working conditions for the whole year (b) and switching off in the summer months (c)

The reduction of concentrations in Scenario 3, compared to Scenario 1, is also depicted in Figure 8.7, where time evolution of PM concentrations at four different receptors within the domain is shown.

As it is shown, a relevant contribution in the ground level concentration is due to the switching off in summer, which implies null emissions and therefore null ground level concentrations. A more significant difference in the day with higher temperatures is observed. In these cases a correct modulation of the boiler can significantly influence the concentration trend.

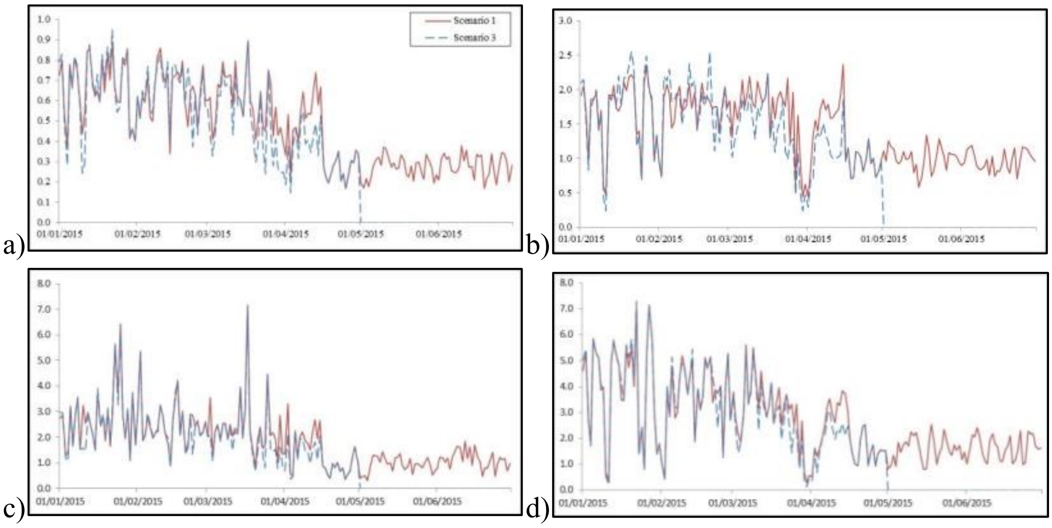

Figure 8.7 – Average daily concentration [µg/m^3] trend for the scenarios 1 and 3 in receptors R1(a), R2(b), R3(c) and R4(d)

8.3 Sensitivity analysis

In Scenario 1, the modulation of the boilers is not influenced by the external temperature, because it is assumed an a priori functioning that remains unchanged for the whole winter period. The variations in the concentration values therefore depend exclusively on the meteorological data and the geometric parameters of buildings and punctual sources. A sensitivity analysis was therefore carried out in order to observe how the results may change varying some input data.

Meteorological data that were considered most significant for the purpose of a sensitivity analysis are solar radiation and wind speed. Therefore additional modeling have been done for the month of January. It was chosen as an example of the winter months. The input data of wind speed and solar radiation were increased and decreased proportionally in two different modeling scenarios.

With regard to the solar radiation, in the modeling carried out, there are no significant changes both as regards the concentration maps that the trend of the concentration values in correspondence of the receptors.

The wind speed has been modified proportionally by 10% and 20%. It can be observed in the graph regarding the trend of the concentration at the receptor R2 for the month of January that the influence of the wind speed values is directly proportional than the concentration values (Figure 8.8).

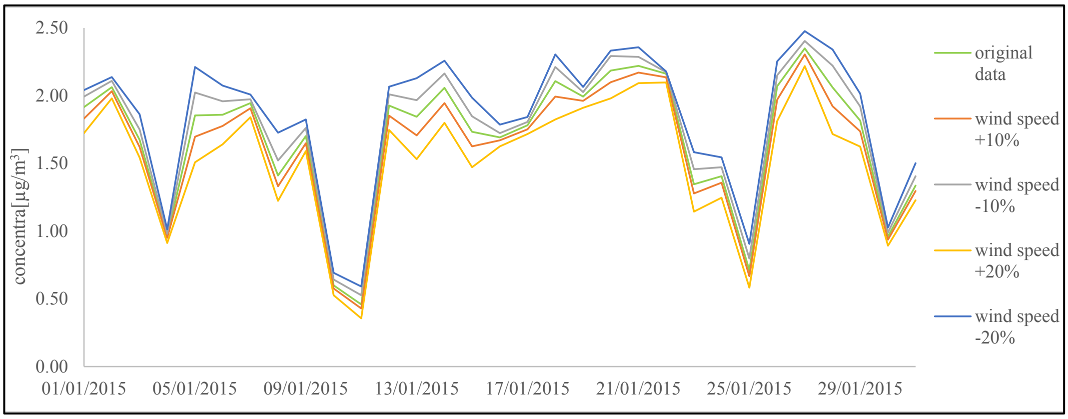

Figure 8.8 – Average daily concentration trend at varying wind speeds in correspondence of the receptor R2

Another significant parameter for the dispersion process is the height of the emission point. The input data have been modified by imposing a constant height of the boilers emission points corresponding respectively to 7 m, , 8.5 m and 10 m. In the receptor R2 concentration trends there are higher values in the hypothesis of higher emission points (Figure 8.9). The greater height of the emission point determines a mayor pollutant dispersion and this can be observed in correspondence of the receptor R2 placed at a certain distance from the city center.

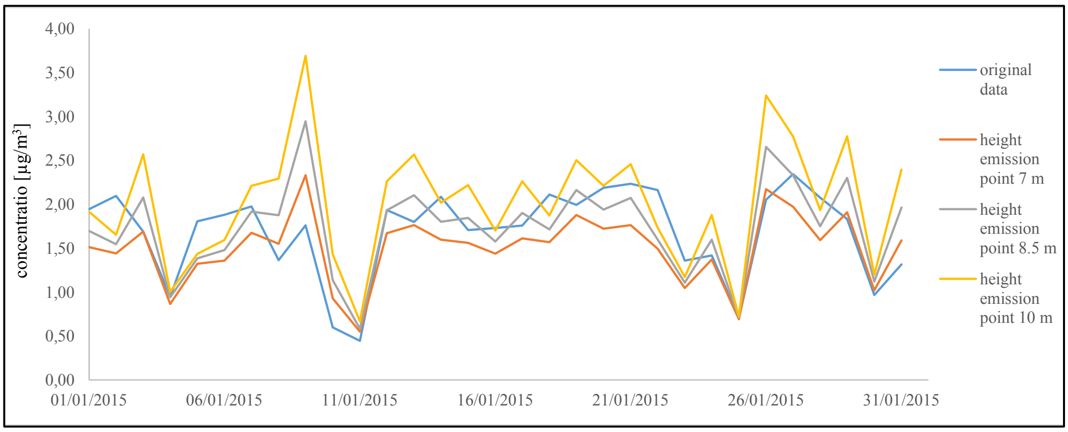

Figure 8.9 – Average daily concentration trend at varying the height of boilers emission point in correspondence of the receptor R2

To observe how the emissive scenario is influenced by variations of the outside temperature a sensitivity analysis was carried out. It has been applied to the data referring to the month of January of Scenario 2. This month was chosen because it has been considered more in line with the average temperatures for the period compared to autumn months. The temperature input have been therefore varied increasing and decreasing them respectively of 2 °C. The modulation of the boiler, and consequently the emissions, has been varied according to these variations. Figure 8.10 shows respectively the concentration map of the original data (Figure 8.10a) and with increased (Figure 8.10b) and decreased temperature (Figure 8.10c).

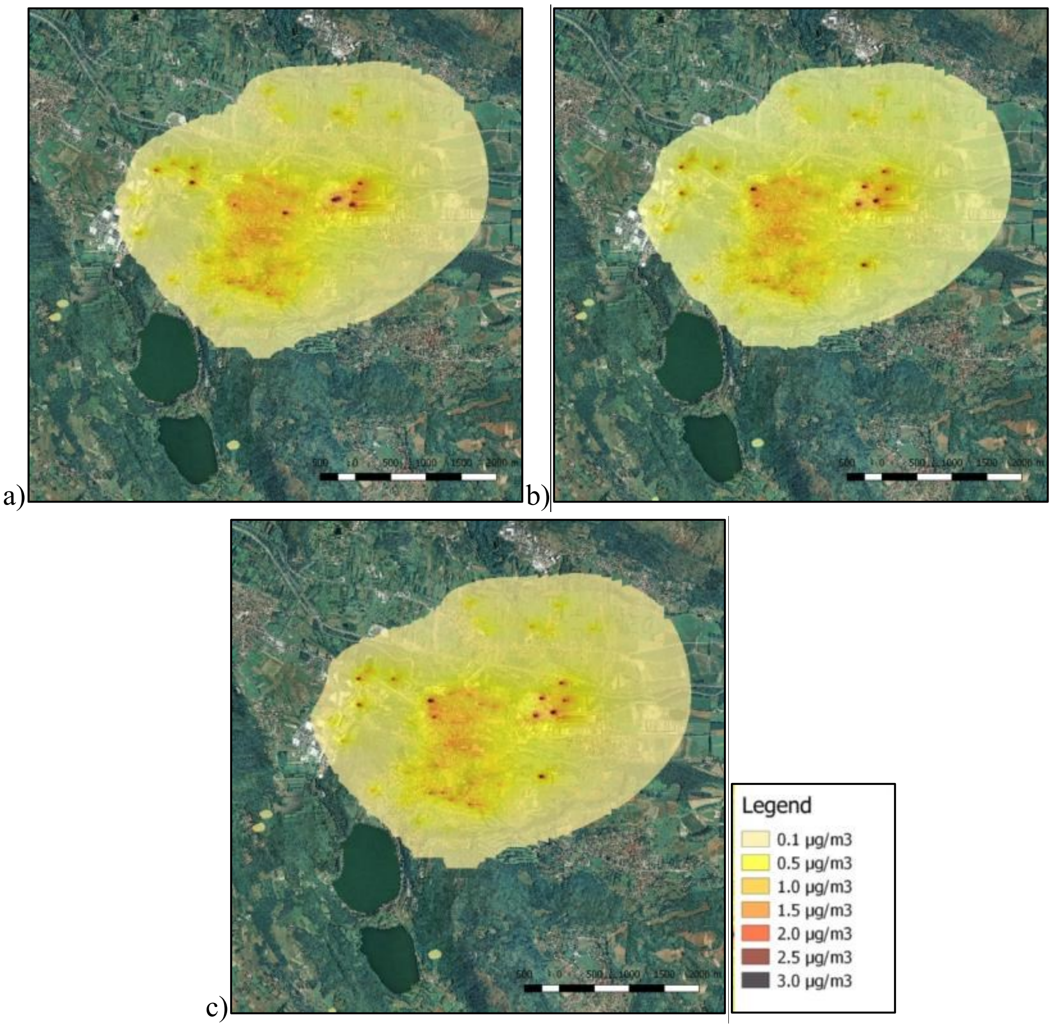

Figure 8.10 - January concentration of PM from the emissions of biomass boilers in Scenario 2 (a) and with increased (b) and decreased (c) of 2°C temperature input data

8.4 Scenario with improved energy classification of buildings

The obtained results showed that the impact on air quality of these design solutions even improved thanks to technological improvements is still significant. Therefore it must be assumed that greater sustainability would be reached in a perspective of improvement of buildings energy performance that would result in a significant reduction in emissions. This scenario is compatible with the bonus policies of such improvements currently present. Indeed, such a scenario is conceivable only if accompanied by the installation of solar panels. They are necessary to ensure the production of sanitary hot water for the summer period. Therefore the input data have only been assumed for the colder months.

In this scenario, the heat demand was calculated assuming an energy class of the buildings significantly better. Taking into account the presence of historic buildings an overall average energy class equal to B was deemed reachable. Based on this value the size of the installed boilers has been changed. The original location has been maintained but the hypnotized boilers have reduced power.

Figure 8.11 shows the concentration maps obtained for the month of January in the hypothesis of improvement of building energy classification. The entire year concentration map is not shown because this solution is compatible only with an assumption of shutdown in the summer. Figure 8.12 shows the concentration for the month of January referred to the Scenario 2.

In addition to highlighting in general a lower diffusion of pollutants, there is a significant difference of about 20 µg/m^3 between the maximum value of the first and second case.

This scenario is most sustainable also from the point of view of used forest resources. To ensure the functioning of the boilers 23000 tons of wet wood chips in the winter months are needed, while in the summer months the boiler shutdown is supposed. For this scenario 36 km^2 of forest should therefore be intended for wood biomass destination.

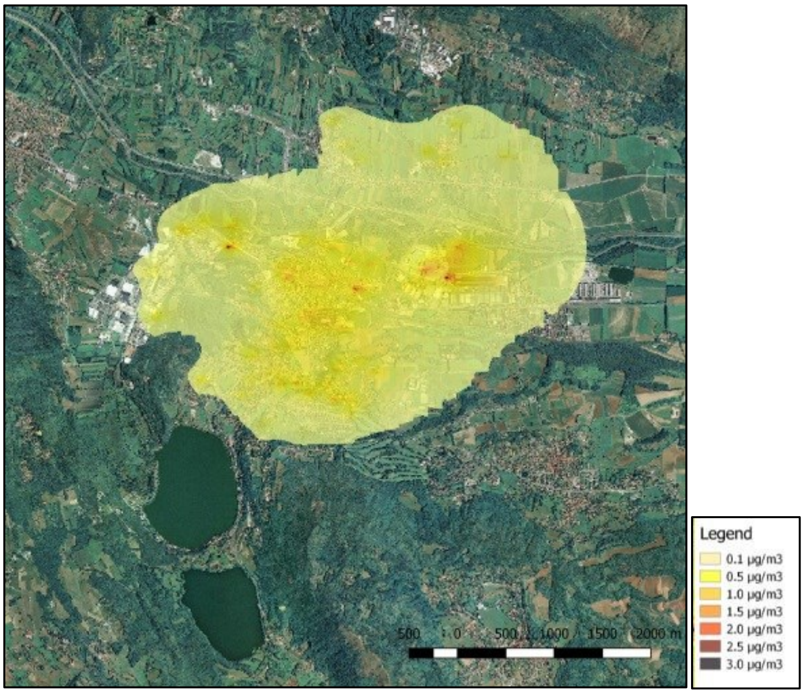

Figure 8.11 - January concentration of PM from the emissions of biomass boilers in the hypothesis of improved buildings energy performance

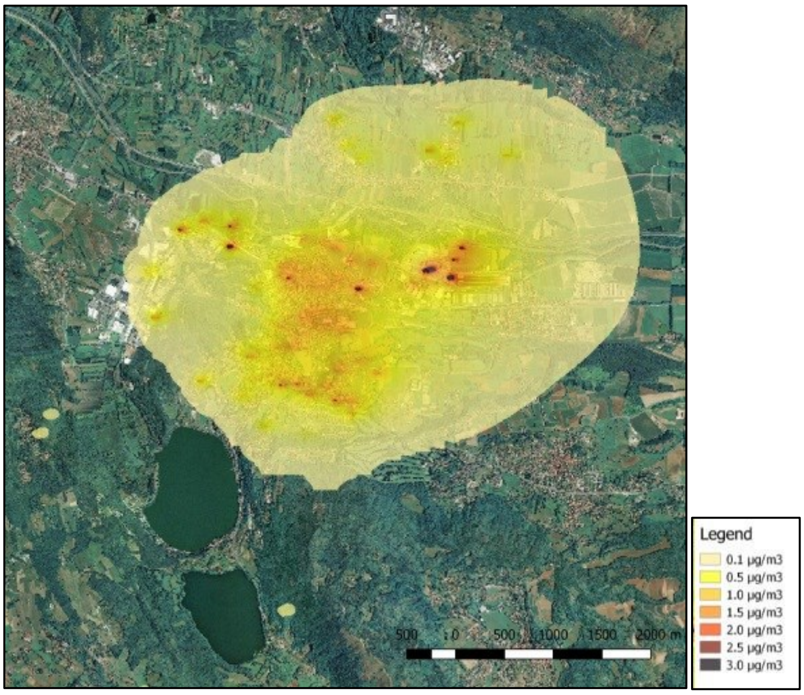

Figure 8.12 - January concentration of PM from the emissions of biomass boilers in Scenario 2 in the hypothesis of actual buildings energy performance

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Section 4: Conclusions

Chapter 9

Final results

Through the described implementations and integrations, a method has been defined that can be made available to operators in the sector and applied by themselves in the necessary analysis of their activities and processes.

Figure 9.1 summarizes the phases of analysis which constitute the method.

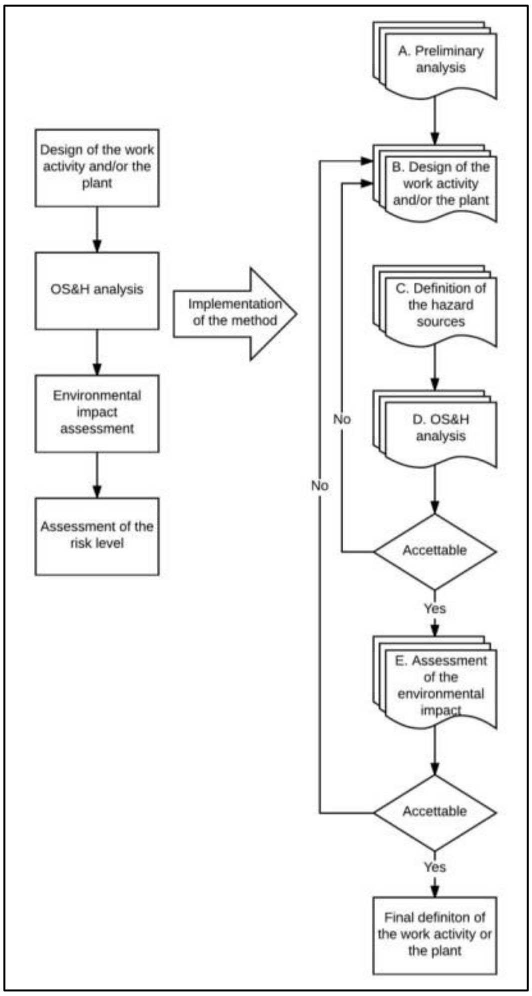

Figure 9.1 – Development of the method and flow chart applicable for the analysis

The formalization of the method has seen the arising of a need to define a check list in order to allow the application of the method also by not experts in field. Moreover, a document tool have been developed starting from the check list to be given to the end-users in order to facilitate the analysis.

9.1 Check list

A. Preliminary analysis

Forest yards

- Locate a suitable place for timber harvesting according to forest management policies and the wood availability;
- Mark the areas to harvest;
- Define the number of tree to be harvested;
- Analyze the surrounding environment;
- Determine the most appropriate technologies according to the characteristics of the work environment
- Delimit the forest yards areas.

Fuel wood terminal

- Locate the work activities and the processes that have to be done at the fuel wood terminal;
- Identify the size of the fuel wood terminal;
- Locate the suitable place for the fuel wood terminal (proximity to forests and/or the energy conversion systems);
- Identify the most suitable location of the different activities within the fuel wood terminal.

Energy conversion systems

- Locate a suitable place for the installation of the system (proximity to forests and/or fuel wood terminal, presence of suitable road infrastructures);
- Define the thermal needs;
- Identify the location of the system;
- Identify the most suitable plant type (energy conversion process, type of used wood fuel);
- Identify the suitable boiler size;
- Define the size wood chips storage tank.

B. Design of the work activity and/or the plant

- Identify the best technological solution to ensure the performance of the activity and/or the execution of the process according to the parameters to be met and the financial resources;

- Organize the work both in terms of location in the work place and as the sequence of the different activities.

C. Definition of the hazard sources
- Define the main phase of the plant process and/or of the work activity;
- Define for each phase, sub phases and elementary processes;
- Identify for each elementary process the used machine, the involved materials (distinguished in raw and complementary materials, products and waste), work environment (macro and micro) and work organization (general and operative conditions).

D. OS&H analysis
- Consult the existing safety documentation for each identified hazard source;
- Consult the reference legislation;
- Identify for each hazard source, the hazard factors associated with them;
- Identify for each hazard factor, the possible deviations and damages associated with them;
- Identify the technical interventions to be implemented to minimize the risk;
- Identify the operative procedures to be implemented to minimize the risk;
- Identify the CPE to provide the workers;
- Identify the PPE to provide the workers;
- Assess the residual risk for the workers and determine its acceptability.

Redesign the activity or system → B
- In case of an unacceptable risk for the workers, redesign the activity or system

E. Assessment of the environmental impact
- According to the identified drivers (sources of hazard factors), determine the pressures that may be induced on the surrounding environment;
- Define the state of the environment through the identification and characterization of suitable environmental indicators;
- Define the impacts on the surrounding environment by identifying and, when possible, quantifying the alterations that the identified pressures can cause on the surrounding environment;
- Define the responses to be implemented to reduce the impacts through action which can act on the drivers, by changing the pressure, or on the pressures themselves, mitigating them;
- Assess again the impact on the surrounding environment.

Redesign the activity or system → B

- In case of an unacceptable impact on the environment, redesign the activity or system

9.2 Document tool

The check list allows to cover all the steps of the analysis. However a tool to ease the application of the method for the operators of the field has been considered necessary. Therefore starting from the check list, a document tool has been developed. Hereinafter, there are some examples of the document tool which can be given to the end-user modified according to the different subjects of the research.

9.2.1 Example 1: Forest yards

Preliminary analysis

- Locate a suitable place for timber harvesting according to forest management policies and the wood availability;
- Mark the areas to harvest;
- Define the number of tree to be harvested;
- Analyze the surrounding environment;
- Determine the most appropriate technologies according to the characteristics of the work environment
- Delimit the forest yards areas.

Design of the work activity and/or the plant

- Identify the best technological solutions to ensure the performance of the activity according to the parameters to be met and the financial resources;
- Organize the work both in terms of location in the work place and as the sequence of the different activities.

Definiton of the hazard sources

- Define the main phases of the work activity (i.e. felling, processing, concentration, extraction, activities at the landing);
- Define for each phase sub phases and elementary processes;
- Identify for each elementary process the used machine, the involved materials (distinguished in raw and complementary materials, products and waste), work environment (macro and micro) and work organization (general and operative conditions).

Working phases	Sub phases	Elementary processes	Machinery	Materials				Work environment		Work organization	
				Raw materials	Complementary materials	Waste	Product	Macro	Micro	General	Operative conditions
Felling											
Processing											
Concentration											
Extraction											
Activity at the landing											

OS&H analysis

- Consult the existing safety documentation for each identified hazard source;
- Consult the reference legislation;
- Identify for each hazard source, the hazard factors associated with them;
- Identify for each hazard factor, the possible deviations and damage associated with them;
- Identify the technical interventions to be implemented to minimize the risk;
- Identify the operative procedures to be implemented to minimize the risk;
- Identify the CPE to provide the workers;
- Identify the PPE to provide the workers;
- Assess the residual risk for the workers and determine its acceptability.

	Elementary processess	Hazard factors	Possible associated deviations and damages	Technical interventions	Procedures	CPE	PPE
Machinery							

	Elementary processess	Hazard factors	Possible associated deviations and damages	Technical interventions	Procedures	CPE	PPE
Materials							

	Elementary processess	Hazard factors	Possible associated deviations and damages	Technical interventions	Procedures	CPE	PPE
Work environment							

	Elementary processess	**Hazard factors**	**Possible associated deviations and damages**	**Technical interventions**	**Procedures**	**CPE**	**PPE**
Work organization							

Redesign the activity

- In case of an unacceptable risk for the workers, redesign the activity or system.

Assessment of the environmental impact

- According to the identified drivers (sources of hazard factors), determine the pressures that may be induced on the surrounding environment;

Elementary processes	**Machinery**	**Materials**				**Work environment**		**Work organization**	
		Raw materials	**Complementary materials**	**Waste**	**Products**	**Macro**	**Mcro**	**General**	**Operative conditions**
Elementary process 1									
Elementary process 2									

- Define the state of the environment through the identification and characterization of suitable environmental indicators (example of set of indicators suitable for the assessment of a natural environment);

Hydrosphere		Biosphere		Lithosphere	Atmosphere	Anthroposphere			
Surface waters	Ground waters	Flora	Fauna			People	Landscape	Culture	Economy
Hydrological and hydrogeological features		Relative wealth of habitat		Prone to flood danger areas	Significant meteorological data	Resident population	Public green		Existing businesses
Hydrographic network		Biodiversity index		Erodibility	Climatic conditions	Population density	Change in overall landscape quality		
Delimitation and description of the basin		Presence of protected natural areas		Geomorphological features	Stationary stations monitoring air quality	Existing road infrastructure	Presence of SCI or SPA		
Surface water circulation		Biotope presence		Altitude	Hydrological balance	Urbanized area			
Surface water and rainwater circulation		Real vegetables /potential vegetables	Presence of dangerous species	Slope	PM concentration	Cultivated area			
Chemical - composition		Natural vegetation	Main species	Length of the slope	NO_X concentration	Traffic flows			
Gradient surface flow		Dominant height		Soil use	Noise level	Nature of the settlement			
Flood risk		Relative distance of vegetation from near natural population		Soil surface coverage		Administrative framework on the ability to maintain and on the health of forests ecosystems			
Physical - composition		Defoliation class distribution		Regime of soil moisture		Density of forest roads			
		Structural diversification		Permeability		Characteristics of forest flows			
		Cut extensions							
		Forest surface							

- Define the impacts on the surrounding environment by identifying and, when possible, quantifying the alterations that the identified pressures can cause on the surrounding environment;

Elementary processess	Hydrosphere		Biosphere		Lithosphere	Atmosphere	Antroposphere			
	Surface waters	Ground waters	Flora	Fauna			People	Landscape	Culture	Economy
Elementary process 1										
Elementary process 2										

- Define the responses to be implemented to reduce the impacts through action which can act on the drivers, by changing the pressure, or on the pressures themselves, mitigating them;
- Assess again the impact on the surrounding environment.

<u>Redesign the activity</u>

9.2.3 Example 2: Fuel wood terminals

Preliminary analysis

- Locate the work activities and the processes that have to be done at the fuel wood terminal;
- Identify the size of the fuel wood terminal;
- Locate the suitable place for the fuel wood terminal (proximity to forests and/or the energy conversion systems);
- Identify the most suitable location of the different activities within the fuel wood terminal.

Design of the work activity and/or the plant

- Identify the best technological solutions to ensure the performance of the activity and/or the execution of the process according to the parameters to be met and the financial resources;
- Organize the work both in terms of location in the work place and as the sequence of the different activities.

Definition of the hazard sources

- Define the main phases of the plant process and/or of the work activity;
- Define for each phase sub phases and elementary processes;
- Identify for each elementary process the used machine, the involved materials (distinguished in raw and complementary materials, products and waste), work environment (macro and micro) and work organization (general and operative conditions).

Working phases	Machinery	Materials				Work environment		Work organization	
		Raw materials	Complementary materials	Waste	Product	Macro	Micro	General	Operative conditions
Discharge of the timber and/or wood chips									
Quality assessment									
Timber for energy purposes identification									
Sending of the better quality timber at the sawmill									
Timber storage in a suitable location for drying									
Storage of wood chips for a short period if necessary									
Periodic checks of the drying process									
Timber movement in the vicinity of the chipper									
Wood chipping									
Loading of wood chips on transportation									

OS&H analysis

- Consult the existing safety documentation for each identified hazard source;
- Consult the reference legislation;
- Identify for each hazard source, the hazard factors associated with them;
- Identify for each hazard factor, the possible deviations and damage associated with them;
- Identify the technical interventions to be implemented to minimize the risk;
- Identify the operative procedures to be implemented to minimize the risk;
- Identify the CPE to provide the workers;
- Identify the PPE to provide the workers;
- Assess the residual risk for the workers and determine its acceptability.

	Elementary processess	Hazard factors	Possible associated deviations and damages	Technical interventions	Procedures	CPE	PPE
Machinery							

	Elementary processess	**Hazard factors**	**Possible associated deviations and damages**	**Technical interventions**	**Procedures**	**CPE**	**PPE**
Materials							

	Elementary processess	**Hazard factors**	**Possible associated deviations and damages**	**Technical interventions**	**Procedures**	**CPE**	**PPE**
Work environment							

	Elementary processess	**Hazard factors**	**Possible associated deviations and damages**	**Technical interventions**	**Procedures**	**CPE**	**PPE**
Work organization							

Redesign the activity or system

- In case of an unacceptable risk for the workers, redesign the activity or system.

Assessment of the environmental impact

- According to the identified drivers (sources of hazard factors), determine the pressures that may be induced on the surrounding environment;

Elementary processes	**Machinery**	**Materials**				**Work environment**		**Work organization**	
		Raw materials	**Complementary materials**	**Waste**	**Products**	**Macro**	**Mcro**	**General**	**Operative conditions**
Elementary process 1									
Elementary process 2									

- Define the state of the environment through the identification and characterization of suitable environmental indicators (example of a set of indicators suitable for the assessment of a anthropic environment);

Hydrosphere		Biosphere		Lithosphere	Atmosphere	Anthroposphere			
Surface waters	Ground waters	Flora	Fauna			People	Landscape	Culture	Economy
Hydrological and hydrogeological features		Presence of protected natural areas		Prone to flood danger areas	Meteorological data	Resident population	Public green		Existing business
Hydrographic network		Biotope presence		Erodibility	Stations monitoring air quality	Population density	Change in landscape quality		
Delimitation and description of the basin		Forest surface		Slope	PM_{10} exceedances daily limits	Existing road infrastructure	Presence of SCI or SPA		
Surface water circulation				Altitude	PM_{10} annual average	Urbanized area			
Flood risk				Soil use		Nature of the settlement			
				Soil surface coverage		Acoustic class in line with the Acoustics Classification Plan			
				Geomorphological features		Supply distance			
				Waste (final destination)		Nearby sensitive receptors			

- Define the impacts on the surrounding environment by identifying and, when possible, quantifying the alterations that the identified pressures can cause on the surrounding environment;

Elementary processess	Hydrosphere		Biosphere		Lithosphere	Atmosphere	Antroposphere			
	Surface waters	Ground waters	Flora	Fauna			People	Landscape	Culture	Economy
Elementary process 1										
Elementary process 2										

- Define the responses to be implemented to reduce the impacts through action which can act on the drivers, by changing the pressure, or on the pressures themselves, mitigating them;
- Assess again the impact on the surrounding environment.

Redesign the activity or system

9.2.3 Example 3: Energy conversion systems

Preliminary analysis

- Locate a suitable place for the installation of the system (proximity to forests and/or fuel wood terminal, presence of suitable road infrastructures);
- Define the thermal needs;
- Identify the location of the system;
- Identify the most suitable plant type (energy conversion process, type of used wood fuel);
- Identify the suitable boiler size;
- Define the size wood chips storage tank.

Design of the work activity and/or the plant

- Identify the best technological solution to ensure the performance of the execution of the process according to the parameters to be met and the financial resources;
- Organize the work both in terms of location in the work place and as the sequence of the different activities.

Definition of the hazard sources

- Define the main phases of the plant process;
- Define for each phase sub phases and elementary processes;
- Identify for each elementary process the used machine, the involved materials (distinguished in raw and complementary materials, products and waste), work environment (macro and micro) and work organization (general and operative conditions).

Process and working phases	Machinery	Materials				Work environment		Work organization	
		Raw materials	Complementary materials	Waste	Product	Macro	Micro	General	Operative conditions
Loading of the storage tank									
Fuel supply system									
Heat generator									
Smoke and/or air purification line									
Combustion waste collection system									
Water heating									
Building heating									
Fuel loading									
Fuel storage									
Maintenance									

OS&H analysis

- Consult the existing safety documentation for each identified hazard source;
- Consult the reference legislation;
- Identify for each hazard source, the hazard factors associated with them;
- Identify for each hazard factor, the possible deviations and damage associated with them;
- Identify the technical interventions to be implemented to minimize the risk;
- Identify the operative procedures to be implemented to minimize the risk;
- Identify the CPE to provide the workers;
- Identify the PPE to provide the workers;
- Assess the residual risk for the workers and determine its acceptability.

	Elementary processess	Hazard factors	Possible associated deviations and damages	Technical interventions	Procedures	CPE	PPE
Machinery							

	Elementary processess	Hazard factors	Possible associated deviations and damages	Technical interventions	Procedures	CPE	PPE
Materials							

	Elementary processess	**Hazard factors**	**Possible associated deviations and damages**	**Technical interventions**	**Procedures**	**CPE**	**PPE**
Work environment							

	Elementary processess	**Hazard factors**	**Possible associated deviations and damages**	**Technical interventions**	**Procedures**	**CPE**	**PPE**
Work organization							

Redesign the system

- In case of an unacceptable risk for the workers, redesign the activity or system.

Assessment of the environmental impact

- According to the identified drivers (source of hazard factors), determine the pressures that may be induced on the surrounding environment;

Elementary processes	**Machinery**	**Materials**				**Work environment**		**Work organization**	
		Raw materials	**Complementary materials**	**Waste**	**Products**	**Macro**	**Mcro**	**General**	**Operative conditions**
Elementary process 1									
Elementary process 2									

- Define the state of the environment through the identification and characterization of suitable environmental indicators(example of a set of indicators suitable for the assessment of a anthropic environment);

Hydrosphere		Biosphere		Lithosphere	Atmosphere	Anthroposphere			
Surface waters	**Ground waters**	**Flora**	**Fauna**			**People**	**Landscape**	**Culture**	**Economy**
Hydrological and hydrogeological features		Presence of protected natural areas		Prone to flood danger areas	Meteorological data	Resident population	Public green		Existing business
Hydrographic network		Biotope presence		Erodibility	Stations monitoring air quality	Population density	Change in landscape quality		
Delimitation and description of the basin		Forest surface		Slope	PM_{10} exceedances daily limits	Existing road infrastructure	Presence of SCI or SPA		
Surface water circulation				Altitude	PM_{10} annual average	Urbanized area			
Flood risk				Soil use		Nature of the settlement			
				Soil surface coverage		Acoustic class in line with the Acoustics Classification Plan			
				Geomorphological features		Supply distance			
				Waste (final destination)		Nearby sensitive receptors			

- Define the impacts on the surrounding environment by identifying and, when possible, quantifying the alterations that the identified pressures can cause on the surrounding environment;

Elementary processess	Hydrosphere		Biosphere		Lithosphere	Atmosphere	Antroposphere			
	Surface waters	**Ground waters**	**Flora**	**Fauna**			**People**	**Landscape**	**Culture**	**Economy**
Elementary process 1										
Elementary process 2										

- Define the responses to be implemented to reduce the impacts through action which can act on the drivers, by changing the pressure, or on the pressures themselves, mitigating them;
- Assess again the impact on the surrounding environment.

Redesign the system

Chapter 10

Concluding remarks

10.1 Drafting process of the proposed method

The development of a suitable, exhaustive and expeditious, method for the analysis of small wood biomass systems and their supply chain required different implementations to achieve an end result that would guarantee the fulfillment of all the set objectives.

For this purpose, the starting point has been a theoretical method, developed to meet the identified objectives, but that did not consider all the implications of applying it to real cases (Chapter 3). Therefore, the method has been applied to standard activities different according to the typology (forest yards, fuel wood terminal or heating systems), size, work activities, spatial characteristics (natural or anthropogenic work environment) and duration in time (temporary or stationary) (Chapters 4 and 5). The results obtained from the application of the method to real cases have allowed to implement and consolidate the method. The criticalities of the method have been identified and it has been modified so to be adaptable to different situations. To verify the validity of the method, the process of design and construction of a prototype plant was followed in order to determine the actual improvements that the method could bring in the design phase. The method is suitable also for an object of analysis that was not standard but that presented univocal characteristics, being a prototype plant (Chapter 6).

The next stage of the research saw the need to validate the proposed method to determine whether it was consistent with the results obtained by the application of standard methods (Chapter 7). Three different standard methodologies have been identified (FMEA, JSA and campaigns of emissions measurement) so that even the validation process take into account the different aspects considered in the analysis. The obtained results prove to be consistent with what come to light in the previous phase of analysis.

However, they confirmed what had already emerged during the application of the method namely how the evaluation of environmental sustainability of the proposed solutions should be implemented in order to allow an assessment of the cumulative impacts on the local air quality and local forest resources (Chapter 8).

Figure 10.1 shows the different phase of analysis which have allowed the development of the final version of the method.

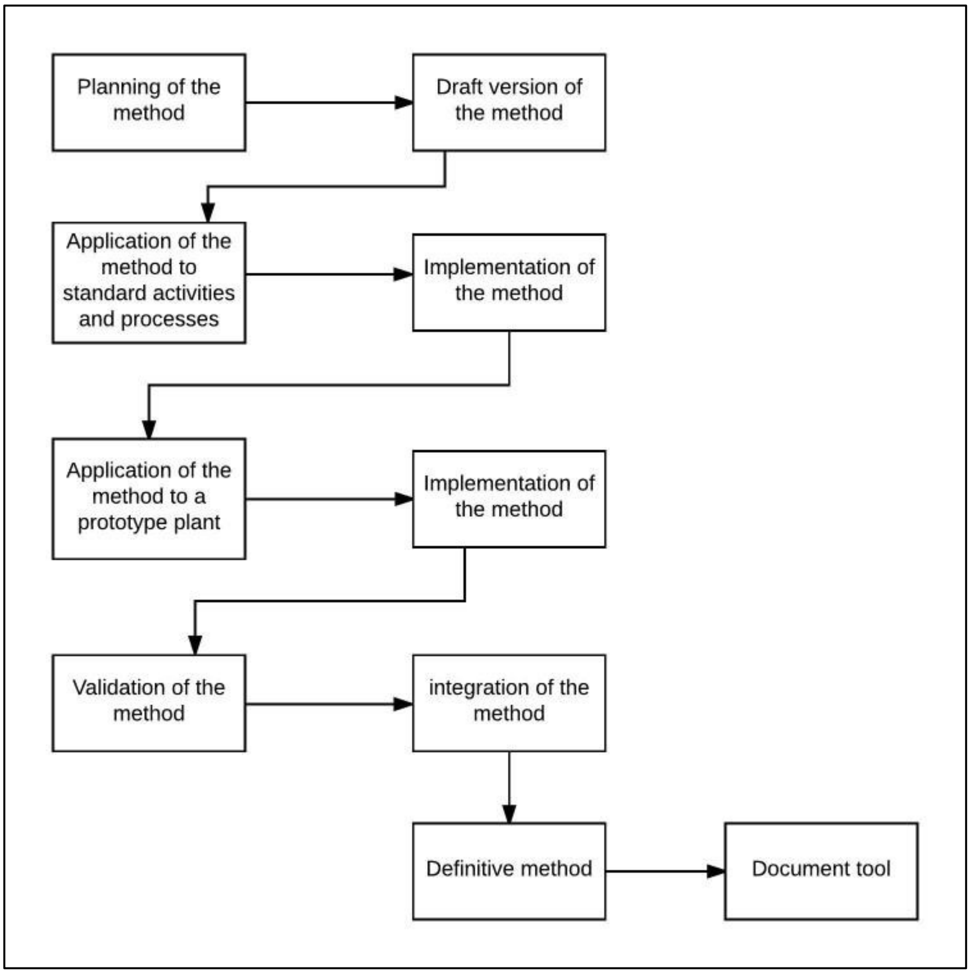

Figure 10.1 – Implementation of the method of analysis

Therefore there is the need to integrate the method with further analysis when it is facing territorial assessments in order to obtain a comprehensive evaluation.

10.2 Review of the environmental sustainability and the land management

The results obtained by the application of the method make explicit how, as regard the environmental impact of the considered systems, is necessary the assessment of the cumulative impacts. This is particularly necessary with regard to emissions of pollutants into the atmosphere and the use of available resources. Therefore a territorial management of the energy solution proposal is essential so that its application is compatible with the environment.

Regarding the assessment of the impact of emissions on air quality, the use of models for the dispersion of pollutants has been proposed and applied. They could be implemented only through the intervention of local authorities. The modeling proposed in Chapter 8 is compatible with the identified objectives and the results confirm the need of a comprehensiveness in the evaluation.

With regard to the environmental sustainability of the analyzed solutions, a stand-alone assessment on the amount of necessary timber and the impact that such use might have on the forest resources of an area should be made. To assess this aspect the emission scenario described in Chapter 8 was examined.

As already described, the hypotheses carried out plan to install 76 boilers with variable power to ensure the thermal requirements of the municipality of Avigliana. In particular there are 56 boilers of 500 kW, 6 boilers of 100 kW, 12 boilers of 1000 kW and 3 boilers of 1500 kW.

To calculate the necessary amount of chips, the calorific value of dry wood chips was assumed equal to 4kW/kg. Therefore in determining the quantity of timber the weight loss in the timber drying process must be considered. The operation of the boilers has been assumed with fixed programming and reduced power operation in the summer months.

Based on the described assumptions to ensure the functioning of the boilers about 42000 t of wet wood chips in winter and 12000 t in the summer months are needed annually. In total, 54000 tons of wet wood chips are therefore necessary. Assuming a density equal to 1 t/m^3, 54000 m^3 of timber shall be provided annually.

Assuming to only use the lower-quality timber and an annual forest growth of 6.5 m^3/ha, 84 km^2 of forest should be intended for wood biomass production annually. Given an overall wooded area for the municipality of Avigliana equal to 792 ha[200], this solution is not feasible. Therefore the wood will to be harvested also from near municipalities. Evidently, this scenario is not feasible and sustainable especially according to the initial hypothesis of short supply chain.

As mentioned earlier the described design scenario is most sustainable if realized side by side with an energy improvement of buildings and the use of solar panels to produce domestic hot water.

In this second case 56 boilers with a power of 250 kW, 6 boilers with a power of 60 kW, 12 boilers of 600 kW and 3 boilers of 800 kW are provided. To ensure their functioning 23000 tons of wet wood chips in the winter months are needed, while in the summer months the boiler shutdown is assumed. For this scenario 36 km^2 of forest should therefore be intended for wood biomass destination. Also for this solution the timber present in the municipality of Avigliana would not be sufficient to satisfy the need of the whole territory.

It is evident that in this context the use of CHP systems that with regard to the considered size of the systems do not yet have a compatible efficiency is not sustainable. Their functioning cannot be guaranteed in a sustainable way in the considered territories.

The results show how this solution is therefore hardly applicable on a large scale, at least with the current performance of existing systems and in the geographic scenarios taken into account. The timber needed to supply a network of wood biomass boilers with the existing performance is not available in the considered regions in this analysis. A solution that could make more feasible this alternative is to boost the use of industrial wood processing by-products for energy purposes, in particular through the pelletizing. In this way some of the currently provided wood chips boilers could be converted to pellets boiler, presenting even higher yields. In such a way an alternative with higher energy efficiency classes but currently very impacting because of transport distances will become more sustainable. In fact now to buy pellets coming from Eastern Europe, where production costs are much lower, is more convenient from an economic point of view. Therefore the use of pellets deriving from the process of wood by-products can be a more sustainable solutions.

The future development of this research project will provide the application of the method also to plants for the pelletizing and the related supply chain, from the wood processing to the energetic use. Such alternative should be analyzed also from an economic point of view in order to determine if the costs of the processing could be competitive. A case study suitable for the application of the methodology has already be identified. The need of a more accurate analysis of this solution has not permitted the application of the methodology in suitable times for the insertion in this thesis.

The implementation of proper management policies by local authorities and a local control is essential. This does not have as its goal the introduction of additional permissions and legislations, but the support of the introduction of the wood biomass through the formation of a culture on the subject.

10.3 Review of the Occupational Safety and Health

The analysis of the activities and processes showed that despite the small size of the plants and the consequent limited economic resources is possible a proper management regarding the OS&H of forest wood energy chain. It is however clear that such an analysis should be carried out by implementing the principles of the Prevention Through Design namely the work activities and processes must be analyzed already in the design phase to ensure that it is possible to put in place the necessary implementations.

The analysis carried out has confirmed what had already emerged during the literature review, or as a high level of mechanization during the activities, especially those carried out in the woods, result in a reduction of the contact factor with the main hazard factors that may occur during this type of activities. However one cannot overlook how regarding environmental sustainability this solution is disadvantageous in terms of impact on the territory. Therefore often the identification of compromises is often to ensure at the same time the safety and health of the workers and the compatibility with the surrounding environment.

The activities carried out in the forest wood energy chain often require the presence of one or maximum two workers devoted to the same activity, greatly simplifying the risk assessment and the identification of the most appropriate operating procedures. However often different activities are carried out in the same span of time and in the same workplace determining the risk of interference between the various operations. Therefore before the beginning of the activities, a careful planning of them is necessary to prevent hazards caused by the overlap of different activities.

Regarding the energy conversion processes analyzed, if the impact on the territory of the individual systems can be considered minimal (in this case the cumulative impacts are considered separately), the same cannot be said with regard to the Occupational Health and Safety. The method provided useful information so that the facilities were designed in order to comply with all safety criteria and at the same time the project parameters. The presence of wood dust, the main hazard factor in these systems, determine how they have to be designed and managed in order to avoid the formation of trigger phenomenon.

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Chapter 11

Conclusions

The subject of the research described in this dissertation is the analysis of the environmental sustainability and Occupational Safety and Health in the forest energy chain for small generation systems.

The aim of the analysis was twofold: to analyze and assess the forest-wood-energy chain from the point of view of Occupational Safety and Health and environmental sustainability and to identify a methodology for expeditious analysis, which could therefore also be applied by the companies and would fit the various phases of the research subject. As the method of analysis is also directed to two different entities, the operators of forest wood energy sector and the local authorities, it has to ensure an expeditious and comprehensive study of the aspects considered and at the same time sustainability of this solution with a view of the territorial spreading.

The literature on the use of the forest wood biomass underlined how, for the considered size, CHP systems have to be excluded as they cannot guarantee the goal of environmental sustainability because of the used resources and the pollutant emissions. The study focused therefore on the heat production through combustion process.

The analysis done in the development and application of the method allows to affirm how if the supply chain and the heating systems are properly designed and managed, satisfactory environmental objectives can be achieved and the health and safety of the workers can be guaranteed. The management has to start from a correct use of the forest resources in order to not deplete the territory until reaching the energy conversion systems with the greatest possible reduction of waste and emissions of pollutants. Furthermore, the activities have to be suitably planned in order to avoid the interference between the different operations and the correct execution of the different tasks.

The main issue met during the development of the methodology is its need to be suitable at the application to often very different workplaces and very different technological alternatives. For this reason, once the methodology has been drafted, it was applied to case studies belonging to different moments of the supply chain to validate it by taking into account the highest number of possible typical characteristics. The method has therefore be implemented according to the obtained results and the difficulties experienced.

The applied and validated methodology fits adequately to the different specificities of the case studies and makes possible to identify the best operational procedures and technical interventions case by case. It also allows to evaluate the criticality for each phase of work and the procedures to be put in place to minimize them. It assesses both the Occupational Safety and Health and the environmental sustainability.

The validation of the method, through application of standardized methodologies, shows how the developed methodology can be consistent with the aims of the research and suitable according to the considered points of view.

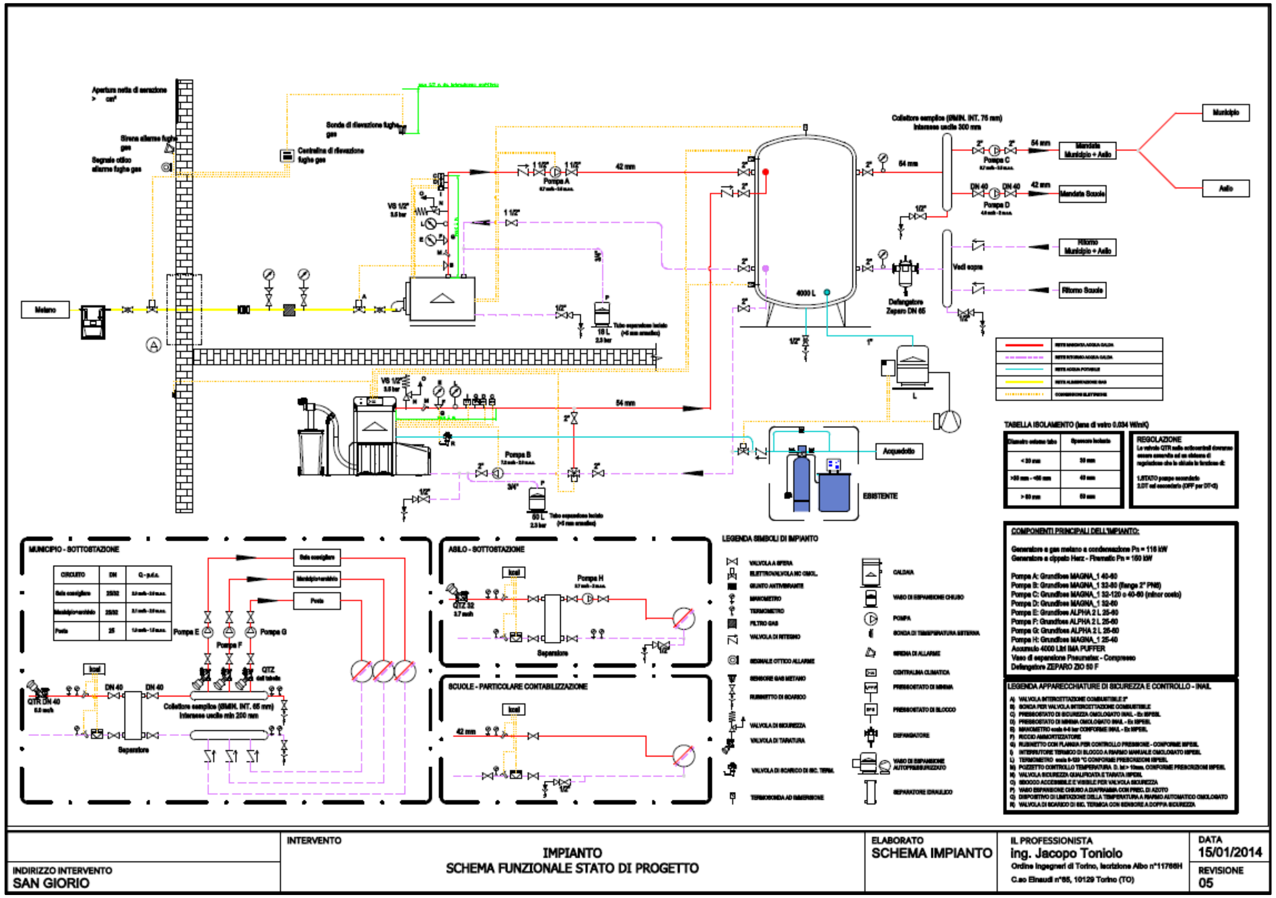
The methodology has enabled the development of a real assessment tool that can be given to the forestry operators and be usable independently. In this way, the method developed can guarantee the objectives set at the beginning of the analysis of easy application and a thorough analysis.

While in the application to single case, the methodology is resulted compatible with the aims of the research, the need to implement dedicated methodologies to assess the cumulative impacts of different plants, as model for the dispersions of pollutants, has emerged from the validation. Therefore in the hypothesis of adoption of this design hypothesis by the local authorities, the methodology should include also the integration constituted by the pollutant dispersion model and evaluation of resources availability such as that applied and proposed in this study

Concluding, the method has the objective to allow the assessment of the whole forest wood energy chain. This objective has been abided cause a complete evaluation of it is possible both for individual spread in the area systems, either for a design scenario that considers an entire territory. In this phase of the analysis only a qualitative assessment of the different design scenario is possible because the first aim of the work has been to guarantee an expeditious and usable assessment. Therefore in a first analysis this can be better guaranteed by a qualitative approach. However, in a pursuance of the research, a quantitative evaluation of the environmental impacts and further detail of the Prevention through Design about the OS&H are the points of possible implementation of the method.

Appendices

Appendix 1 – Example of scheme of the analyzed system for heat generation



Appendix 2 – Application of the FMEA to the plant

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Water heating	Boiler	Insufficient chips/ pellet supply	Jammed screw conveyor	4	Flame shutdown	8	Boiler control unit	4	128	Programmed maintenance/ quality assessment of the fuel	3	8	4	96
			Failure in the boiler control unit	4	Flame shutdown	8	System reliability analysis.	4	128	Programmed maintenance	3	8	4	96
			Empty chips/ pellet storage	5	Flame shutdown	8	Boiler control unit	3	120	Properly planned supplies	2	8	4	64
		Excessive chips/ pellet supply	Failure in the boiler control unit	4	Flame shutdown	8	System reliability analysis	4	128	Programmed maintenance	3	8	4	96
		No power supply	Blackout	3	Flame shutdown	8	Boiler control unit	3	72	Assess the feasibility of uninterruptible backup	3	8	3	72
			Failure in the electrical connection	4	Flame shutdown	8	System reliability analysis.	4	128	Programmed maintenance	3	8	1	24
			Not properly designed electrical system	6	Flame shutdown	8	Control of the design	3	144	System reliability analysis	3	8	3	72
		Not sufficient water heating	Excessive water pumping	4	Low efficiency of the system	5	Boiler control unit	3	60	System reliability analysis	3	5	3	45
					Failure to achieve the design benchmark	8	Boiler control unit	3	96	System reliability analysis	3	8	3	72
			Failure in the boiler control unit	4	Low efficiency of the system	5	System reliability analysis.	4	80	Programmed maintenance	3	5	4	60
					Failure to achieve the design benchmark	8	System reliability analysis.	4	128	Programmed maintenance	3	8	4	96
		Excessive water heating	Failure in the boiler control unit	4	Grow of the temperature	9	System reliability analysis. Thermometer	3	108	Programmed maintenance	3	9	3	81

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Water heating	Boiler	Excessive water heating	Excessive chips/ pellet supply at the screw conveyor	4	Grow of the temperature	9	Boiler control unit	3	108	Proper loading of the storage tank	3	9	3	81
			Wrong setting of the boiler control unit	6	Grow of the temperature	9	Periodic control of the settings. System reliability analysis.	3	162	Correct information, formation and training of the workers	3	9	3	81
	Boiler control unit	Wrong setting of the boiler recirculating pumps	Wrong setting of the boiler control unit	6	Excessive water heating	8	Boiler control unit	3	144	Correct information, formation and training of the workers	4	8	3	96
					Not sufficient water heating	8	Boiler control unit	3	144			8		96
			Failure in the boiler control unit	4	Excessive water heating	8	System reliability analysis.	4	128	Programmed maintenance	3	8	4	96
					Not sufficient water heating	8			128	Programmed maintenance	3	8		96
	Water tank to flood the screw conveyor	Water leak	Corrosion	4	Water on the floor of the container	4	Periodic control of the tank	6	96	Check the suitability of the material	3	4	6	72
	Chips/ pellet storage tank	Empty storage tank	Not fuel supply	5	Flame shutdown	8	Boiler control unit	3	120	Properly planned supplies	2	8	3	48
			Excessive fuel consumption	5	Flame shutdown	8	Boiler control unit	3	120	Periodic control of the fuel consumption	3	8	3	72
		Not correct tank sizing	Not correct design	6	Not fuel supply	8	Control of the design	3	144	Slightly overestimate the required size of tank	2	8	3	48
		Chips/pellet with not suitable characteristics	Not correct drying process	6	Uncontrolled flame	8	Boiler control unit	3	144	Quality assessment of the fuel	4	8	3	96
			Failure in quality assessment	4	Uncontrolled flame	8	Boiler control unit	3	96	No info available	4	8	3	96
	Chips screw conveyor	Jam	Excessive chips/ pellet supply at the screw conveyor	4	Flame shutdown	8	Boiler control unit	3	96	Proper loading of the storage tank	3	8	3	72

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Water heating	Chips screw conveyor	Jam	Excessive water heating	5	Flame shutdown	8	Boiler control unit	3	120	Quality assessment of the fuel	4	8	3	96
			Presence of extraneous matter in the pellet	5	Flame shutdown	8	Boiler control unit	3	120	Quality assessment of the fuel	4	8	3	96
		Fire	Backfire	3	Water in the screw conveyor	8	Flame anti-roll	3	72	No info available	3	8	3	72
	Boiler temperature sensor	Failure to send the signal	Cable wear	5	Boiler shutdown	8	Boiler control unit	3	120	Programmed maintenance	3	8	3	72
			Sensor failure	4	Boiler shutdown	8	Boiler control unit	3	96	Periodic sensor calibration	3	8	3	72
		Wrong temperature	Sensor failure	4	Opening when not necessary of the thermostatic valve	8	System reliability analysis.	4	128	Periodic sensor calibration	3	8	4	96
					Boiler shutdown	8			128	Periodic sensor calibration	3	8		96
	Fumes chimney	Not maintaining of the delivery pressure	Not airtight door	4	Uncontrolled flame	8	Leak test	3	96	Periodic leak test	3	8	3	72
			Joint corrosion	5	Uncontrolled flame	8	Leak test	3	120		3	8	3	72
		Not correct fumes flow	Presence of soot deposits	6	Uncontrolled fumes	7	Boiler control unit	3	126	Periodic chimney cleaning	4	7	3	84
			Joint corrosion	5	Uncontrolled fumes	7	Periodic visual inspection	6	210	Check the suitability of the material	2	7	6	84
	Lambda sensor	Failure to send the signal	Cable wear	5	Uncontrolled flame	8	Boiler control unit	3	120	Programmed maintenance	3	8	3	72
			Sensor failure	4	Uncontrolled flame	8	Boiler control unit	3	96	Periodic sensor calibration	3	8	3	72
	Ball valves	Insufficient or lack of water circulation	Valve partly/fully closed due to personnel misuse	6	Failure in the water heating	8	Boiler control unit	3	144	Correct information, formation and training of the workers	4	8	3	96

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Water heating	Ball valves	Insufficient or lack of water circulation	Wear	4	Excessive grow of temperature	9	Boiler control unit	3	108	System reliability analysis.	3	9	3	81
		Water leak	Wear	4	Failure in the water heating	8	Boiler control unit	3	96	System reliability analysis	3	8	3	72
			Corrosion	3	Failure in the water heating	8	Periodic visual inspection	6	144	Check the suitability of the material	2	8	6	96
	Three-way temperature valve	Not correct temperature of water at the boiler	Wear	4	Condensation in the boiler	8	Thermometer	3	96	System reliability analysis	2	8	3	48
			Corrosion	3	Condensation in the boiler	8	Thermometer	3	72	Check the suitability of the material	2	8	3	48
			Failure in the temperature sensor	4	Condensation in the boiler	8	Thermometer	3	96	Periodic sensor calibration	3	8	3	72
	Pressure gauge	Wrong pressure	Pressure gauge failure	5	Total or partial valve closure not necessary	5	System reliability analysis.	4	100	Periodic sensor calibration	3	5	4	60
					Failure in the water heating	8			160			8		96
	Thermometer	Wrong temperature	Failure in the temperature sensor	4	Failure in the water heating	8	System reliability analysis	4	128	Periodic sensor calibration	3	8	4	96
	Thermic discharge valve	Not opening when necessary	Failure in the temperature sensor	4	Excessive grow of the temperature	9	Thermometer	3	108	Periodic sensor calibration	3	9	3	81
			Jammed valve	6	Excessive grow of the temperature	9	Boiler control unit	3	162	Programmed maintenance	3	9	3	81
		Opening when not necessary	Failure in the temperature sensor	4	Flooding of the screw conveyor	8	Boiler control unit	3	96	Periodic sensor calibration	3	8	3	72
			Wear	4	Flooding of the screw conveyor	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
		Water leak	Wear	4	Water in the screw conveyor	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
					Flame shutdown	8	Boiler control unit	3	96	Programmed maintenance	3	8		72

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Water heating	Thermic discharge valve	Water leak	Corrosion	3	Water in the screw conveyor	8	Boiler control unit	3	72	Check the suitability of the material	2	8	3	48
					Flame shutdown	8	Boiler control unit	3	72	Check the suitability of the material	2	8		48
	Water tank temperature sensors	Failure to send the signal	Cable wear	5	Failure in the water heating	8	Boiler control unit	3	120	Programmed maintenance	3	8	3	72
					Excessive grow of the temperature	9	Boiler control unit	3	135	Programmed maintenance	3	9	3	81
			Sensor failure	4	Failure in the water heating	8	Boiler control unit	3	96	Periodic sensor calibration	3	8	3	72
					Excessive grow of the temperature	9	Boiler control unit	3	108	Periodic sensor calibration	3	9		81
	Boiler recirculating pump	Pump breakage	Wear	4	Excessive grow of the temperature	9	Boiler control unit	3	108	Programmed maintenance	3	9	3	81
			Not correct design of the system	6	Excessive grow of the temperature	9	Control of the design	3	162	Programmed maintenance	3	9	3	81
					Failure in the water heating	8			144	Programmed maintenance	3	8		72
		Not correct water circulation	Failure in the boiler control unit	4	Excessive grow of the temperature	9	Pressure gauge	3	108	Programmed maintenance	3	9	3	81
					Failure in the water heating	8			96	Programmed maintenance	3	8	3	72
	Power supply	No power supply	Blackout	3	Failure in the water heating	8	Boiler control unit	3	72	Assess the feasibility of uninterruptible backup	3	8	3	72
			Failure in the electrical system	4	Failure in the water heating	8	System reliability analysis.	4	128	Programmed maintenance	3	8	4	96
		Overload	Failure in the electrical system	4	Failure in the water heating	8	System reliability analysis.	4	128	Programmed maintenance	3	8	4	96
			Failure in the control unit	4	Failure in the water heating	8	System reliability analysis	4	128	Programmed maintenance	3	8	4	96

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Water heating	Power supply	Failure in the fuel supply	Wrong supply programming	6	Failure in the water heating	8	Boiler control unit	3	144	Properly planned supplies	2	8	3	48
					Flame shutdown	8	Boiler control unit	3	144	Properly planned supplies	2	8		48
		Fuel with incorrect characteristics	Failure in quality assessment	4	Not correct water heating	6	Boiler control unit	3	72	System reliability analysis	3	6	3	54
Hot water transport	Boiler	Insufficient chips/ pellet supply	Jammed screw conveyor	3	No maintenance of the system parameters	6	Boiler control unit	3	54	Programmed maintenance/ quality assessment of the fuel	3	6	3	54
			Failure in the boiler control unit	4	No maintenance of the system parameters	6	System reliability analysis.	4	96	Programmed maintenance	3	6	4	72
			Empty chips/ pellet storage	3	No maintenance of the system parameters	6	Boiler control unit	3	54	Properly planned supplies	2	6	3	36
		Excessive chips/ pellet supply	Failure in the boiler control unit	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72
		No power supply	Blackout	3	No maintenance of the system parameters	6	Boiler control unit	3	54	Assess the feasibility of uninterruptible backup	3	6	3	54
			Failure in the electrical connection	4	No maintenance of the system parameters	6	System reliability analysis.	4	96	Programmed maintenance	3	6	4	72
			Not properly designed electrical system	6	No maintenance of the system parameters	6	Control of the design	3	108	No info available	6	6	3	108
		Not sufficient water heating	Excessive water pumping	6	No maintenance of the system parameters	6	Boiler control unit	3	108	System reliability analysis	3	6	3	54
			Failure in the boiler control unit	4	No maintenance of the system parameters	6	System reliability analysis.	4	96	Programmed maintenance	3	6	4	72

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Hot water transport	Boiler	Excessive water heating	Failure in the control unit	4	No maintenance of the system parameters	6	System reliability analysis. Thermometer	3	72	Programmed maintenance	3	5	3	45
			Excessive chips/ pellet supply at the screw conveyor	4	No maintenance of the system parameters	6	Boiler control unit	3	72	Proper loading of the storage tank	3	6	3	54
			Wrong setting of the control unit	6	No maintenance of the system parameters	6	Periodic control of the settings. System reliability analysis.	3	108	Correct information, formation and training of the workers	3	6	3	54
			Not sufficient water pumping	5	No maintenance of the system parameters	6	Boiler control unit	3	90	System reliability analysis	3	6	3	54
	Boiler control unit	Wrong setting of the boiler recirculating pump	Worker wrong setting	6	No maintenance of the system parameters	6	Boiler control unit	3	108	Correct information, formation and training of the workers	4	6	3	72
			Failure in the boiler control unit	4	No maintenance of the system parameters	6	System reliability analysis.	4	96	System reliability analysis	3	6	4	72
	PLC	Wrong setting of the recirculating pumps	Pipes temperature sensor failure	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Periodic sensor calibration	3	6	4	72
			Water tank temperature sensor failure	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Periodic sensor calibration	3	6	4	72
			Worker wrong setting	6	No maintenance of the system parameters	6	PLC	3	108	Correct information, formation and training of the workers	4	6	3	72
			PLC failure	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Hot water transport	Water tank	Water leak	Corrosion	3	No maintenance of the system parameters	6	Boiler control unit	3	54	Check the suitability of the material	2	6	3	36
	Optical-acoustical alarm	Lack of alarm when necessary	Failure temperature sensor	4	Too high water temperature	9	Boiler control unit	3	108	Periodic sensor calibration	3	9	3	81
			Failure optical-acoustical system	4	Too high water temperature	9	Boiler control unit	3	108	Programmed maintenance	3	9	3	81
		Not necessary alarm start	Failure temperature sensor	4	No maintenance of the system parameters	6	Boiler control unit	3	72	Periodic sensor calibration	3	6	3	54
			Failure optical-acoustical system	4	No maintenance of the system parameters	6	Boiler control unit	3	72	Programmed maintenance	3	6	3	54
Hot water transport	Water feeding manifold	Not sufficient water supply at the dryer	Valve partly/fully closed due to personnel misuse	6	No maintenance of the system parameters	6	PLC	3	108	Correct information, formation and training of the workers	4	6	3	72
			Water leak	5	No maintenance of the system parameters	6	System reliability analysis	4	120	Periodic visual inspection	3	6	4	72
			Air presence in the piping	6	No maintenance of the system parameters	6	Vents	2	72	No info available	2	6	2	24
	Ball valves	Insufficient or lack of water circulation	Valve partly/fully closed due to personnel misuse	6	No maintenance of the system parameters	6	PLC	3	108	Correct information, formation and training of the workers	4	6	3	72
			Wear	4	No maintenance of the system parameters	6	PLC	3	72	System reliability analysis	3	6	3	54
		Water leak	Wear	4	No maintenance of the system parameters	6	Periodic visual inspection	6	144	System reliability analysis	3	6	6	108

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Hot water transport	Ball valves	Water leak	Corrosion	3	No maintenance of the system parameters	6	Periodic visual inspection	6	108	Check the suitability of the material	2	6	6	72
	Seals	Water leak	Material defects	7	No maintenance of the system parameters	6	Periodic visual inspection	6	252	Check the suitability of the material	4	6	6	144
			Wear	4	No maintenance of the system parameters	6	Periodic visual inspection	6	144	System reliability analysis	3	6	6	108
Hot water transport	Three-way solenoid valve	Not correct opening of the valve	Wear	4	No maintenance of the system parameters	6	Install pressure sensor	3	72	System reliability analysis	3	6	4	72
			Corrosion	3	No maintenance of the system parameters	6	Install pressure sensor	3	54	Check the suitability of the material	2	6	4	48
	Three-way temperature valve	Not correct temperature of water at the boiler	Wear	4	No maintenance of the system parameters	6	Thermometer	3	72	System reliability analysis	3	6	3	54
			Corrosion	3	No maintenance of the system parameters	6	Thermometer	3	54	Check the suitability of the material	2	6	3	36
			Failure in the temperature sensor	4	No maintenance of the system parameters	6	Thermometer	3	72	Periodic sensor calibration	3	6	3	54
	Pressure gauge	Wrong pressure	Pressure gauge failure	5	Total or partial valve closure not necessary	5	System reliability analysis	4	100	Periodic sensor calibration	3	5	4	60
	Thermometer	Wrong temperature	Temperature sensor failure	4	Valve closure not necessary	5	System reliability analysis	4	80	Periodic sensor calibration	3	5	4	60
	Maximum manostat	Not correct opening of the valve	Wear	4	No maintenance of the system parameters	6	Install pressure sensor	4	96	System reliability analysis	3	6	4	72

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Hot water transport	Maximum manostat	Not correct opening of the valve	Corrosion	3	No maintenance of the system parameters	6	Install pressure sensor	4	72	Check the suitability of the material	2	6	4	48
	Minimum manostat	Not correct opening of the valve	Wear	4	No maintenance of the system parameters	6	Install pressure sensor	4	96	System reliability analysis	3	6	4	72
			Corrosion	3	No maintenance of the system parameters	6	Install pressure sensor	4	72	Check the suitability of the material	2	6	4	48
	Safety diaphragm valve	Opening of the valve	Too high pressure	4	Flow of water at high pressure and temperature	8	Optical-acoustic alarm	3	96	The area surrounding the valve have to be marked and delimited	4	6	3	72
					System emptying	7			84	No info available	4	7	3	84
	Y-filter	Clogged filter	Incorrect planning of filter replacement	3	Not correct water flow circulation	6	Periodic control	6	108	No info available	3	6	6	108
			High amount of impurities in the water	3	Not correct water flow circulation	6	Periodic control	6	108	No info available	3	6	6	108
		Water leak	Wear	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Periodic visual inspection	2	6	6	72
			Corrosion	3	No maintenance of the system parameters	6	System reliability analysis	4	72	Check the suitability of the material	2	6	6	72
	Water tank temperature sensors	Failure to send the signal	Cable wear	5	No maintenance of the system parameters	6	Boiler control unit	3	90	Programmed maintenance	3	6	3	54
			Sensor failure	4	No maintenance of the system parameters	6	Boiler control unit	3	72	Periodic sensor calibration	3	6	3	54
		Wrong temperature	Sensor failure	4	No maintenance of the system parameters	6	Boiler control unit	3	72	Periodic sensor calibration	3	6	3	54

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Hot water transport	Pipes temperature sensor	Failure to send the signal	Cable wear	5	No maintenance of the system parameters	6	PLC	3	90	Programmed maintenance	3	6	3	54
			Sensor failure	4	No maintenance of the system parameters	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
	Pipe brackets on the container walls	Detachment of the pipelines from the container walls	Material defects	7	Pipe deformations	7	Periodic visual inspection	6	294	Check the suitability of the material	4	7	6	168
					Water leak	6			252	Check the suitability of the material		6		144
			Not correctly designed fastenings	6	Pipe deformations	7	Control of the design	3	126	Periodic visual inspection	6	7	2	84
					Water leak	6			108	Periodic visual inspection		6	2	72
	Power supply	No power supply	Blackout	3	System shutdown	8	PLC	3	72	Assess the feasibility of uninterruptible backup	3	8	3	72
			Failure in the electrical system	4	System shutdown	8	System reliability analysis	4	128	Programmed maintenance	3	8	4	96
		Overload	Failure in the electrical system	4	System shutdown	8	System reliability analysis	4	128	Programmed maintenance	3	8	4	96
			Failure in the boiler control unit	4	System shutdown	8	System reliability analysis	4	128	Programmed maintenance	3	8	4	96
			Failure in the PLC	4	System shutdown	8	System reliability analysis	4	128	Programmed maintenance	3	8	4	96
Hot water storage	Boiler	Insufficient chips/ pellet supply	Jammed screw conveyor	3	No maintenance of the system parameters	6	System reliability analysis	3	54	Programmed maintenance/ quality assessment of the fuel	3	6	4	72
			Failure in the boiler control unit	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Hot water storage	Boiler	Insufficient chips/ pellet supply	Empty chips/ pellet storage	3	No maintenance of the system parameters	6	Boiler control unit	3	54	Properly planned supplies	2	6	3	36
		Excessive chips/ pellet supply	Failure in the boiler control unit	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72
		No power supply	Blackout	3	No maintenance of the system parameters	6	Boiler control unit	3	54	Assess the feasibility of uninterruptible backup	3	6	3	54
			Failure in the electrical connection	4	No maintenance of the system parameters	6	System reliability analysis.	4	96	Programmed maintenance	3	6	4	72
			Not properly designed electrical system	6	No maintenance of the system parameters	6	Control of the design	3	108	No info available	6	6	3	108
		Not sufficient water heating	Excessive water pumping	6	Water tank emptying	5	Boiler control unit	3	90	No info available	6	5	4	120
			Failure in the boiler control unit	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72
		Excessive water heating	Failure in the boiler control unit	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72
			Excessive chips/ pellet supply at the screw conveyor	4	No maintenance of the system parameters	5	Boiler control unit	3	60	Proper loading of the storage tank	3	5	3	45
			Wrong setting of the control unit	6	No maintenance of the system parameters	5	Periodic control of the settings	3	90	Correct information, formation and training of the workers	4	5	3	60
			Not sufficient water pumping	6	No maintenance of the system parameters	5	Boiler control unit	3	90	System relibility analysis	3	5	3	45

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Hot water storage	Boiler control unit	Wrong setting of the boiler recirculating pumps	Worker wrong setting	6	Excessive water heating	8	Periodic control of the settings. System reliability analysis.	3	144	Correct information, formation and training of the workers	4	8	3	96
					Not sufficient water heating	8	Periodic control of the settings. System reliability analysis.	3	144			8		96
			Failure in the boiler control unit	4	Excessive water heating	8	System reliability analysis	4	128	Programmed maintenance	3	8	4	96
					Not sufficient water heating	8	System reliability analysis	4	128			8		96
	System control unit	Wrong setting of the boiler recirculating pumps	Pipes temperature sensor failure	4	No maintenance of the system parameters	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
Hot water storage	PLC	Wrong setting of the recirculating pumps	Water tank temperature sensor failure	4	No maintenance of the system parameters	6	Boiler control unit	3	72	Periodic sensor calibration	3	6	3	54
			Worker wrong setting	6	No maintenance of the system parameters	6	PLC	3	108	Correct information, formation and training of the workers	4	6	3	72
			PLC failure	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72
	Water tank	Water leak	Corrosion	3	No maintenance of the system parameters	6	PLC	3	54	Check the suitability of the material	2	6	3	36
	Three-way solenoid valve	Not correct opening of the valve	Wear	4	No maintenance of the system parameters	6	Install pressure sensor	3	72	System reliability analysis	3	6	4	72
			Corrosion	3	No maintenance of the system parameters	6	Install pressure sensor	3	54	Check the suitability of the material	2	6	4	48

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Hot water storage	Three-way temperature valve	Not correct temperature of water at the boiler	Wear	4	No maintenance of the system parameters	6	Thermometer	3	72	System reliability analysis	3	6	3	54
			Corrosion	3	No maintenance of the system parameters	6	Thermometer	3	54	Check the suitability of the material	2	6	3	36
			Failure in the temperature sensor	4	No maintenance of the system parameters	6	Thermometer	3	72	Periodic sensor calibration	3	6	3	54
	Discharge collector funnel	Water leak	Valve failure	5	Water tank emptying	5	Periodic visual inspection	6	150	System reliability analysis	3	5	6	90
			Corrosion	3	Water tank emptying	5	Periodic visual inspection	6	90	Check the suitability of the material	2	5	6	60
		Incorrect water discharge	Valve failure	5	Water tank emptying	5	Periodic visual inspection	6	150	System reliability analysis	3	5	6	90
			Valve partly/fully closed due to personnel misuse	6	Water tank emptying	5	Periodic visual inspection	6	180	Correct information, formation and training of the workers	4	5	6	120
	Water tank temperature sensors	Failure to send the signal	Cable wear	5	No maintenance of the system parameters	6	Boiler control unit	3	90	Programmed maintenance	3	6	3	54
		Failure to send the signal	Sensor failure	4	No maintenance of the system parameters	6	Boiler control unit	3	72	Periodic sensor calibration	3	6	3	54
		Wrong temperature	Sensor failure	4	No maintenance of the system parameters	6	Boiler control unit	3	72	Periodic sensor calibration	3	6	3	54
	Pipes temperature sensor	Failure to send the signal	Cable wear	5	No maintenance of the system parameters	6	PLC	3	90	Programmed maintenance	3	6	3	54
			Sensor failure	4	No maintenance of the system parameters	6	PLC	3	72	Periodic sensor calibration	3	6	3	54

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Hot water storage	Boiler recirculating pump	Pump breakage	Wear	4	No maintenance of the system parameters	6	Boiler control unit	3	72	Programmed maintenance	3	6	3	54
			Not correct design of the system	6	No maintenance of the system parameters	6	Control of the design	3	108	Programmed maintenance	3	6	3	54
		Not correct water circulation	Failure in the boiler control unit	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72
	Recirculating pump	No water supply	Failure in the waterworks	4	No maintenance of the system parameters	6	PLC	3	72	No info available	4	6	3	72
			Lack of water	3	No maintenance of the system parameters	6	PLC	3	54	No info available	3	6	3	54
		Pump breakage	Wear	4	No maintenance of the system parameters	6	PLC	3	72	Programmed maintenance	3	6	3	54
			Not correct design of the system	6	No maintenance of the system parameters	6	Control of the design	3	108	Programmed maintenance	3	6	3	54
		Not correct water circulation	Failure in the PLC	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72
	Floating air outlet	Non opening when necessary	Wear	4	Air in the water tank	8	System reliability analysis	4	128	No info available	4	8	4	128
			Corrosion	3			System reliability analysis	4	96	Check the suitability of the material	2	8	4	64
		Opening when not necessary	Wear	4	Too low pressure in the water tank	5	System reliability analysis	4	80	Periodic visual inspection	3	5	4	60
			Corrosion	3			System reliability analysis	4	60	Check the suitability of the material	1	5	4	20
			Not correct design of the system	6			Control of the design	3	90	No info available	6	5	3	90

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Hot water storage	Power supply	No power supply	Blackout	3	System shutdown	8	Boiler control unit	3	72	No info available	3	8	3	72
			Failure in the electrical system	4	System shutdown	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
		Overload	Failure in the electrical system	4	System shutdown	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
			Failure in the control unit	4	System shutdown	8	System reliability analysis	4	128	Programmed maintenance	3	8	4	96
Cold water transport	Boiler	Insufficient pellet supply	Jammed screw conveyor	3	No maintenance of the system parameters	6	Boiler control unit	3	54	Programmed maintenance/ quality assessment of the fuel	3	6	3	54
			Failure in the boiler control unit	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72
			Empty chips/ pellet storage	3	No maintenance of the system parameters	6	Boiler control unit	3	54	Properly planned supplies	2	6	3	36
		Excessive chips/ pellet supply	Failure in the boiler control unit	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72
		No power supply	Blackout	3	No maintenance of the system parameters	6	Boiler control unit	3	54	Assess the feasibility of uniterruptible backup	3	6	3	54
			Failure in the electrical connection	4	No maintenance of the system parameters	6	Boiler control unit	3	72	Programmed maintenance	3	6	3	54
			Not properly designed electrical system	6	No maintenance of the system parameters	6	Control of the design	3	108	System reliability analysis	3	6	3	54
		Not sufficient water heating	Excessive water pumping	6	No maintenance of the system parameters	6	Boiler control unit	3	108	Install thermometer	6	6	2	72
			Failure in the control unit	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Cold water transport	Boiler	Excessive water heating	Excessive chips/ pellet supply at the screw conveyor	4	No maintenance of the system parameters	6	Boiler control unit	3	72	Proper loading of the storage tank	3	6	3	54
			Wrong setting of the control unit	6	No maintenance of the system parameters	6	Boiler control unit	3	108	Correct information, formation and training of the workers	4	6	3	72
			Not sufficient water pumping	5	No maintenance of the system parameters	6	Install pressure sensor	4	120	System reliability analysis	3	6	4	72
	Boiler control unit	Wrong setting of the boiler recirculating pump	Worker wrong setting	6	No maintenance of the system parameters	6	Boiler control unit	3	108	Correct information, formation and training of the workers	4	6	3	72
			Failure in the boiler control unit	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72
	System control unit	Wrong setting of the recirculating pumps	Pipes temperature sensor failure	4	No maintenance of the system parameters	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
			Water tank temperature sensor failure	4	No maintenance of the system parameters	6	Boiler control unit	3	72	Periodic sensor calibration	3	6	3	54
			Worker wrong setting	6	No maintenance of the system parameters	6	PLC	3	108	Correct information, formation and training of the workers	4	6	3	72
			PLC failure	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Programmed maintenance	3	6	3	54
	Water return manifold	Not return of the water	Valve partly/fully closed due to personnel misuse.	6	No maintenance of the system parameters	6	PLC	3	108	Correct information, formation and training of the workers	4	6	3	72

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Cold water transport	Water return manifold	Not return of the water	Water leak	5	No maintenance of the system parameters	6	Periodic visual inspection	6	180	Check the suitability of the material	2	6	6	72
			Air presence in the piping	6	No maintenance of the system parameters	6	Install vents	2	72	No info available	6	6	2	72
	Water tank	Wrong temperature	Sensor failure	4	No maintenance of the system parameters	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
	Ball valves	Insufficient or lack of water circulation	Valve partly/fully closed due to personnel misuse	6	No maintenance of the system parameters	6	Boiler control unit	3	108	Correct information, formation and training of the workers	4	6	3	72
			Wear	4	No maintenance of the system parameters	6	Boiler control unit	3	72	System reliability analysis	3	6	3	54
		Water leak	Wear	4	No maintenance of the system parameters	6	Periodic visual inspection	6	144	System reliability analysis	3	6	6	108
			Corrosion	3	No maintenance of the system parameters	6	Periodic visual inspection	6	108	Check the suitability of the material	2	6	6	72
	Seals	Water leak	Material defects	7	No maintenance of the system parameters	6	Boiler control unit	3	126	Check the suitability of the material	4	6	3	72
			Wear	4	No maintenance of the system parameters	6	Periodic visual inspection	6	144	System reliability analysis	3	6	6	108
	Three-way temperature valve	Not correct opening of the valve	Wear	4	No maintenance of the system parameters	6	Install pressure sensor	4	96	System reliability analysis	3	6	4	72
			Corrosion	3	No maintenance of the system parameters	6	Install pressure sensor	4	72	Check the suitability of the material	2	6	4	48

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Cold water transport	Three-way temperature valve	Not correct temperature of water at the boiler	Wear	4	No maintenance of the system parameters	6	Thermometer	3	72	System reliability analysis	3	6	3	54
			Corrosion	3	No maintenance of the system parameters	6	Thermometer	3	54	Check the suitability of the material	2	6	3	36
			Failure in the temperature sensor	4	No maintenance of the system parameters	6	Thermometer	3	72	Periodic sensor calibration	3	6	3	54
	Pressure gauge	Wrong pressure	Pressure gauge failure	5	Total or partial valve closure not necessary	5	System reliability analysis	4	100	Periodic sensor calibration	3	5	4	60
	Thermometer	Wrong temperature	Temperature sensor failure	4	Valve closure not necessary	5	System reliability analysis	4	80	Periodic sensor calibration	3	5	4	60
	Maximum manostat	Not correct opening of the valve	Wear	4	No maintenance of the system parameters	6	Install pressure sensor	4	96	System reliability analysis	3	6	4	72
			Corrosion	3	No maintenance of the system parameters	6	Install pressure sensor	4	72	Check the suitability of the material	2	6	4	48
	Minimum manostat	Not correct opening of the valve	Wear	4	No maintenance of the system parameters	6	Install pressure sensor	4	96	System reliability analysis	3	6	4	72
			Corrosion	3	No maintenance of the system parameters	6	Install pressure sensor	4	72	Check the suitability of the material	2	6	4	48
	Non-return valve	Opening when not necessary	Valve failure	6	Incorrect water circulation	5	Boiler control unit	3	90	System reliability analysis	3	5	3	45
		Not opening when necessary	Valve failure	6	Incorrect water circulation	5	Boiler control unit	3	90	System reliability analysis	3	5	3	45

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Cold water transport	Expansion tank	Not maintaining of the system pressure	Diaphragm failure	6	High water volume	9	Boiler control unit	3	162	System reliability analysis	3	9	3	81
					Low water volume	5	Boiler control unit	3	90			5		45
	Safety diaphragm valve	Opening of the valve	Too high pressure	4	Flow of water at high pressure and temperature	8	Boiler control unit	3	96	The area surrounding the valve have to be marked and delimited	4	6	3	72
					System emptying	7	Boiler control unit	3	84	System reliability analysis	3	7	3	63
	Y-filter	Clogged filter	Incorrect planning of filter replacement	3	Not correct water flow circulation	5	Boiler control unit	3	45	System reliability analysis	2	5	3	30
			High amount of impurities in the water	3	Not correct water flow circulation	5	Boiler control unit	3	45			5	3	30
		Water leak	Wear	4	Not correct water flow circulation	5	Boiler control unit	3	60	System reliability analysis	2	5	3	30
			Corrosion	3	Not correct water flow circulation	5	Boiler control unit	3	45	Check the suitability of the material	2	5	3	30
	Water tank temperature sensors	Failure to send the signal	Cable wear	5	No maintenance of the system parameters	6	Boiler control unit	3	90	Programmed maintenance	3	6	3	54
			Sensor failure	4	No maintenance of the system parameters	6	Boiler control unit	3	72	Periodic sensor calibration	3	6	3	54
		Wrong temperature	Sensor failure	4	No maintenance of the system parameters	6	Boiler control unit	3	72	Periodic sensor calibration	3	6	3	54
	Pipes temperature sensor	Failure to send the signal	Cable wear	5	No maintenance of the system parameters	6	PLC	3	90	Programmed maintenance	3	6	3	54
			Sensor failure	4	No maintenance of the system parameters	6	PLC	3	72	Periodic sensor calibration	3	6	3	54

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Cold water transport	Boiler recirculating pump	Pump breakage	Wear	4	No maintenance of the system parameters	6	Boiler control unit	3	72	Programmed maintenance	3	6	3	54
			Not correct design of the system	6	No maintenance of the system parameters	6	Boiler control unit	3	108	Programmed maintenance	3	6	3	54
		Not correct water circulation	Failure in the boiler control unit	4	No maintenance of the system parameters	6	Boiler control unit	3	72	Programmed maintenance	3	6	4	72
	Recirculating pump	No water supply	Failure in the waterworks	4	No maintenance of the system parameters	6	PLC	3	72	No info available	4	6	3	72
			Lack of water	3	No maintenance of the system parameters	6	PLC	3	54	No info available	3	6	3	54
		Pump breakage	Wear	4	No maintenance of the system parameters	6	PLC	3	72	Programmed maintenance	3	6	3	54
			Not correct design of the system	6	No maintenance of the system parameters	6	Control of the design	3	108	Programmed maintenance	3	6	3	54
		Not correct water circulation	Failure in the control unit	4	No maintenance of the system parameters	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72
	Pipe brackets on the container walls	Detachment of the pipelines from the container walls	Material defects	7	Pipe deformations	5	Boiler control unit	3	105	Check the suitability of the material	4	5	6	120
			Material defects		Water leak	6			126	Check the suitability of the material	4	6	3	72
			Not correctly designed fastenings	5	Pipe deformations	5	Control of the design	3	75	Periodic visual inspection	5	5	2	50
					Water leak	6			90	Periodic visual inspection	5	6	2	60
	Power supply	No power supply	Blackout	3	System shutdown	8	Boiler control unit	3	72	Assess the feasibility of uninterruptible backup	3	8	3	72

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Cold water transport	Power supply	No power supply	Failure in the electrical system	4	System shutdown	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
		Overload	Failure in the electrical system	4	System shutdown	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
			Failure in the control unit		System shutdown	8	System reliability analysis	4	128	Programmed maintenance	3	8	4	96
Fumes discharge	Boiler	Excessive chips/ pellet supply	Failure in the control unit	4	Uncontrolled fumes	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72
		Not sufficient water heating	Excessive water pumping	3	Uncontrolled fumes	6	Install pressure sensor	4	72	No info available	3	6	4	72
			Failure in the control unit	4	Uncontrolled fumes	6	System reliability analysis	4	96	System reliability analysis	2	6	4	48
		Excessive water heating	Failure in the control unit	4	Uncontrolled fumes	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72
			Excessive chips/ pellet supply at the screw conveyor	4	Uncontrolled fumes	6	Proper loading of the storage tank	5	120	Proper loading of the storage tank	3	6	5	90
			Wrong setting of the control unit	6	Uncontrolled fumes	6	Boiler control unit	3	108	Correct information, formation and training of the workers	4	6	3	72
	Boiler control unit	Wrong setting of the recirculating pumps	Pipes temperature sensor failure	4	Uncontrolled fumes	6	Boiler control unit	3	72	System reliability analysis	3	6	3	54
			Water tank temperature sensors failure	4	Uncontrolled fumes	6	Boiler control unit	3	72	System reliability analysis	3	6	3	54
			Worker wrong setting	6	Uncontrolled fumes	6	Periodic control of the settings	3	108	Correct information, formation and training of the workers	4	6	3	72
			Control unit failure	4	Uncontrolled fumes	6	Boiler control unit	3	72	System reliability analysis	2	7	4	56

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Fumes discharge	Fumes chimney	Not maintaining of the delivery pressure	Not airtight door	4	Leak of fumes	8	Leak test	3	96	Periodic leak test	3	8	3	72
			Joint corrosion	5	Leak of fumes	8			120		3	8		72
		Not correct fumes flow	Presence of soot deposits	6	Pollutant emissions increasing	6	Boiler control unit	3	108	Periodic chimney cleaning	4	6	4	96
			Joint corrosion	3	Pollutant emissions increasing	6	Periodic visual inspection	6	108	Check the suitability of the material	2	6	6	72
	Lambda sensor	Failure to send the signal	Cable wear	5	Uncontrolled fumes	6	Boiler control unit	3	90	Programmed maintenance	3	6	3	54
			Sensor failure	4	Uncontrolled fumes	6	Boiler control unit	3	72	Periodic sensor calibration	3	6	3	54
	Pipe brackets on the container walls	Detachment of the pipelines from the container walls	Material defects	7	Pipe deformations	5	Periodic visual inspection	6	210	Check the suitability of the material	5	5	6	150
					Water leak	6			252	Check the suitability of the material	5	6	6	180
			Not correctly designed fastenings	5	Pipe deformations	5	Control of the design	3	75	Periodic visual inspection	5	5	2	50
					Water leak	6			90	Periodic visual inspection	5	6	2	60
	Power supply	No power supply	Blackout	3	System shutdown	8	Boiler control unit	3	72	Assess the feasibility of uninterruptible backup	3	8	3	72
			Failure in the electrical system	4	System shutdown	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
		Overload	Failure in the electrical system	4	System shutdown	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
			Failure in the control unit	4	System shutdown	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
	Fuel supply	Failure in the fuel supply	Wrong supply programming	6	System shutdown	8	Boiler control unit	3	144	Properly planned supplies	2	8	3	48

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Fumes discharge	Fuel supply	Fuel with incorrect characteristics	Failure in quality assessment	4	Uncontrolled fumes	7	Boiler control unit	3	84	No info available	4	7	3	84
	Atmospheric emissions	Limit overcoming	Uncontrolled flame	6	Air quality alteration	7	Boiler control unit	3	126	No info available	6	7	3	126
			Fuel with incorrect characteristics	4	Air quality alteration	7	Boiler control unit	3	84	No info available	4	7	3	84
Water supply	Ball valves	Insufficient or lack of water circulation	Valve partly/fully closed due to personnel misuse	6	No maintenance of the system parameters	6	Boiler control unit	3	108	Correct information, formation and training of the workers	4	6	3	72
			Wear	4	No maintenance of the system parameters	6	Boiler control unit	3	72	System reliability analysis	2	6	6	72
		Water leak	Wear	4	No maintenance of the system parameters	6	Periodic visual inspection	6	144	System reliability analysis	2	6	6	72
			Corrosion	3	No maintenance of the system parameters	6	Periodic visual inspection	6	108	Check the suitability of the material	2	6	6	72
	Seals	Water leak	Material defects	7	Excessive water consumption	6	Boiler control unit	3	126	Check the suitability of the material	4	6	3	72
			Wear	3	Excessive water consumption	6	Periodic visual inspection	6	108	System reliability analysis	2	6	6	72
	Pressure gauge	Wrong pressure	Pressure gauge failure	5	Total or partial valve closure not necessary	5	Boiler control unit	3	75	Periodic sensor calibration	3	5	3	45
	Non-return valve	Opening when not necessary	Valve failure	6	Incorrect water circulation	5	Boiler control unit	3	90	System reliability analysis	4	5	3	60
		Not opening when necessary	Valve failure	6	Incorrect water circulation	5	Boiler control unit	3	90	System reliability analysis	4	5	3	60

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Water supply	Hydrodynamic proportional dispenser	Not maintaining the correct proportion of salts	Dispenser failure	6	Pipes fouling	4	System reliability analysis	4	96	Programmed maintenance	4	4	4	64
			Clogged dispenser	6	Pipes fouling	4			96	Programmed maintenance	4	4	4	64
	Pipe brackets on the container walls	Detachment of the pipelines from the container walls	Material defects	7	Pipe deformations	7	Periodic visual inspection	6	294	Check the suitability of the material	5	7	6	210
					Water leak	6			252	Check the suitability of the material	5	6	6	180
			Not correctly designed fastenings	6	Pipe deformations	7	Control of the design	3	126	Periodic visual inspection	6	7	2	84
					Water leak	6			108	Periodic visual inspection	6	6	2	72
	Power supply	No power supply	Blackout	3	System shutdown	8	Boiler control unit	3	72	Assess the feasibility of uninterruptible backup	3	8	3	72
			Failure in the electrical system	4	System shutdown	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
		Overload	Failure in the electrical system	4	System shutdown	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
			Failure in the control unit	4	System shutdown	8	System reliability analysis	4	128	Programmed maintenance	3	8	3	72
Ashes discharge	Boiler	Excessive chips/ pellet supply	Failure in the control unit	4	Excessive amount of ashes	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72
	Ashes screw conveyor	Jammed screw conveyor	Excessive amount of ashes	7	Failure in the ashes discharge	7	Boiler control unit	3	147	Programmed maintenance/ quality assessment of the fuel	3	7	3	63
			Presence of extraneous matter in the chips/ pellet	5	Failure in the ashes discharge	7	Boiler control unit	3	105	Quality assessment of the fuel	4	7	3	84
		Failure to empty	Failure in the control unit	4	Failure in the ashes discharge	7	Boiler control unit	3	84	Programmed maintenance	3	7	3	63

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Ashes discharge	Ashes screw conveyor	Failure to empty	Failure in the screw conveyor	4	Failure in the ashes discharge	7	Boiler control unit	3	84	Programmed maintenance	3	7		63
	Power supply	No power supply	Blackout	3	System shutdown	8	Boiler control unit	3	72	Assess the feasibility of uninterruptible backup	3	8	3	72
			Failure in the electrical system	4	System shutdown	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
		Overload	Failure in the electrical system	4	System shutdown	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
			Failure in the control unit	4	System shutdown	8	System reliability analysis	4	128	Programmed maintenance	3	8	4	96
	Ashes disposal	Ashes chemical composition not correct	Fuel with incorrect characteristics	4	Higher cost of ashes disposal	7	Quality assessment of the fuel	5	140	No info available	4	7	5	140
			Not complete combustion				Boiler control unit	3	84	Periodic control of the settings	3	7	3	63
Fuel supply	Boiler	No power supply	Blackout	3	System shutdown	8	Boiler control unit	3	72	Assess the feasibility of uninterruptible backup	3	8	3	72
			Failure in the electrical connection	4	System shutdown	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
			Not properly designed electrical system	6	System shutdown	8	Boiler control unit	3	144	Programmed maintenance	3	8	3	72
		Excessive water heating	Failure in the control unit	4	Excessive fuel consumption	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72
			Excessive chips/ pellet supply at the screw conveyor	4	Excessive fuel consumption	6	Boiler control unit	3	72	Proper loading of the storage tank	3	6	3	54
			Wrong setting of the control unit	6	Excessive fuel consumption	6	Periodic control of the setting. System reliability analysis	4	144	Correct information, formation and training of the workers	4	6	4	96

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Fuel supply	Boiler control unit	Wrong setting of the recirculating pumps	Pipes temperature sensor failure	4	Excessive fuel consumption	6	Boiler control unit	3	72	Periodic sensor calibration	3	6	3	54
			Water tank temperature sensors failure	4	Excessive fuel consumption	6	Boiler control unit	3	72	Periodic sensor calibration	3	6		54
			Worker wrong setting	6	Excessive fuel consumption	6	Boiler control unit	3	108	Correct information, formation and training of the workers	4	6	3	72
			Control unit failure	4	Excessive fuel consumption	6	System reliability analysis	4	96	Programmed maintenance	3	6	4	72
	Chips/ pellet storage tank	Empty storage tank	Not fuel supply	3	System shutdown	8	Boiler control unit	3	72	Properly planned supplies	2	8	3	48
			Excessive fuel consumption	5	System shutdown	8	Boiler control unit	3	120	Periodic control of the fuel consumption	3	8	3	72
		Not correct tank sizing	Not correct design	3	System shutdown	8	Control of the design	3	72	Slightly overestimate the required size of tank	2	8	3	48
		Chips/pellet with not suitable characteristics	Not correct drying process	6	Excessive fuel consumption	6	Boiler control unit	3	108	Quality assessment of the fuel	4	6	3	72
			Failure in quality assessment	4	Excessive fuel consumption	6	Boiler control unit	3	72	No info available	4	6	3	72
	Screw conveyor	Jam	Excessive chips/ pellet supply at the screw conveyor	4	Screw conveyor breaking	7	Boiler control unit	3	84	Proper loading of the storage tank	3	7	5	105
			Not regular chips/ pellet	5	Screw conveyor breaking	7	Boiler control unit	3	105	Quality assessment of the fuel	4	7	3	84
			Presence of extraneous matter in the chips/ pellet	5	Screw conveyor breaking	7	Boiler control unit	3	105	Quality assessment of the fuel	4	7	3	84
		Fire	Backfire	4	Water in the screw conveyor	8	Flame anti-roll	8	256	No info available	4	8	8	256

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Fuel supply	Thermic discharge valve	Not opening when necessary	Failure in the temperature sensor	4	Excessive grow of the temperature	9	Thermometer	3	108	Periodic sensor calibration	3	9	3	81
			Jammed valve	6	Excessive grow of the temperature	9	Boiler control unit	3	162	Programmed maintenance	3	9	3	81
		Opening when not necessary	Failure in the temperature sensor	4	Flooding of the screw conveyor	8	Boiler control unit	3	96	Periodic sensor calibration	3	8	3	72
			Wear	4	Flooding of the screw conveyor	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
		Water leak	Wear	4	Water in the screw conveyor	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
			Corrosion	3	Water in the screw conveyor	8	Boiler control unit	3	72	Check the suitability of the material	2	8	3	48
	Power supply	No power supply	Blackout	3	System shutdown	8	Boiler control unit	3	72	Assess the feasibility of uninterruptible backup	3	8	3	72
			Failure in the electrical system	4	System shutdown	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
		Overload	Failure in the electrical system	4	System shutdown	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72
			Failure in the control unit	4	System shutdown	8	System reliability analysis	4	128	Programmed maintenance	3	8	4	96
Timber drying	Boiler	Insufficient chips/ pellet supply	Jammed screw conveyor	5	Failure in the timber drying	8	Boiler control unit	3	120	Programmed maintenance	3	8	3	72
			Failure in the control unit	4	Failure in the timber drying	8	System reliability analysis	4	128	Programmed maintenance	3	8	4	96
			Empty chips/ pellet storage	3	Failure in the timber drying	8	Boiler control unit	3	72	Properly planned supplies	2	8	2	32
		No power supply	Blackout	3	Failure in the timber drying	8	Boiler control unit	3	72	Assess the feasibility of uninterruptible backup	3	8	3	72
			Failure in the electrical connection	4	Failure in the timber drying	8	Boiler control unit	3	96	Programmed maintenance	3	8	3	72

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Timber drying	Boiler	No power supply	Not properly designed electrical system	6	Failure in the timber drying	8	Boiler control unit	3	144	System reliability analysis	3	8	3	72
		Not sufficient water heating	Excessive water pumping	2	Not correct timber drying	5	Boiler control unit	3	30	System reliability analysis	3	5	4	60
			Failure in the PLC	4	Not correct timber drying	5	System reliability analysis	4	80	Programmed maintenance	3	5	4	60
		Excessive water heating	Failure in the PLC	4	Not correct timber drying	5	System reliability analysis	4	80	System reliability analysis	2	5	4	40
			Excessive chips/ pellet supply at the screw conveyor	3	Not correct timber drying	5	Proper loading of the storage tank	5	75	No info available	3	5	5	75
			Wrong setting of the control unit	6	Not correct timber drying	5	Periodic control of the settings	6	180	Correct information, formation and training of the workers	4	5	6	120
Timber drying	PLC	Wrong setting of the fans	Pipes temperature sensor failure	4	Failure in the timber drying	8	PLC	3	96	Programmed maintenance	3	8	3	72
					Not correct timber drying	5	PLC	3	60	Programmed maintenance	3	5	3	45
			Worker wrong setting	6	Failure in the timber drying	8	PLC	3	144	Correct information, formation and training of the workers	4	8	3	96
					Not correct timber drying	5	PLC	3	90	Correct information, formation and training of the workers		5		60
			Failure in the PLC	4	Failure in the timber drying	8	System reliability analysis	4	128	Programmed maintenance	3	8	4	96
					Not correct timber drying	5			80	Programmed maintenance	3	5		60
			Air hygrometer failure	4	Failure in the timber drying	8	PLC	3	96	Programmed maintenance	3	8	3	72

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Timber drying	PLC	Wrong setting of the fans	Air hygrometer failure		Not correct timber drying	5	PLC	3	60	Programmed maintenance	3	5		45
			Air thermometer failure	4	Not correct timber drying	5	PLC	3	60	Programmed maintenance	3	5	3	45
					Failure in the timber drying	8	PLC	3	96	Programmed maintenance	3	8		72
			Wood hygrometer failure	4	Not correct timber drying	5	Programmed maintenance	4	80	Programmed maintenance	3	5	4	60
					Failure in the timber drying	8			128	Programmed maintenance	3	8		96
		No power supply	Blackout	3	Excessive grow of temperature	9	PLC	3	81	Aperture of air inlets and oulets in case of lack of power	3	8	3	72
	Pipes temperature sensors	Failure to send the signal	Cable wear	5	Not correct timber drying	5	PLC	3	75	Programmed maintenance	3	5	3	45
					Failure in the timber drying	8	PLC	3	120	Programmed maintenance	3	8		72
			Sensor failure	4	Not correct timber drying	5	PLC	3	60	Programmed maintenance	3	5	3	45
					Failure in the timber drying	8	PLC	3	96	Programmed maintenance	3	8		72
	Ball valves	Insufficient or lack of water circulation	Valve partly/fully closed due to personnel misuse.	6	Not correct timber drying	5	PLC	3	90	Correct information, formation and training of the workers	4	5	3	60
			Wear	3	Not correct timber drying	5	PLC	3	45	Programmed maintenance	3	5	3	45
		Water leak	Wear	3	Not correct timber drying	5	PLC	3	45	Programmed maintenance	3	5	3	45
			Corrosion	3	Not correct timber drying	5	PLC	3	45	Programmed maintenance	3	5	3	45
			Too high water pressure	5	Not correct timber drying	5	PLC	3	75	System reliability analysis	3	5	3	45

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Timber drying	Seals	Water leak	Material defects	7	Excessive water consumption	6	PLC	3	126	Check the suitability of the material	5	6	3	90
			Wear	3	Excessive water consumption	6	PLC	3	54	System reliability analysis	3	6	3	54
			High water pressure	5	Excessive water consumption	6	PLC	3	90	No info available	5	6	3	90
	Pressure gauge	Wrong pressure	Pressure gauge failure	5	Not correct control of the pressure	4	PLC	3	60	Periodic sensor calibration	3	4	3	36
	Thermometers	Wrong temperature	Temperature sensor failure	4	Not correct timber drying	5	PLC	3	60	Periodic sensor calibration	3	5	6	90
	Fans	Not correct dryer ventilation	Fans failure	4	Not correct timber drying	5	PLC	3	60	Programmed maintenance	3	5	3	45
					Failure in the timber drying	8	PLC	3	96	Programmed maintenance	3	8		72
	Wood hygrometers	Failure to send the signal	Cable wear	5	Not correct timber drying	5	PLC	3	75	Programmed maintenance	3	5	3	45
					Failure in the timber drying	8	PLC	3	120	Programmed maintenance	3	8		72
			Sensor failure	4	Not correct timber drying	5	PLC	3	60	Periodic sensor calibration	3	5	3	45
					Failure in the timber drying	8	PLC	3	96	Periodic sensor calibration	3	8		72
		Low wood moisture	Excessive drying	5	Too lower humidity	7	PLC	3	105	Closing air inlets	3	7	3	63
	Hot air chimneys	Not correct air circulation	Clogged filters	6	Not correct timber drying	5	Boiler control unit	3	90	Periodic filter substitution	4	5	3	60
					Failure in the timber drying	8			144	No info available	6	8	3	96
		Not correct air circulation	Not correct design	6	Not correct timber drying	5	Control of the design	3	90	No info available	6	5	3	90
					Failure in the timber drying	8			144	No info available		8		144

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Timber drying	Air hygrometers	Failure to send the signal	Cable wear	5	Not correct timber drying	5	PLC	3	75	System reliability analysis. Install wood hygrometer	2	5	3	30
					Failure in the timber drying	8	PLC	3	120			8		48
			Sensor failure	4	Not correct timber drying	5	PLC	3	60	Periodic sensor calibration	3	7	3	63
					Failure in the timber drying	8	PLC	3	96			8		72
		Air humidity lower than 65%	Excessive drying	5	Risk of formation of explosive atmosphere	9	PLC	3	135	System shutdown	5	8	3	120
			Water sprayer failure	5	Risk of formation of explosive atmosphere	9	PLC	3	135	System shutdown. Programmed maintenance	3	8	3	72
		Air humidity lower than 80%	Excessive drying	5	Too low humidity	7	PLC	3	105	Closing air inlets	3	7	3	63
			Water sprayer failure	5	Too low humidity	7	PLC	3	105	Programmed maintenance	3	7	3	63
	Recirculating pump	Pump breakage	Pump breakage	4	System shutdown	8	PLC	3	96	Programmed maintenance	3	8	3	72
		Not correct water circulation	Failure in the PLC	4	Not correct timber drying	5	System reliability analysis	3	60	Programmed maintenance	3	5	3	45
	Power supply	No power supply	Blackout	3	System shutdown	8	PLC	3	72	No info available	3	8	3	72
			Failure in the electrical system	4	System shutdown	8	PLC	3	96	Programmed maintenance	3	8	3	72
		Overload	Failure in the electrical system	4	System shutdown	8	PLC	3	96	Programmed maintenance	3	8	3	72
			Failure in the PLC	4	System shutdown	8	System reliability analysis	4	128	Programmed maintenance	3	8	4	96
Timber drying	Pipe brackets on the container walls	Detachment of the pipelines from the container walls	Material defects	7	Pipe deformations	7	Periodic visual inspection	6	294	Check the suitability of the material	5	7	6	210
					Water leak	6			252			6		180
			Not correctly designed fastenings	6	Pipe deformations	7	Control of the design	3	126	Periodic visual inspection	6	7	2	84
					Water leak	6			108	Periodic visual inspection	6	6	2	72

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Dryer ventilation	PLC	Wrong setting of the fans	Pipes temperature sensor failure	4	Not correct dryer ventilation	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
			Worker wrong setting	6	Not correct dryer ventilation	6	PLC	3	108	Correct information, formation and training of the workers	4	6	3	72
			Failure in the PLC	4	Not correct dryer ventilation	6	PLC	3	72	Programmed maintenance	3	6	3	54
			Air hygrometer failure	4	Not correct dryer ventilation	6	PLC	3	72	Programmed maintenance	3	6	3	54
			Air thermometer failure	4	Not correct dryer ventilation	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
			Wood hygrometer failure	4	Not correct dryer ventilation	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
		Wrong opening of air inlets	Pipes temperature sensor failure	4	Not correct dryer ventilation	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
			Failure in the PLC	4	Not correct dryer ventilation	6	PLC	3	72	Programmed maintenance	3	6	3	54
			Air hygrometer failure	4	Not correct dryer ventilation	6	PLC	3	72	Programmed maintenance	3	6	3	54
			Air thermometer failure	4	Not correct dryer ventilation	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
			Wood hygrometer failure	4	Not correct dryer ventilation	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
		Wrong opening of air outlets	Pipes temperature sensor failure	4	Not correct dryer ventilation	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
	PLC	Wrong opening of air outlets	Failure in the PLC	4	Not correct dryer ventilation	6	PLC	3	72	Programmed maintenance	3	6	3	54
			Air hygrometer failure	4	Not correct dryer ventilation	6	PLC	3	72	Programmed maintenance	3	6	3	54
			Air thermometer failure	4	Not correct dryer ventilation	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
			Wood hygrometer failure	4	Not correct dryer ventilation	6	PLC	3	72	Periodic sensor calibration	3	6	3	54

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Dryer ventilation	Thermometers	Not correct temperature of water in the piping	Cable wear	5	Not correct dryer ventilation	6	PLC	3	90	No info available	3	6	6	108
			Sensor failure	4	Not correct dryer ventilation	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
	Fans	Not correct dryer ventilation	Fans failure	5	Not correct dryer ventilation	6	PLC	3	90	Programmed maintenance	3	6	3	54
			System control unit failure	4	Not correct dryer ventilation	6	PLC	3	72	Programmed maintenance	3	6	3	54
	Air thermometers	Failure to send the signal	Cable wear	5	Not correct dryer ventilation	6	PLC	3	90	No info available	3	6	3	54
			Sensor failure	4	Not correct dryer ventilation	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
		Temperature higher than 90 °C	Excessive water heating	4	Risk of formation of explosive atmosphere	9	PLC	3	108	System shutdown	4	8	3	96
		Temperature higher than 85 °C	Excessive water heating	4	Risk of formation of explosive atmosphere if humidity lower than 70%	8	PLC	3	96	Controll of the settings	3	8	3	72
	Air hygrometers	Failure to send the signal	Cable wear	5	Not correct dryer ventilation	6	PLC	3	90	No info available	3	6	3	54
			Sensor failure	4	Not correct dryer ventilation	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
		Air humidity lower than 65%	Not correct ventilation	5	Risk of formation of explosive atmosphere	9	PLC			System shutdown	5	8	3	120
		Air humidity lower than 65%	Water sprayer failure	5	Risk of formation of explosive atmosphere	9	PLC			System shutdown	5	8	3	120
		Air humidity lower than 70%	Not correct ventilation	5	Risk of formation of explosive atmosphere if temperature higher than 85 °C	9	PLC	3	135	System shutdown	5	8	3	120

Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Dryer ventilation	Air hygrometers	Air humidity lower than 70%	Water sprayer failure	5	Risk of formation of explosive atmosphere if temperature higher than 85 °C	9	PLC	3	135	System shutdown. Programmed maintenance	3	8	3	72
		Air humidity lower than 80%	Not correct ventilation	5	Too lower humidity	7	PLC	3	105	Closing air inlets	3	7	3	63
			Water sprayer failure	5	Too lower humidity	7	PLC	3	105	Programmed maintenance	3	7	3	63
		Not correct choice of sensor	Not correct design	4	Not correct dryer ventilation	6	Control of the design	3	72	System reliability analysis	3	6	3	54
	Air inlets	Excessive air input	Not correct regulation of the inlets	5	Too lower humidity	7	PLC	3	105	Programmed maintenance	3	7	3	63
		Low air input	Not correct regulation of the inlets	5	Too high humidity	7	PLC	3	105	Programmed maintenance	3	7	3	63
	Wood hygrometers	Failure to send the signal	Cable wear	5	Not correct dryer ventilation	6	PLC	3	90	No info available	3	6	3	54
		Failure to send the signal	Sensor failure	4	Not correct dryer ventilation	6	PLC	3	72	Periodic sensor calibration	3	6	3	54
		Low wood moisture	Excessive drying	5	Too lower humidity	7	PLC	3	105	Closing air inlets	3	7	3	63
		Not correct choice of sensor	Not correct design	4	Not correct dryer ventilation	6	Control of the design	3	72	System reliability analysis	3	6	3	54
	Hot air chimneys	Not correct air emission	Clogged filters	6	Not correct dryer ventilation	6	PLC	3	108	Periodic filter substitution	4	6	3	72
			Not correct design	6	Not correct dryer ventilation	6	Control of the design	3	108	No info available	6	6	3	108
	Power supply	No power supply	Blackout	3	System shutdown	8	PLC	3	72	No info available	3	8	3	72
			Failure in the electrical system	4	System shutdown	8	PLC	3	96	Programmed maintenance	3	8	3	72
		Overload	Failure in the electrical system	4	System shutdown	8	PLC	3	96	Programmed maintenance	3	8	3	72

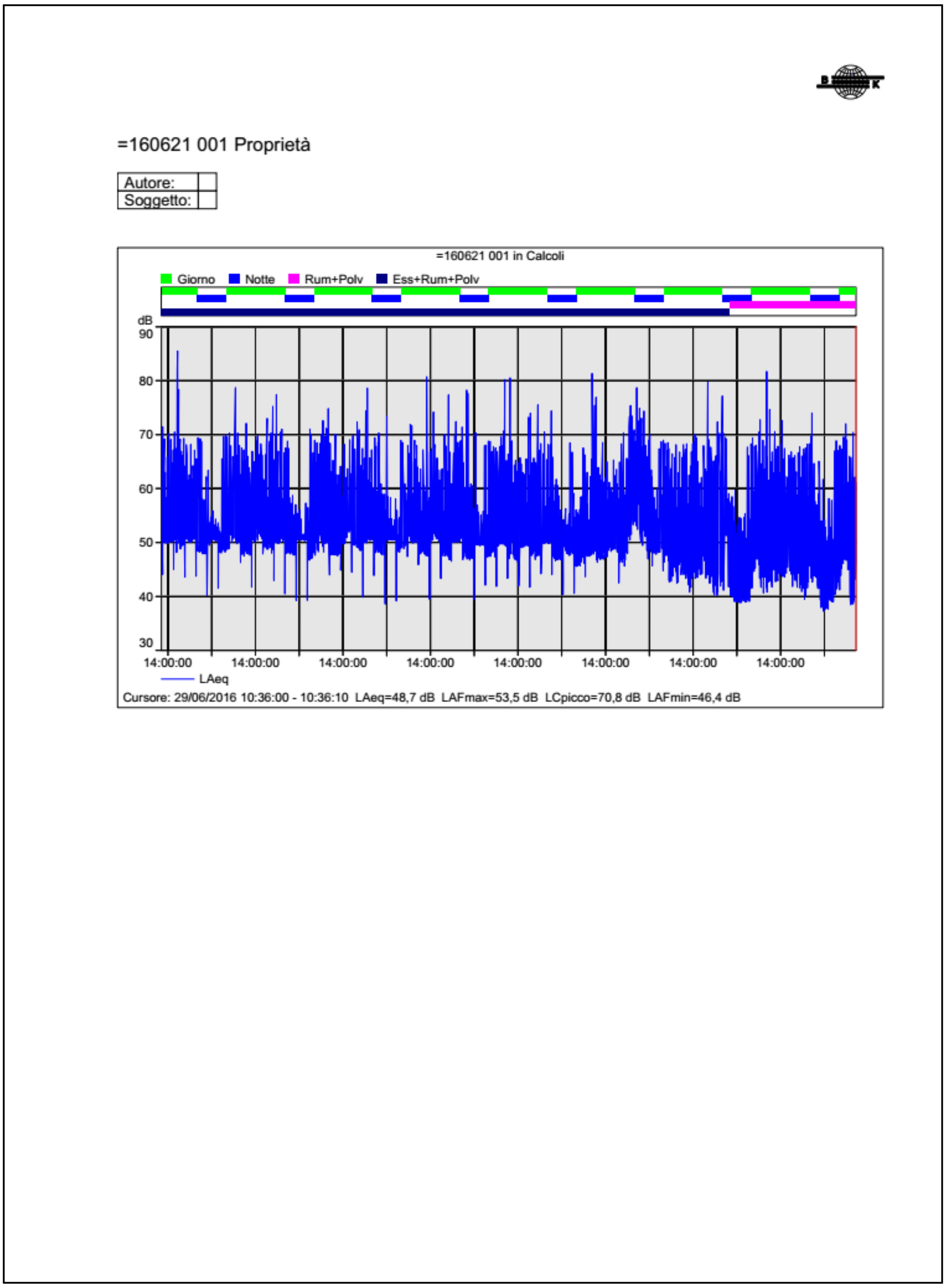
Functions	Components/ Interfaces	Potential failure mode	Potential cause/ mechanism of failure	Occurrence	Potential effects of failure	Severity	Detection design control	Detection	RPN	Recommended actions	New O	New S	New D	New RPN
Dryer ventilation	Power supply	Overload	Failure in the PLC	4	System shutdown	8	Programmed maintenance	4	128	Programmed maintenance	3	8	4	96
	Recirculating pump	Pump breakage	Pump breakage	4	System shutdown	8	PLC	3	96	Programmed maintenance	3	8	3	72
		Not correct water circulation	Failure in the PLC	4	Not correct timber drying	5	System reliability analysis	3	60	Programmed maintenance	3	5	3	45

Appendix 3 – Meteorological data for the period of measurements

	Rain [mm]	**Average temperature [°C]**	**Average wind speed [m/s]**	**Average atmospheric pressure [bar]**
13/06/2016	0	22.48	5.34	753.2
14/06/2016	0	21.59	7.1	750.8
15/06/2016	0	20.05	5.22	751.7
16/06/2016	3.8	17.71	4.98	752.6
17/06/2016	0	19.74	6.6	757.5
18/06/2016	5.2	16.22	3.28	764.1
19/06/2016	0.2	19.2	6.49	763.9
20/06/2016	0	22.17	5.38	764.2
21/06/2016	0	22.14	3	766.7
22/06/2016	0	23.99	3.41	767.8
23/06/2016	0	26.04	3.31	766.6
24/06/2016	0	26.28	2.94	763.3
25/06/2016	0.4	24.11	2.6	759.5
26/06/2016	0	24.91	5.46	759.2
27/06/2016	0	24.9	5.65	761
28/06/2016	0	23.02	3.48	763.3
29/06/2016	5.4	23.69	4.05	762.1
30/06/2016	3.6	20.68	1.34	762.2
01/07/2016	0.2	22.58	3.15	763.5
02/07/2016	0	23.79	3.38	761.6
03/07/2016	0	26.19	8.59	761.1
04/07/2016	0,0	22,5	3,3	764,5
05/07/2016	0,0	23,2	1,9	762,9
06/07/2016	0,0	25,6	4,8	761,4
07/07/2016	0,0	25,3	3,4	763,2
08/07/2016	0,0	25,4	3,1	763,7
09/07/2016	0,0	27,7	5,2	762,9
10/07/2016	0,0	26,8	3,4	762,2
11/07/2016	0,4	25,7	3,6	760,9
12/07/2016	0,2	21,8	3,4	759,5
13/07/2016	0,2	22,0	11,2	757,4

Appendix 4 – Sheets of noise monitoring results

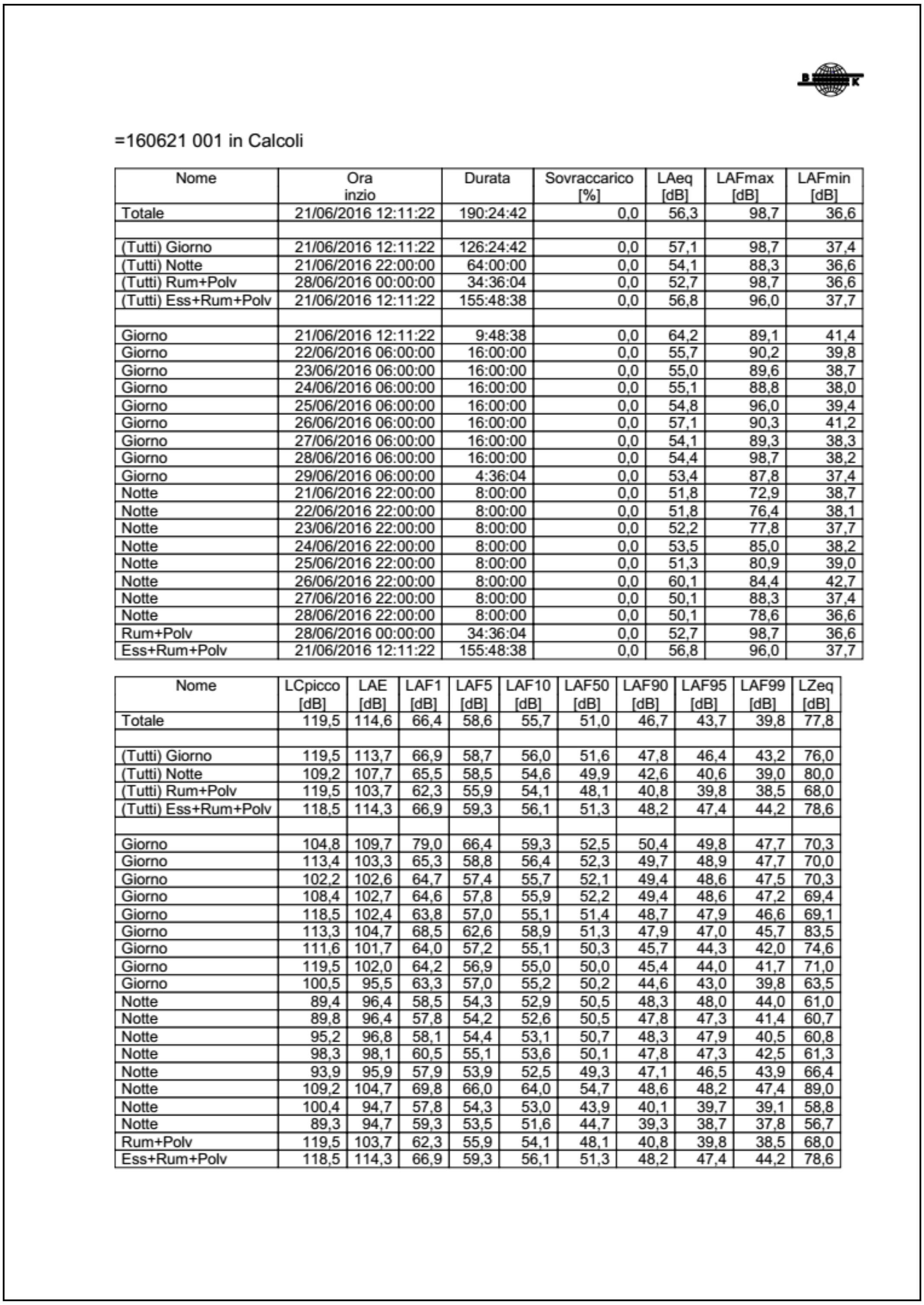
Mesure A



=160621 001 Proprietà

Autore:	
Soggetto:	

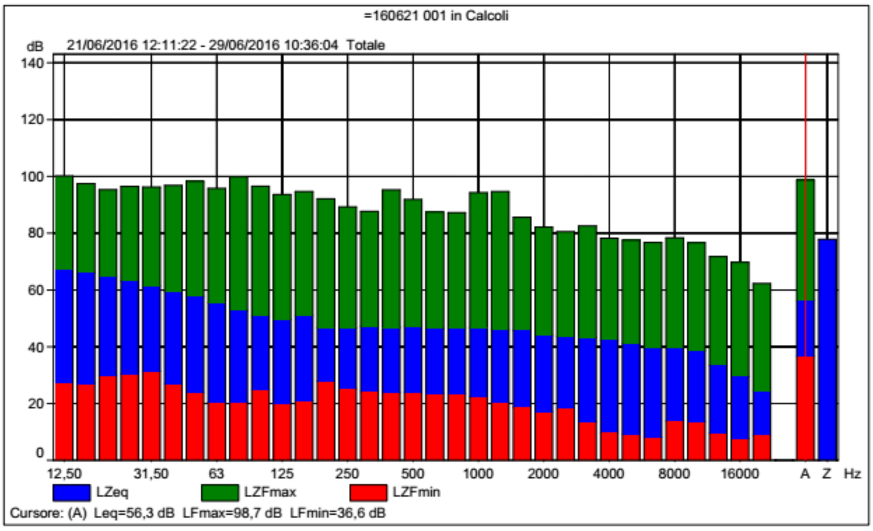
Cursore: 29/06/2016 10:36:00 - 10:36:10 LAeq=48,7 dB LAFmax=53,5 dB LCpicco=70,8 dB LAFmin=46,4 dB



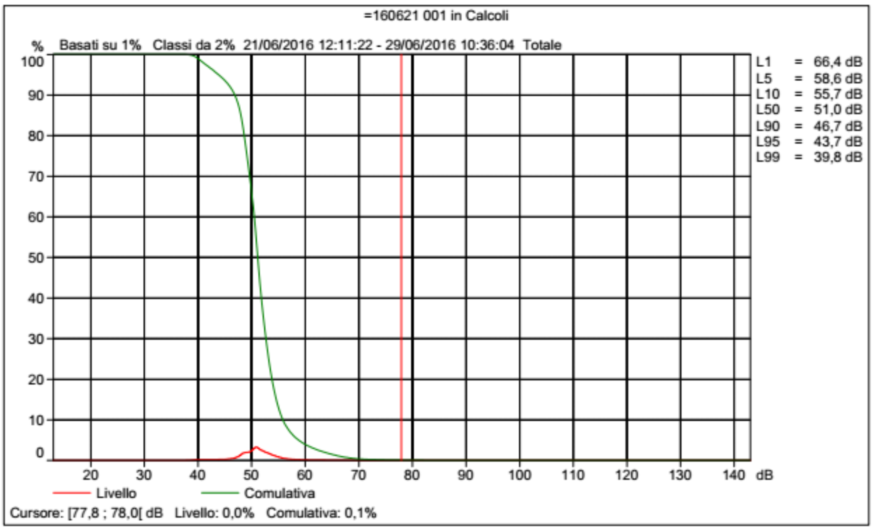
=160621 001 in Calcoli

Nome	Ora inzio	Durata	Sovraccarico [%]	LAeq [dB]	LAFmax [dB]	LAFmin [dB]
Totale	21/06/2016 12:11:22	190:24:42	0,0	56,3	98,7	36,6
(Tutti) Giorno	21/06/2016 12:11:22	126:24:42	0,0	57,1	98,7	37,4
(Tutti) Notte	21/06/2016 22:00:00	64:00:00	0,0	54,1	88,3	36,6
(Tutti) Rum+Polv	28/06/2016 00:00:00	34:36:04	0,0	52,7	98,7	36,6
(Tutti) Ess+Rum+Polv	21/06/2016 12:11:22	155:48:38	0,0	56,8	96,0	37,7
Giorno	21/06/2016 12:11:22	9:48:38	0,0	64,2	89,1	41,4
Giorno	22/06/2016 06:00:00	16:00:00	0,0	55,7	90,2	39,8
Giorno	23/06/2016 06:00:00	16:00:00	0,0	55,0	89,6	38,7
Giorno	24/06/2016 06:00:00	16:00:00	0,0	55,1	88,8	38,0
Giorno	25/06/2016 06:00:00	16:00:00	0,0	54,8	96,0	39,4
Giorno	26/06/2016 06:00:00	16:00:00	0,0	57,1	90,3	41,2
Giorno	27/06/2016 06:00:00	16:00:00	0,0	54,1	89,3	38,3
Giorno	28/06/2016 06:00:00	16:00:00	0,0	54,4	98,7	38,2
Giorno	29/06/2016 06:00:00	4:36:04	0,0	53,4	87,8	37,4
Notte	21/06/2016 22:00:00	8:00:00	0,0	51,8	72,9	38,7
Notte	22/06/2016 22:00:00	8:00:00	0,0	51,8	76,4	38,1
Notte	23/06/2016 22:00:00	8:00:00	0,0	52,2	77,8	37,7
Notte	24/06/2016 22:00:00	8:00:00	0,0	53,5	85,0	38,2
Notte	25/06/2016 22:00:00	8:00:00	0,0	51,3	80,9	39,0
Notte	26/06/2016 22:00:00	8:00:00	0,0	60,1	84,4	42,7
Notte	27/06/2016 22:00:00	8:00:00	0,0	50,1	88,3	37,4
Notte	28/06/2016 22:00:00	8:00:00	0,0	50,1	78,6	36,6
Rum+Polv	28/06/2016 00:00:00	34:36:04	0,0	52,7	98,7	36,6
Ess+Rum+Polv	21/06/2016 12:11:22	155:48:38	0,0	56,8	96,0	37,7

Nome	LCpicco [dB]	LAE [dB]	LAF1 [dB]	LAF5 [dB]	LAF10 [dB]	LAF50 [dB]	LAF90 [dB]	LAF95 [dB]	LAF99 [dB]	LZeq [dB]
Totale	119,5	114,6	66,4	58,6	55,7	51,0	46,7	43,7	39,8	77,8
(Tutti) Giorno	119,5	113,7	66,9	58,7	56,0	51,6	47,8	46,4	43,2	76,0
(Tutti) Notte	109,2	107,7	65,5	58,5	54,6	49,9	42,6	40,6	39,0	80,0
(Tutti) Rum+Polv	119,5	103,7	62,3	55,9	54,1	48,1	40,8	39,8	38,5	68,0
(Tutti) Ess+Rum+Polv	118,5	114,3	66,9	59,3	56,1	51,3	48,2	47,4	44,2	78,6
Giorno	104,8	109,7	79,0	66,4	59,3	52,5	50,4	49,8	47,7	70,3
Giorno	113,4	103,3	65,3	58,8	56,4	52,3	49,7	48,9	47,7	70,0
Giorno	102,2	102,6	64,7	57,4	55,7	52,1	49,4	48,6	47,5	70,3
Giorno	108,4	102,7	64,6	57,8	55,9	52,2	49,4	48,6	47,2	69,4
Giorno	118,5	102,4	63,8	57,0	55,1	51,4	48,7	47,9	46,6	69,1
Giorno	113,3	104,7	68,5	62,6	58,9	51,3	47,9	47,0	45,7	83,5
Giorno	111,6	101,7	64,0	57,2	55,1	50,3	45,7	44,3	42,0	74,6
Giorno	119,5	102,0	64,2	56,9	55,0	50,0	45,4	44,0	41,7	71,0
Giorno	100,5	95,5	63,3	57,0	55,2	50,2	44,6	43,0	39,8	63,5
Notte	89,4	96,4	58,5	54,3	52,9	50,5	48,3	48,0	44,0	61,0
Notte	89,8	96,4	57,8	54,2	52,6	50,5	47,8	47,3	41,4	60,7
Notte	95,2	96,8	58,1	54,4	53,1	50,7	48,3	47,9	40,5	60,8
Notte	98,3	98,1	60,5	55,1	53,6	50,1	47,8	47,3	42,5	61,3
Notte	93,9	95,9	57,9	53,9	52,5	49,3	47,1	46,5	43,9	66,4
Notte	109,2	104,7	69,8	66,0	64,0	54,7	48,6	48,2	47,4	89,0
Notte	100,4	94,7	57,8	54,3	53,0	43,9	40,1	39,7	39,1	58,8
Notte	89,3	94,7	59,3	53,5	51,6	44,7	39,3	38,7	37,8	56,7
Rum+Polv	119,5	103,7	62,3	55,9	54,1	48,1	40,8	39,8	38,5	68,0
Ess+Rum+Polv	118,5	114,3	66,9	59,3	56,1	51,3	48,2	47,4	44,2	78,6



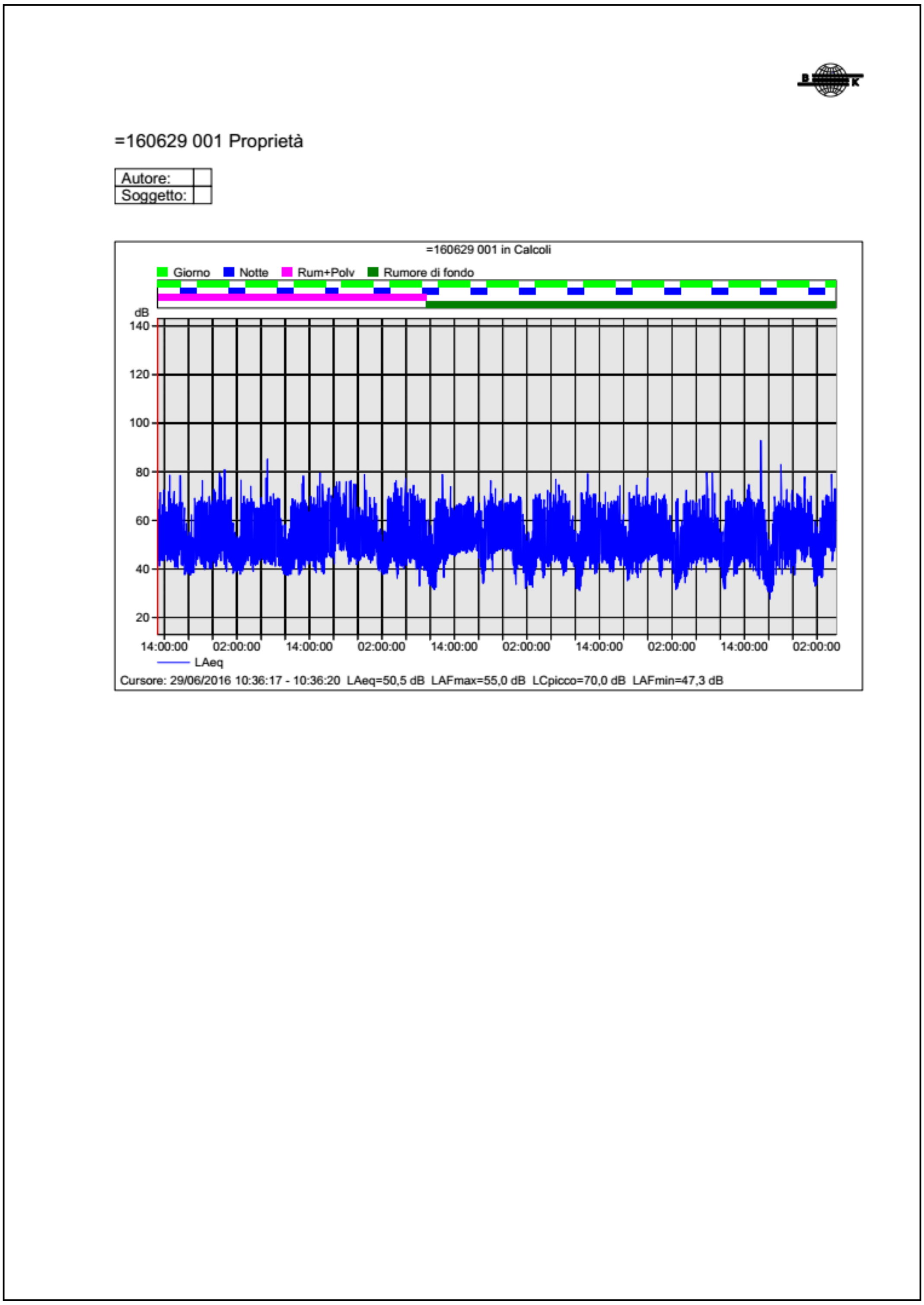
Cursore: (A) Leq=56,3 dB LFmax=98,7 dB LFmin=36,6 dB



L1 = 66,4 dB
L5 = 58,6 dB
L10 = 55,7 dB
L50 = 51,0 dB
L90 = 46,7 dB
L95 = 43,7 dB
L99 = 39,8 dB

Cursore: [77,8 ; 78,0[dB Livello: 0,0% Comulativa: 0,1%

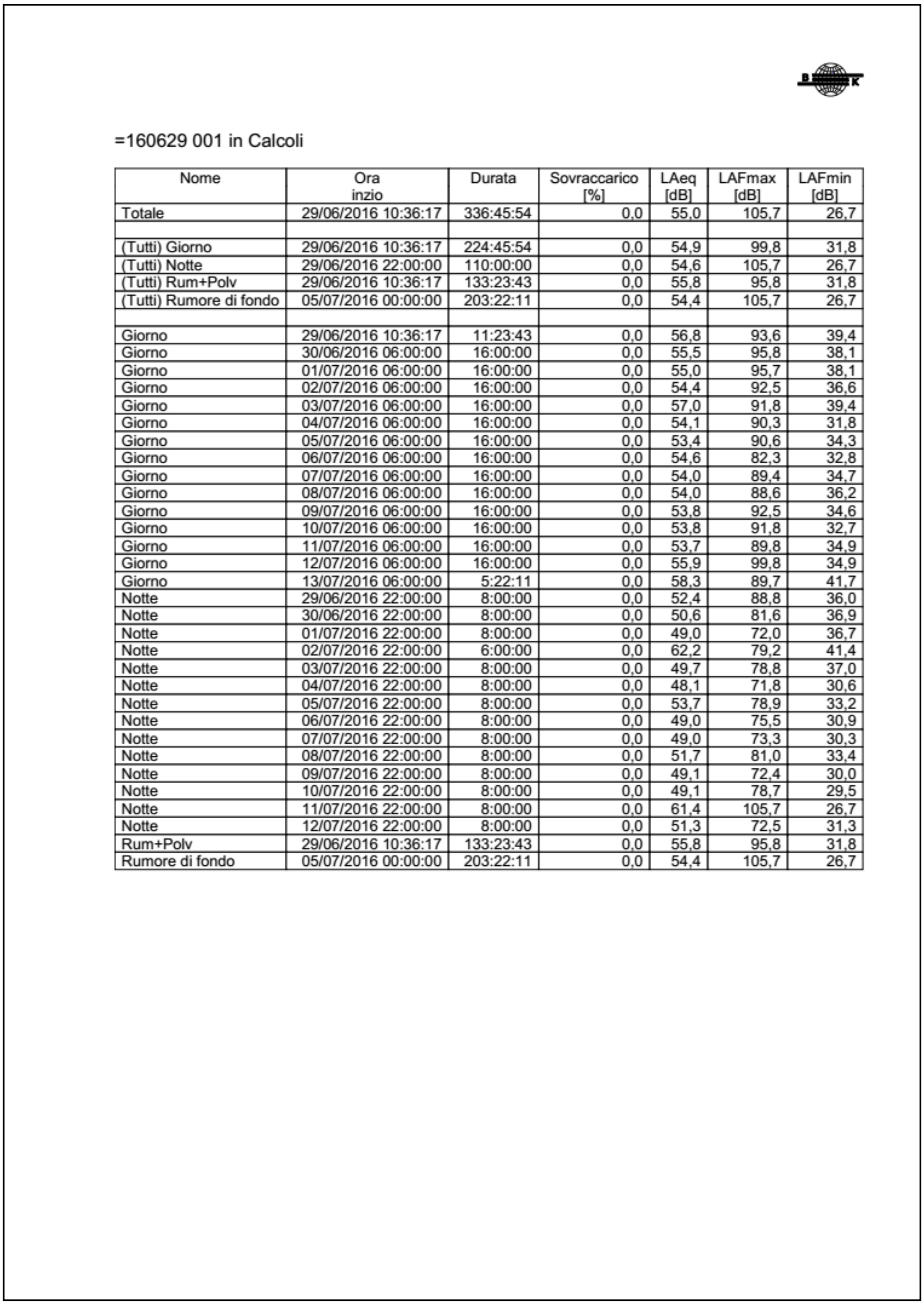
Mesure B



=160629 001 Proprietà

Autore:	
Soggetto:	

Cursore: 29/06/2016 10:36:17 - 10:36:20 LAeq=50,5 dB LAFmax=55,0 dB LCpicco=70,0 dB LAFmin=47,3 dB



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Nome	Ora inzio	Durata	Sovraccarico [%]	LAeq [dB]	LAFmax [dB]	LAFmin [dB]
Totale	29/06/2016 10:36:17	336:45:54	0,0	55,0	105,7	26,7
(Tutti) Giorno	29/06/2016 10:36:17	224:45:54	0,0	54,9	99,8	31,8
(Tutti) Notte	29/06/2016 22:00:00	110:00:00	0,0	54,6	105,7	26,7
(Tutti) Rum+Polv	29/06/2016 10:36:17	133:23:43	0,0	55,8	95,8	31,8
(Tutti) Rumore di fondo	05/07/2016 00:00:00	203:22:11	0,0	54,4	105,7	26,7
Giorno	29/06/2016 10:36:17	11:23:43	0,0	56,8	93,6	39,4
Giorno	30/06/2016 06:00:00	16:00:00	0,0	55,5	95,8	38,1
Giorno	01/07/2016 06:00:00	16:00:00	0,0	55,0	95,7	38,1
Giorno	02/07/2016 06:00:00	16:00:00	0,0	54,4	92,5	36,6
Giorno	03/07/2016 06:00:00	16:00:00	0,0	57,0	91,8	39,4
Giorno	04/07/2016 06:00:00	16:00:00	0,0	54,1	90,3	31,8
Giorno	05/07/2016 06:00:00	16:00:00	0,0	53,4	90,6	34,3
Giorno	06/07/2016 06:00:00	16:00:00	0,0	54,6	82,3	32,8
Giorno	07/07/2016 06:00:00	16:00:00	0,0	54,0	89,4	34,7
Giorno	08/07/2016 06:00:00	16:00:00	0,0	54,0	88,6	36,2
Giorno	09/07/2016 06:00:00	16:00:00	0,0	53,8	92,5	34,6
Giorno	10/07/2016 06:00:00	16:00:00	0,0	53,8	91,8	32,7
Giorno	11/07/2016 06:00:00	16:00:00	0,0	53,7	89,8	34,9
Giorno	12/07/2016 06:00:00	16:00:00	0,0	55,9	99,8	34,9
Giorno	13/07/2016 06:00:00	5:22:11	0,0	58,3	89,7	41,7
Notte	29/06/2016 22:00:00	8:00:00	0,0	52,4	88,8	36,0
Notte	30/06/2016 22:00:00	8:00:00	0,0	50,6	81,6	36,9
Notte	01/07/2016 22:00:00	8:00:00	0,0	49,0	72,0	36,7
Notte	02/07/2016 22:00:00	6:00:00	0,0	62,2	79,2	41,4
Notte	03/07/2016 22:00:00	8:00:00	0,0	49,7	78,8	37,0
Notte	04/07/2016 22:00:00	8:00:00	0,0	48,1	71,8	30,6
Notte	05/07/2016 22:00:00	8:00:00	0,0	53,7	78,9	33,2
Notte	06/07/2016 22:00:00	8:00:00	0,0	49,0	75,5	30,9
Notte	07/07/2016 22:00:00	8:00:00	0,0	49,0	73,3	30,3
Notte	08/07/2016 22:00:00	8:00:00	0,0	51,7	81,0	33,4
Notte	09/07/2016 22:00:00	8:00:00	0,0	49,1	72,4	30,0
Notte	10/07/2016 22:00:00	8:00:00	0,0	49,1	78,7	29,5
Notte	11/07/2016 22:00:00	8:00:00	0,0	61,4	105,7	26,7
Notte	12/07/2016 22:00:00	8:00:00	0,0	51,3	72,5	31,3
Rum+Polv	29/06/2016 10:36:17	133:23:43	0,0	55,8	95,8	31,8
Rumore di fondo	05/07/2016 00:00:00	203:22:11	0,0	54,4	105,7	26,7

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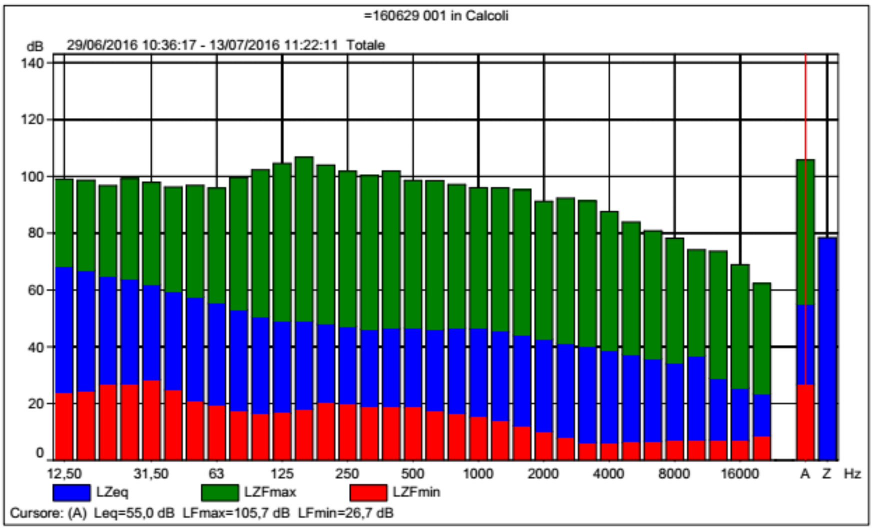
Nome	LCpicco [dB]	LAE [dB]	LAF1 [dB]	LAF5 [dB]	LAF10 [dB]	LAF50 [dB]	LAF90 [dB]	LAF95 [dB]	LAF99 [dB]	LZeq [dB]
Totale	134,4	115,8	65,8	58,4	55,6	49,3	41,2	39,0	34,6	78,4
(Tutti) Giorno	115,0	114,0	65,6	58,3	55,8	50,2	45,2	43,6	40,2	76,0
(Tutti) Notte	134,4	110,6	65,5	57,6	54,2	45,2	38,0	35,7	32,9	79,9
(Tutti) Rum+Polv	115,3	112,6	67,1	60,6	56,5	49,4	42,0	40,2	38,6	80,9
(Tutti) Rumore di fondo	134,4	113,0	64,1	57,3	55,1	49,2	40,5	37,6	33,7	75,2
Giorno	113,2	102,9	67,7	61,8	57,3	50,5	46,2	44,9	42,6	77,0
Giorno	114,4	103,1	65,2	57,2	55,2	50,2	45,3	44,0	41,5	67,3
Giorno	110,0	102,6	64,8	57,1	55,0	50,0	45,5	44,3	42,3	70,5
Giorno	104,0	102,0	64,5	56,3	54,0	49,0	43,9	42,2	39,6	69,1
Giorno	110,7	104,6	66,7	62,0	59,3	51,5	47,1	45,9	43,8	84,0
Giorno	104,1	101,7	64,4	56,5	54,7	49,7	44,4	43,0	39,7	69,7
Giorno	103,9	101,0	63,5	56,2	54,5	50,3	46,8	45,8	43,1	63,9
Giorno	106,0	102,2	66,0	57,7	55,4	51,0	46,8	44,7	40,3	70,4
Giorno	101,0	101,6	65,1	57,0	55,1	49,9	44,8	43,1	39,6	71,8
Giorno	102,3	101,6	65,4	57,5	55,3	49,8	44,5	43,0	40,3	71,2
Giorno	101,8	101,4	64,7	57,3	54,9	49,6	44,4	42,7	39,4	71,5
Giorno	104,8	101,4	62,5	56,2	54,3	49,5	43,2	40,9	37,2	70,6
Giorno	114,3	101,3	64,9	56,9	54,7	49,3	44,3	42,7	39,5	70,0
Giorno	115,0	103,5	65,9	59,1	57,2	51,9	46,3	44,7	41,5	76,5
Giorno	106,1	101,2	67,7	62,9	60,7	55,1	50,8	49,6	47,5	85,7
Notte	115,3	97,0	64,3	55,4	52,1	43,6	39,3	38,8	38,1	62,5
Notte	90,2	95,2	59,5	53,6	51,3	44,1	39,9	39,3	38,3	57,4
Notte	89,4	93,6	57,5	53,1	51,4	44,2	38,9	38,3	37,7	56,5
Notte	112,7	105,6	72,2	68,2	66,1	57,8	49,9	48,1	45,3	91,2
Notte	92,1	94,3	57,8	54,2	52,5	44,1	39,5	39,0	38,3	56,6
Notte	90,6	92,7	58,0	52,3	50,2	42,6	35,4	34,1	32,6	56,3
Notte	104,8	98,3	62,6	58,9	57,0	50,8	41,2	38,7	35,7	83,0
Notte	91,3	93,5	58,1	53,1	51,1	42,8	36,3	35,2	33,5	58,8
Notte	91,7	93,5	57,9	52,7	50,8	44,1	35,5	34,3	32,7	56,8
Notte	100,4	96,3	59,8	55,6	53,8	48,0	41,6	39,5	36,3	78,1
Notte	92,3	93,7	57,5	53,4	51,8	45,1	35,4	34,2	32,4	57,8
Notte	91,7	93,6	57,7	52,9	51,0	44,9	38,6	36,6	33,7	57,1
Notte	134,4	106,0	67,1	54,7	51,3	42,2	33,3	31,9	30,3	69,1
Notte	102,1	95,9	60,8	57,0	54,9	45,6	38,1	36,5	34,3	79,1
Rum+Polv	115,3	112,6	67,1	60,6	56,5	49,4	42,0	40,2	38,6	80,9
Rumore di fondo	134,4	113,0	64,1	57,3	55,1	49,2	40,5	37,6	33,7	75,2



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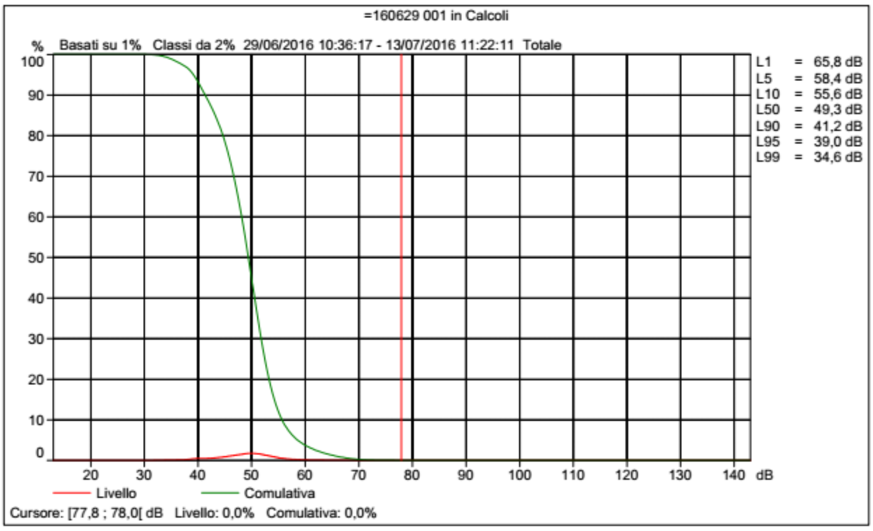
Cursore: (A) Leq=55,0 dB LFmax=105,7 dB LFmin=26,7 dB



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L1 = 65,8 dB
L5 = 58,4 dB
L10 = 55,6 dB
L50 = 49,3 dB
L90 = 41,2 dB
L95 = 39,0 dB
L99 = 34,6 dB

Cursore: [77,8 ; 78,0[dB Livello: 0,0% Comulativa: 0,0%

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