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TECHNOLOGY AND ECONOMY ANALYSIS OF WASTE TRUCK TIRES MANAGEMENT

by

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2019

This thesis, submitted by Irina Tsiryapkina in partial fulfillment of the requirements for the Degree of Master of Science in Energy Systems Engineering from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

Dean of the School of Graduate Studies

Date

PERMISSION

Title	Technology and economy analysis of waste truck tires management
Department	Energy Systems Engineering
Degree	Master of Science

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Irina Tsiryapkina

April 24, 2019

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Abbreviation	Definition
BR	butadiene rubber
BT	benzothiazole
CB	Carbon black
CEPCI	Chemical Engineering plant cost index
CSBR	Conical spouted bed reactor
DCFRR	Discounted cash flow rate of return
DEG	Diethylene glycol
ER	Equivalent ratio
EPC	Engineering, procurement, and construction
FOC	Fixed operating costs
FR	Feeding rate
GTR	Ground tire rubber
HR	Heating rate
HTL	Hydrothermal liquefaction
HV	Heating value
IRR	Internal rate of return
ISBL	Inside battery limits
MBR	Moving bed reactor
MBT	2-mercaptobenzothiazole
MFSP	Minimum fuel selling price
NPV	Net present value
NR	Natural rubber
OC	Operating costs
OOM	Order of magnitude

P	Pressure
PAH	Polycyclic aromatic hydrocarbons
PBP	Payback period
PCT	Passenger scrap tires
PFD	Process flow diagram
PM2.5	Particulate matter 2.5
PN	Particle number
SBR	Sliding bed reactor
SC	Scrap tires
SE	Study estimate
SPCT	Scrap car tires
SS	Sample size
T	Temperature
TCI	Total capital investment
TDC	Total direct cost
TDF	Tire derived fuel
TDO	Tire derived oil
TFCI	Total fixed capital investment
TIC	Total investment capital
TT	Truck tire
USSR	Union of Soviet Socialist Republics
VOC	Variable operating costs
WC	Working capital
WT	Waste tires
WTR	Waste tire rubber
WTT	Waste truck tires
XBR	Fixed bed reactor
XBR-FT	Fixed bed reactor – fire tubes

ACKNOWLEDGEMTS

I wish to express my sincere appreciation to the members of my advisory Committee, Dr. Michael Mann, Dr. Nickil Patel, Dr. Sean T. Hammond, and Dr. Haochi Zheng, for their guidance and support during my time in the master's program at the University of North Dakota. I would also like to thank the Fulbright and Institute of International Education, for the opportunity to study at the University of North Dakota. Also, I would like to personally thank my family and friends for their support.

ABSTRACT

The main objective of this work was to develop a waste truck tires recycling facility for the Siberian coal transportation company “SibTreid NK” in the Kemerovo region, Russia. For years, the company has been stockpiling old scrap tires at their warehouse or dumping them into open strip mines. Taking this into account as well as existing environmental concerns due to the continually growing coal industry in the Kemerovo region, it is highly necessary to make an operational facility to deal with the large number of accumulated waste truck tires.

To achieve this goal, this project reviewed different methods and technologies for managing scrap tires, investigated economic feasibility for the most attractive options, and provided a list of recommendations for the company.

The current practices that “SibTreid NK” uses are dumping, landfilling, and retreading. To address the first part of the research, the strengths and weaknesses of the following scrap tire management techniques have been analyzed: grinding, thermochemical conversion processes that involve incineration, hydrothermal liquefaction, gasification, and pyrolysis, as well as existing methods.

Taking into account interests of the company in converting waste truck tires into oil, gas, and solids, the work is primarily focused on thermochemical processes such as pyrolysis. In total five scenarios of the pyrolytic process are considered in the study. For each scenario I developed the flowchart diagrams. These flowcharts show the

following characteristics at each stage of the recycling practices: the feedstock flow within the company, associated expenses, and relevant emissions.

In order to determine the size of the future facility, necessary equipment, quantity of each by-product, and to evaluate the operating costs of the project, I analyzed the most typical size of a recycling facility used in literature. According to various literature sources, the most appropriate size of the future facility is 30 ton/day.

As input data to the process, I used the average composition of worn out truck tires. In this case use of averages for data is acceptable for several reasons. First, for study purpose ±30% accuracy is admissible. Second, it helps to avoid over-complication of the model to keep the project feasible. The final reason is the inability to obtain the data about the composition of a particular model truck tire by a particular brand, as this information is protected by the tire companies. Also, in articles dedicated to tire recycling, authors usually mention proximate and ultimate analysis of raw material, but almost never talk about whether they used a truck or a car tire or what brand. As the result the raw material was chosen to have steel concentration of 20%. The distribution of the byproducts on steel-free bases is adopted from the research dedicated to the pyrolysis of truck tires and equals 35.5% for the char, 12.5% for the gas, and 52% for the liquid fraction.

The next step of my research was to investigate the viability of the project. Economic analysis of all five scenarios for using the pyrolysis technology has performed, including conversion of low-value waste tires to high-value chemicals, tire derived oil, with and without pre-treatment of the initial feedstock. Using the minimum possible lifetime of the chemical facility (10 years) and current economic indexes of Russia, such as revenue tax, the exchange value of the ruble, fixed operating labor costs

per year, I developed a program to calculate the internal rate of return (IRR), payback period (PBP), and net present value (NPV) of the project. The result showed that the most economically attractive option was the base case scenario option that considered the pre-treatment of the raw material, pyrolysis process itself, and the separation of the tire-derived oil. The NPV was 10.39 MM$, payback period was about 3.6 years, and IRR was 31.5%. Then I conducted the sensitivity analysis for the base case scenario. It showed that the process is extremely sensitive to the fluctuation of the limonene yield and limonene price.

This study could be used by the company to produce extra revenue from selling pyrolytic by-products like steel, char, tire-derived oil, steam, and high-value chemicals. Variable costs of the company, such as fuel expenses, can also be decreased. The results of this work will help to mitigate a series of environmental problems caused by dumping and stockpiling in my region and decrease the amount of emissions that otherwise would be emitted during production of steel, char, oil, and valuable chemicals, if waste truck tires were not recycled. Reduction of total emission will contribute to the obligation of the Russian Federation to address climate change and, ultimately, will have a positive impact on humans' health in the Kemerovo region.

CHAPTER I: INTRODUCTION

1.1 General information about the problem

Increased attention to the environment and sustainability made recycling a more preferable option for various waste streams, including waste rubber, than disposal of these streams [1]. Nowadays, the growing amount of waste tres (WT) worldwide is an important subject of research. In total, as it was estimated in [2], the total number of WT produced in 2011 was approximately 1,500,000,000 pieces. Until recently the majority of WT were landfilled or illegally dumped into open areas. Approximately 4 billion of WT are landfilled or stock-pilled worldwide [3]. This type of polymeric waste causes serious environmental and public health problems, occupies large space, and it is not biodegradable. Disposed tires are an ideal environment for the insects breeding. Increasing number of tire fires represents one of the major problems associated with dumping of WT in to open areas. Tire fires contaminate such important natural objects for humans as soil, groundwater, and air, but also this type of fire emits up to 3-4 times more mutagenic emissions than combustion of oil, coal, wood in utility boilers [4].

Nowadays there are several options of using scrap tires (ST). Due to such characteristics as high energy content and excellent resistance to wide range of disturbances, WT can be reused, recycled, and disposed in an appropriate facility [5]. Taking into account such a major political and economic issue as constantly growing energy demand worldwide and finite amount of fossil fuels resources and its unequal distribution, the waste refinery concept can be considered as one of the possible solutions to mentioned problems, especially refining of waste tires [6].

This work is focused on finding the ways of possible waste truck tires (WTT) management at Siberian coal transportation company “SibTreid NK”. For years, the company has been stockpiling old waste tires at their warehouse on the territory of the company or dumping them into open strip mines. Taking this into account as well as existing environmental concerns due to the constantly growing coal industry in Kuzbass [7], it is highly necessary that an operational decision will be taken how to deal with large amount of WT producing every year.

1.2 Aims and objectives

In order to achieve the aim of this study, six main objectives are defined as follows:

Objective 1: Description of the company and the location, including general characteristics of Kemerovo region, status of coal mining industry for Kuzbass, and company’s profile.

Objective 2: Characterization of tires’ disposal problem in the company, analysis of WTT life cycle within and outside the company and description of the composition of WTT.

Objective 3: Investigation of current technologies and methods for waste tire management.

Objective 4: Economic evaluation of the future recycling facility.

Objective 5: Carry out sensitivity analysis for the most attractive scenarios.

Objective 6: Write a list of recommendations for the company.

1.3 About the region and the company

Kemerovo region is located in the south-west of Siberian Federal District, Russia. The total area of the region is 95,500 square kilometers (36,900 sq mi). Relative to most other nations, Russia has very large coal reserves. In the territory of Kemerovo region (or Kuzbass), the Kuznetsk coal basin is located. The Kuznetsk coal basin is considered as one of the major coal fields in Russia.

Since the collapse of the USSR, coal production has increased dramatically from 124 mln t in 1991 to 241.5 mln t of coal in 2017. Today the share of Kuzbass is over 50% in domestically produced coal and over 80% of coking coal. About 40% of the coal is exported to more than 40 countries; this is over 80% of the national export of coal [7]. Most Russian coking coal is mined in the Kuznetsk Basin and used in coke production [8].

Company “SibTreid NK” is located in Novokuznetsk agglomeration (Talgino town) in the south of Kemerovo region where underground and opencast mines are located in all urban and municipal areas. “SibTreid” is one of the major transportation companies in Kemerovo region. Its’ main activities are:

1) Repair and maintenance of the dump trucks BelAZ (Belorussia);
2) Spare parts for BelAZ dump trucks with carrying capacity from 50 to 220 tons;
3) Transportation of coal and overburden.

This work is focused on the management of by-product of the third activity - waste truck tires. “Transportation of coal and overburden” is carried out by “SibTreid NK” sub-company “Region 42”. This company is fully responsible for the organization and implementation of transport operations in the mining industry of Kemerovo region.

Capacity and characteristics of "Region 42". The company has been operating since 2006. Besides transportation service 24/7, "Region 42" provides constant technical support, and repair service for both BelAZ trucks itself and their tires. "Region 42" has a constantly growing vehicles fleet. The company mostly uses BelAZ trucks of 55-, 120- and 220-ton carrying capacity. Nowadays the total number of 55- and 120/220-ton trucks is 300 and 200 respectively. Due to the expansion of coal production in Kuzbass, the company is going through replacement of its 55-trucks to larger capacity 120- and 220-ton trucks. All these dumps trucks daily serve 11 the largest open coal strip mines of Kuzbass: "Zarechnij', "Kamyshanskiy", "Maiskiy", "Yuzhnyy 1", "Yuzhnyy 2", "Coke Section", "Belovskaya", "TD Sibir 3", "TD Sibir 5", "Energougol", and open strip mine "Taldinskij" (Figure 1).

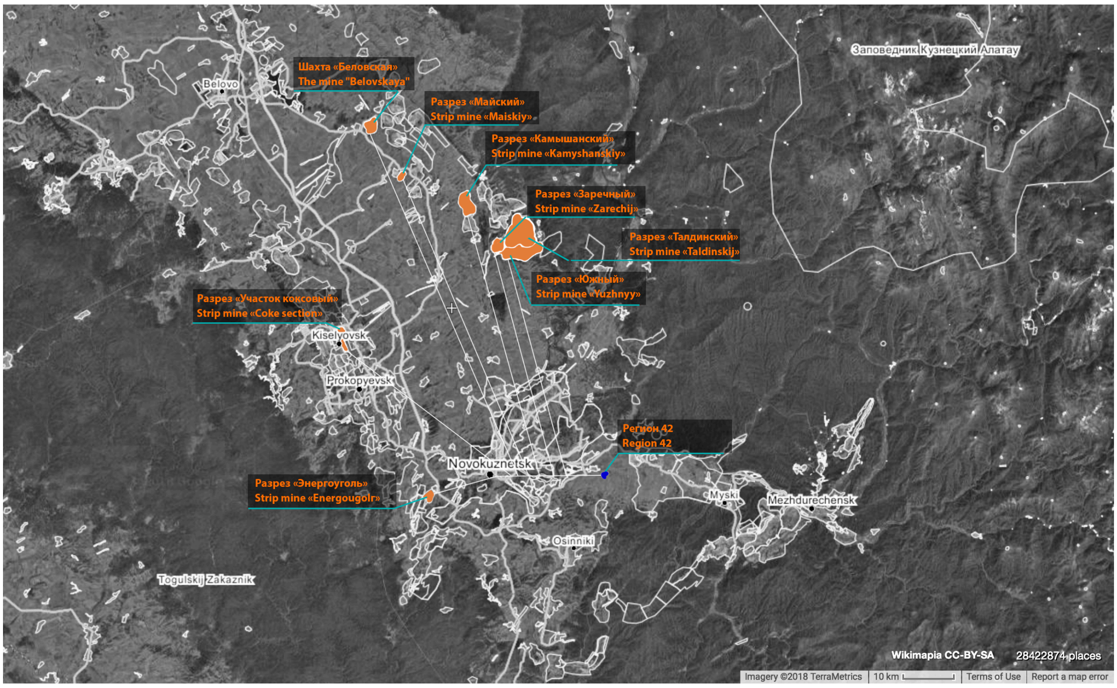

Figure 1. Map of coal strip mines

1.4 Description of the problem

Since the beginning of the company functioning, all waste tires were either stored on the territory of the company or illegally buried in strip mines. Due to the building of the tires repair facility in 2012, the total number of waste truck tires per month (and per year) has been considerably reduced but not completely eliminated.

Because there is no waste tire recycling facility on the territory of the company or in Kuzbass, the constantly growing number of waste truck tires will eventually enter the waste stream representing a major potential waste and environmental problem.

According to the company data, the exact total number of accumulated waste truck tires is currently unknown for lack of the necessity to count it. An approximate number of waste truck tires inflow is 2 tires per day, the approximate quantity of waste tires on the company warehouse is many hundreds among them mostly from 120- and 220-ton trucks. The number of buried tires is many thousands. Fortunately, the cost of their transportation to the company could be considered free as they are transported with trucks which are needed the tire's service.

There are two types of worn out tires used in this work. The first type is partially worn out tire that can be retreaded at the company’s facility and then used by the company in its original purpose. The second type of used tires is "waste" or "scrap" truck tire that cannot be retreated by the company and reused in the coal transportation sector. Dealing with the second type of worn out tires is the main focus of this project. The simplified scheme of truck tires life cycle within the company “SibTreidNK” including several blocks “outside” the company (raw material extraction stage, preparation of used tires by the third party, collecting of tires by the third party to reuse) is shown in Figure 2 (adapted from [9]).

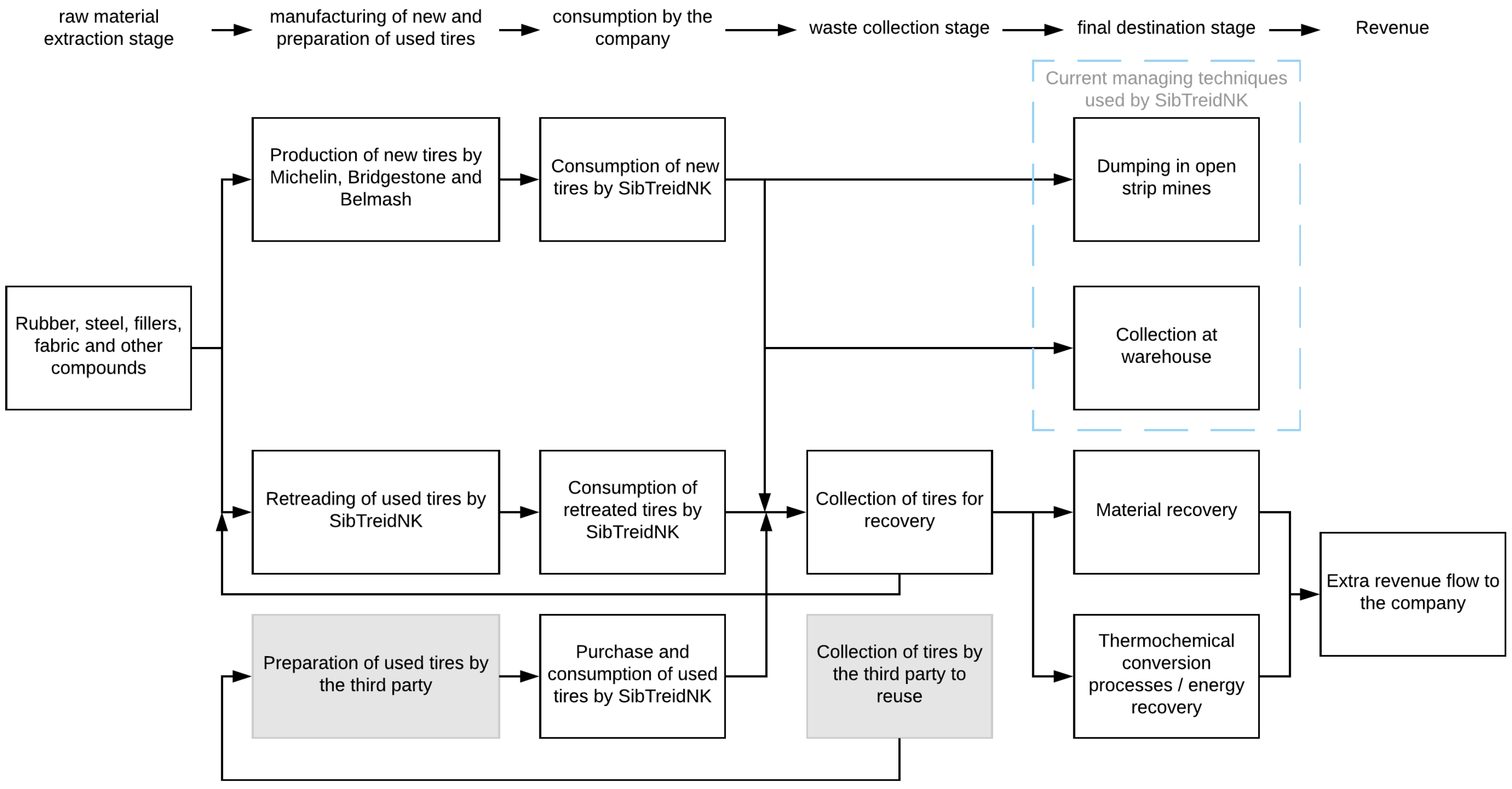

Figure 2. The simplified life cycle of truck tires at "SibTreidNK

CHAPTER II: METHODOLOGY

The possible solution of the presented problem can be achieved by dividing the problem into three parts as shown in Figure 3. All these should be accomplished in the order shown in the figure. However, all of them are connected between each other.

The first part includes the description of the problem in general in order to explain why it is important to deal with problems. Also, this chapter shows what are the aims that should be achieved to develop a decision. Finally, the last component of the first part is to describe the region where the future facility should be built in and the company itself. The description of the company includes the trucks the company uses, their quantity, what is the geography of the company, what types of the tires the company uses, and what is the tire disposal rate. This data is necessary for the further development of the recycling facility.

The second part includes the description of possible solutions of the problems, the description of the current methods used by the company to deal with the problem of disposal, and analysis of the raw material. The composition of the raw material is analyzed by using other research dealing specifically with the truck tires due to the inability to get a composition of all tires used by the company. The description of the various methods to deal with scrap truck tires is used in the third part of the research to choose the most applicable technology from maturity and company points of view. Later the most applicable technology, in the framework of this study the most applicable

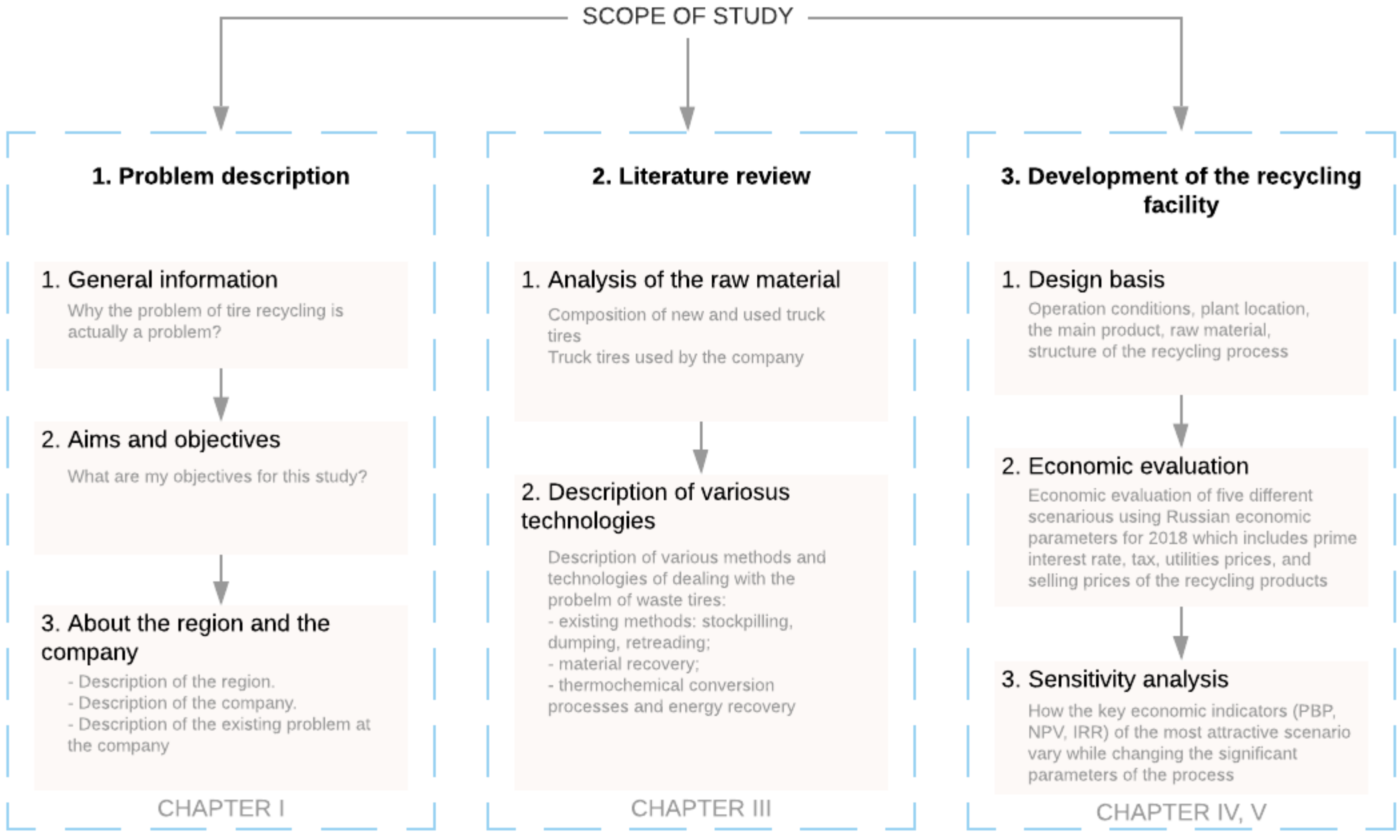

Figure 3. Graphical representation of the scope of this study

technology is pyrolysis treatment with further recovery of limonene, is used to generate possible solutions of the problem that later would be analyzed for economic feasibility.

The third part includes the development of the future facility, economic evaluation of the different scenarios, and conducting of the sensitivity analysis for the most attractive option from the economic perspective of view. The development of the future facility implies the description of working conditions, size of the facility, defining of the targeted chemical, identification of the byproducts that later can be sold and create extra revenue source for the company. In the economic evaluation of the system, I defined the accuracy of the evaluation, the base year, the economic parameters of Russia for the base year, the price of utilities of the Kemerovo region, and other costs. The costs of the equipment are adjusted by using the CEPCI values. Five possible scenarios for the pyrolysis process was developed. Each of this process is described in the fifth chapter of the research. The profitability analysis is done by using the discounted cash flow rate of return method using the prime interest of the Russian Federation for 2018. In the economic analysis I used the least possible lifetime of the project. The depreciation of the equipment is linear with zero salvage value at the end of the lifetime. The key economic indicators that define the attractiveness of each scenario are payback period, net present value, and internal rate of return.

After defining the most attractive option, I used the first-order sensitivity analysis to check how the variation of the critical parameters affect the key economic parameters.

CHAPTER III: LITERATURE REVIEW

Overview of the chapter

This chapter describes the composition of truck tires and waste truck tires, what tires are used by the company. Also, in this chapter various methods of dealing with waste truck tires are described.

3.1 Tire composition and truck tire brands used by the company

Before analyzing the various methods of scrap truck tires treatment, it is helpful to know the composition of the material forming the tire and structure of the tire. Tires are very complex product of engineering activity. In total there seven key parts of truck tire: the inner liner, carcass, bead, sidewall, belts, undertread, and tread. Being engineered over several decades, tires are able to withstand the stresses and at the same time travel for a long distance before retreading or replacement.

The composition of tires varies significantly because of the different types of applications [6]. Tire consists of different types of carbon black, different types of rubber, steel cords and fabric for reinforcement, fillers like clay, silica, and minerals or chemicals to allow or accelerate vulcanization [2], [10-14]. The amount of reinforcement layers depends on tire type. Usually, truck tires require more steel.

The proportion of each compound depends on the tire application, for instance composition of motorcycle, car, and truck tires are different [6], and on the manufacturing company. Also, it is worthwhile to mention, each company has its own way to make tires which is considered as company’s intellectual property and usually is not in open access, however the ingredients that are mainly used in tire manufacturing are the same (Table 1).

Table 1. Ingredient breakdown for a new truck tire [10]

Material	Truck tire (%)
Natural rubber	27
Synthetic rubber	14
Fillers (carbon black, silica)	26-28
Plasticizers (oil, resin)	5-6
Chemical additives	5-6
Metal for reinforcement	25
Textile for reinforcement	-

In tire manufacturing two types of rubber are used: natural and synthetic [10]. Thermal stability and high mechanical resistance are the benefits of using natural rubber (NR). Synthetic rubber (SB) derived from oil enables resistance to mechanical deformations. SB is found in a form of styrene-butadiene (SBR) and butadiene rubbers (BR) [10]. The difference in car and truck tire scrap rubber composition according to Ucar in [12] is given in Table 2. These differences will be important when the potential methods of treating the tires. For example, Ucar showed that oil yield from WTT can be 7-8% higher than oil yield from scrap passenger car tires (SPCT) due to the higher NR content.

Table 2. Rubber composition of scrap tires, wt% [12]

	SPCT (car)	TT (truck)
Natural rubber (NR)	35	51
Styrene butadiene rubber (SBR)	-	39
Butadiene rubber (BR)	65	10

Therefore, the key prior to any treatment of scrap tire is understanding of the initial material properties. The proximate and ultimate analysis of truck scrap tires containing no steel and textile are shown in Table 3 [12].

Table 3. Ultimate analysis of scrap truck tires [12]

Proximate analysis	Truck tire (wt%)
Moisture	0.82 - 1.40
Volatile matter	62.7 - 66.10
Fixed Carbon	27.50 - 32.31
Ash	4.17 - 5.00
Ultimate analysis	Truck tire (dry, %)
C	80.30 - 83.20
H	7.18 - 7.70
N	0.5 - 1.50
O (calculated from difference)	6.16 – 10.8
S	1.19 - 1.44
Gross calorific value, MJ/kg	33.3-34.4

The composition of a waste truck tire is different from the new one (

Table 4). The main reasons are:

- Treadwear during operation. This increased share of non-rubber components (metals and others);
- Crumb rubber of STT incorporates contamination of metals and fibers;
- Crumb rubber includes the rubber/elastomers, carbon black, the sulphur, the “additives” and most of the zinc oxide;
- Unavoidably, a small share of rubber materials adheres to the metal.

Table 4. Post-consumer truck tire material [12]

Product yield	WTT (%)
Crumb rubber	70
Metal	27
Fiber & Scrap	3

The company uses three brands of truck tires: Micheline, Bridgestone, and BELMASH (Belorussia). Table 5 represents which tire models truck with a particular carrying capacity uses from each of the mentioned brands and how much tires are required. This information will be necessary to make an approximate estimation of raw material feedstock.

Knowledge about the waste rubber tires available is essential to decide the size of the future facility as well as the type of disposal method. “Region 42” does not have data about tire models the company uses and in which quantity. Also, there is no precise information about amount and size of tires stored in the company’s warehouse or buried in strip mines. Therefore, in this project average values for truck tires composition, and weight will be used.

As can be noticed from

, tires for a truck with certain carrying capacity are almost the same in terms of weight and size. Taking this into account, the following mean tire's weight values will be used:

1. 794 kg (1750 lbs) for a truck with carrying capacity 55 tons.
2. 1860 kg (4100 lbs) for a truck with carrying capacity 120 tons.
3. 3874 kg (8540 lbs) for a truck with carrying capacity 220 tons.

Table 5. Tire model for trucks with a certain carrying capacity

№	Carrying capacity, ton	BeLAZ truck model	Number of tires	Model of tires	Bridgestone	Michelin	BELSHINA
1	55	7555A 7555B 7555D 7555E	6	24.00-35	VRLS E4 E2A TL 1. Weight, kg (lbs): 748.5 (1930) Diameter, m (inch): 2.2 (86.4) 2. Weight, kg (lbs): 875.4 (1930) Diameter, m (inch): 2.2 (86.4) 3. Weight, kg (lbs): 775.6 (1710) Diameter, m (inch): 2.16 (85.6)	XDT A E4T 1. Weight, kg (lbs): 748.5 (1650) Diameter, m (inch): 2 (81.18) 2. Weight, kg (lbs): 774 (1705) Diameter, m (inch): 2.16 (85.1) 3. Weight, kg (lbs): 839 (1850) Diameter, m (inch): 2.15 (84.9)	FBEL-150 E4 TL 1. Weight, kg (lbs): 743.9 (1640) Diameter, m (inch): 2.18 (86.6)

Table 5.cont.

№	Carrying capacity, ton	BeLAZ truck model	Number of tires	Model of tires	Bridgestone	Michelin	BELSHINA
1	55	7555A 7555B 7555D 7555E	6	24.00-35	Diameter, m (inch): 2.16 (85.6) 5. Weight, kg (lbs): 784.7 (1730) Diameter, m (inch): 2.1 (85.4)	Diameter, m (inch): 2.16 (85.1) 5. Weight, kg (lbs): 748 (1650) Diameter, m (inch): 2 (81.18)	FBEL-150 E4 TL 1. Weight, kg (lbs): 743.9 (1640) Diameter, m (inch): 2.18 (86.6)
2	120	7514 75141 75145	6	33.00-51	Weight, kg (lbs): 1723 (3800)	XDT B E4 TL 1. Diameter, m (inch): 3.0 (119)	FT116AM2 E4 TL 1. Weight, kg (lbs): 1995 (4400) Diameter, m (inch): 3.02 (119.8)
3	220	75302 75306	6	40.00R57; 46/90-57	VRDP E4 E2A 1. Weight, kg (lbs): 3874 (8540) Diameter, m (inch): 3.55 (140)	XDR2 B4 E4 TL 1. Diameter, m (inch): 3.55 (140.9)	

3.2 Technology analysis

In this chapter the advantages, disadvantages, and characteristics of the following techniques will be described: landfilling and dumping, retreading, grinding, and thermochemical conversion processes that involves incineration, hydrothermal liquefaction, gasification, and pyrolysis.

3.2.1 Stockpiling, landfilling and dumping into open areas

Landfilling is one of the least desirable options of managing scrap tires (ST) due to countless environmental and humans’ health problems. Even though the tire itself is not treated somehow this practice cannot be considered as environmentally neutral [9]. Although, this practice is unsustainable and is a waste of potentially valuable raw material, landfilling is straightforward to implement, easy to achieve and does not require any additional capital investment from a company. Stockpiling of waste truck tires (WTT) is even worse than landfilling because of necessity to build depots. Other than that, this practice is easy to achieve and cheaper option to deal with ST from capital investment perspective than techniques which will be discussed below. Together with stockpiling, landfilling and dumping are the current WTT managing techniques used by “SibTreidNK."

Another type of landfilling that can be used for WTT disposal is monofilling. This technique can be considered as more desirable one, as monofills could be used as tire collection sites and distribution centers in the future [9].

The implications of stockpiling, landfilling and dumping.

1. As already mentioned before, landfilling and stockpiling is a waste of potentially valuable raw materials [14]. WTT can be used as a construction material, chemical feedstock, and energy source due to the high energy density of 29-37 MJ per kg [15].

2. Tires are difficult to degrade. Preparation of the tire to be naturally destroyed takes more than 100 years. The complex chemical composition, construction features of tires, and vulcanization contribute to creating elastic and at the same time an extremely resistant product to abrasion and water, exposure to chemicals, heat, electricity, actions of microorganisms and the physical impacts. Each material constituent like carbon black, natural and synthetic rubbers, steel, fabrics, silica, various organic and inorganic compounds, curing compounds promote longer life and particular characteristics to the final product. The proportions of compounds might vary from one brand to another. The final quality and longevity of wear life of the product are correlated with the initial composition [16] [10].

3. As a result of the previous point, ST could occupy a large amount of land. Nearly 75 % of total tire volume is void space. The amount of space occupied during landfilling and stockpiling of the whole tires cannot be reduced due to relative incompressibility of tires. This characteristic is achieved during the vulcanization process, adhesion of the fabrics to the rubber and steel to the structural components of tires belts, and the total number of layers [10] [17]. According to the [17], the total number of fabric layers and steel bed wire in truck tires could be up to 40.

4. Waste tires are a suitable environment for pests, rodents, mosquitos, and other insects breeding that spread contagious and various diseases [10] [18]. The tires' shape and impermeability tend to hold water for long periods while providing an ideal

breeding environment. In addition, stockpiling could potentially introduce invasive species to the region if used tires are imported to the area from other countries. These new species could be more difficult to control and spread the non-usual disease for the particular area.[17]

5. Contamination of soil and water by leaching [19]. Even though tires are a slow degradable material, they are still degradable. The rate of leaching depends on the size of tires. More fine crumbed tires or metal pieces are more toxic than the whole tires due to the higher contact surface. Leaching of metals and other materials are eco-toxic for the environment. The compounds used in tire manufacturing are benzothiazole (BT) and BT derivatives as 3-methyl-1, 2-benzisothiazole, 2(3H)-benzothiazolone, 2-mercaptobenzothiazole, 2,2-dithiobisbenzothiazole, etc. also are commonly found in wastewaters derived from rubber additives manufacturing and in leaching at landfills. These compounds are poorly degradable, and some of them are toxic. In [20] authors showed that benzothiazole and 2-mercaptobenzothiazole (MBT) have toxic effects to fish and bacteria with other microorganisms respectively.

6. Potential of uncontrolled fire which is very difficult to extinguish due to high energy density of material (in some cases higher than coal) and 75% of void space in a whole waste tire which makes it difficult to cut off access to the air or to quench the fire with water [15][17]. The tire fire emits a dense smoke plume with an acrid and irritating odor, releases pyrolytic oil to the environment, hazardous emissions to the atmosphere which reflects the chemical composition of tires. As have been noticed in [15], during the landfill fire in Iowa City in 2002 when approximately 1.3 million WT were burned tires, the concentration of CO, CO_2, SO_2, particle number (PN), fine particulate (PM2.5) mass, elemental carbon (EC), and polycyclic aromatic hydrocarbons (PAH) were

significantly increased. In [15] authors also found out that PM2.5 from tire combustion could contain PAH with nitrogen heteroatoms and picene. Pollutions from tire burning are toxic, carcinogenic, and mutagenic; together, they present significant health hazards [15] [21]. The total amount of mutagenic emission from tire fire is up to 3-4 times bigger than from combustion of coal, oil, and wood in utility boilers [4]. The generalized process flowchart is shown in Figure 4. The diagram also includes environmental and economic flows for the process.

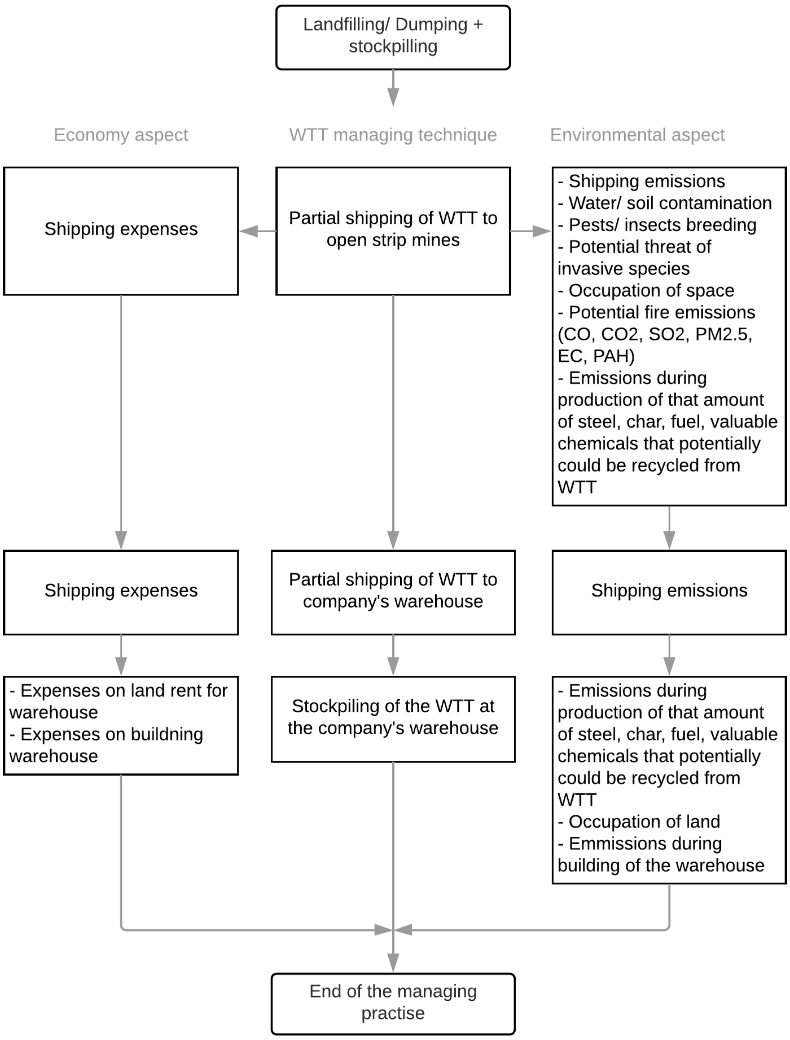

Figure 4. Flowchart of stockpiling/ dumping of WTT together with economic and pollution flows

3.2.2 Retreading and recovery

The process of replacement of the outer layer of the used tire with a new rubber layer by vulcanization is called retreading [10]. Retreading is a very efficient method to save energy on the production of a new tire. The amount of used energy is 2.3 times less to retread the used tire than to produce a new one. This technique is an efficient way to save resources on the production of the new tires, thereby cutting the worldwide tire manufacturing emissions. Installation of truck tires retreading equipment can significantly reduce the operating costs of the companies as truck tires can be retreaded three to four times [9][10].

Within the framework of this project, retreading as a separate technology is not described because it is already set up by the company. Therefore, the technology is not discussed in further detail. Retreading will be taken into account during the development of recycling facility model as essential part of the system that affects the flow of raw material, in our case the flow of WTT in the company.

3.2.3 Material recovery

3.2.3.1 Reuse of whole tires

Due to WTT physical characteristics they can be used as an artificial reef, playground equipment, erosion control, highway crash barriers, breakwaters and floatation, noise barriers, and bales [7], [8], [11], [16].

3.2.3.2 Grinding

As have been mentioned before, WTT are resistant to mildew, heat, moisture, sunlight, bacterial growth, oils, acids; ST have good elastic and impact-protected properties. All of these make WTT suitable for use in civil infrastructure projects [10], [16]. The reuse application of ground tires closely relates to the tire's particle size [17].

Rubber chips (pieces about 20-50 mm) are commonly used in drainage and insulation [16].

Rubber granules (particles of about 0.8-20 mm) are typically used in solid wheels, livestock mattresses, floor tiles, roofing materials, vibration, articles for road marking, asphalt, sports flooring, rubber asphalt, curbs, road barriers, and crash cushions [16].

Rubber powder (particles less than 0.8 mm) can be used as a compound to mix with virgin material. For instance in road construction, waterproofing agent, paint, spray, sports facilities, cables, automobile parts, etc. [16] The final physical quality of the produced rubber is significantly reduced in comparison with a virgin rubber [17].

WTT downsizing is a technologically sophisticated process. It requires specialized equipment which can shred and grid to a required size [11]. In conjunction the with grinding process, removing of the textile and steel is carried out. Pneumatic separators are used to remove textile from WTT, and the electromagnetic separator is necessary to remove steel [22].

The general scheme of ST downsizing consists of shredding, separation, granulation, and classification [23]. Also, in some cases before grinding to smaller particles, the tire should be cut into smaller pieces [23].

There are several different types of grinding:

1. Mechanical grinding.

The process takes place at ambient temperature [10]. Equipment includes shredder, mills, knife granulators, and rolling mills with ribbed rollers. The system is set up in a way that grinding will repeat till the necessary size of particles is obtained [24]. The minimum size of particles that one can get is 0.2 - 0.3 mm with very rough surface [23]. Steel and textile are taken out with separator and electromagnetic equipment respectively.

Disadvantages: temperature during the process could increase to 130 °C and can cause oxidation of the rubber particles. To prevent spontaneous combustion of the process line, additional cooling mechanism of the crumb rubber should be implemented [10], [11], [22].

2. Cryogenic grinding.

First, waste tires are cooled below its glass transition temperature to -80- (-100) °C in liquid nitrogen to get hard and relatively brittle "glassy" tires. Second, frozen waste tires are crushed down into small particles following which steel and textile are removed in the same way as in mechanical grinding. The final size of particles is less than 50 mm and with a smooth surface [10]. Cooling of the rubber up to -80°C reduces the energy needed for grinding. Additionally, the removed steel and fiber are "cleaner" in the cryogenic process due to the absence of oxidation and the surface/mass ratio [23]. Grains obtained in this method have a smooth surface and sharp edges [24].

Disadvantages: the use of liquid nitrogen makes operational cost very high. To reduce nitrogen consumption, the liquid nitrogen can be replaced with a compressor system [10]. Another disadvantage is the presence of moisture in particles and the necessity to dry them before the extraction of textile and steel [10], [11].

3. Wet grinding.

This process uses pre-shredded waste tires [10]. The rubber granulate obtained by this method is treated with stationary and moving grindstones [24]. Water is used to cool the product and the system. The final product is very fine rubber dust with the grain size of 10-20 μm, large specific grain area and with a low level of granulate degradation [10], [11]. Recycled rubber could be used as a filler to rubber mixtures where high quality of the end material is necessary, for instance in tire's manufacturer [24].

Disadvantages: this method requires shredding of tires before grinding and drying of final particles [11].

4. Water-jet grinding.

This method was developed to recycle highly resistant and large size tires [24]. Waste tires are shredded into narrow strips by the jet of water with high velocity and pressure (> 2000 bar) [10]. This process is environmentally-friendly, less energy intensive than other processes, has low noise pollutions, and does not generate other pollutants [10]. The final ground rubber is of a high degree of purity because only rubber is ground while steel banding is remaining unaffected [24].

Disadvantages: this method requires high pressure and trained personnel [10], [11].

5. Berstoff's method.

This method is considered as an improved version of mechanical grinding [24]. Waste tires are shredded by a rolling mill equipped with ribbed rollers and a twin-screw extruder. The process consists of three steps: 1) removing of the steel parts and cutting tires in a knife mill into 85×50 mm pieces; 2) further processing of the particles in ribbed rolling mills into 6 mm size pieces, additional removing the steel and textile cord from the particles; 3) further downsizing of the particles in twin-screw extruders [24]. The final particles are irregular-shaped, dust size, with a large specific area and low humidity [10].

The summary table of all popular grinding methods with a short description, advantages, and disadvantages is represented below (Table 6).

Table 6. General methods of waste tire downsizing [11]

Method	Description	Advantages	Disadvantages
Mechanical grinding	• Particles size: 0.2 - 0.3 mm with rough surface. • Repeating grinding with shredder, mills, knife granulators, and rolling mills with ribbed rollers.	• High surface area and volume ratio.	• Oxidation of the rubber particles. • Temperature could increase to 130 °C. • The necessity to introduce cooling mechanism into the system.
Cryogenic grinding	• Particles size: 50 mm with a smooth surface and sharp edges. • Tires are cooled down to a glass transition temperature and then crushed down into small particles.	• No surface oxidation of granulates. • Cleaner granulates.	• High operating costs. • Moisture in particles.
Wet grinding	• Particles size: 10-20 µm. • The rubber granulate is treated by mills with stationary and moving grindstones.	• High surface area and volume ratio. • Low granulate degradation.	• The necessity of pre-treatment. • Drying step of shredded tires.
Water-jet grinding	• Tires are shredded into narrow strips. • For large tires. • Use of high pressure (>2000 bar) and velocity water jet.	• Recycled rubber has high purity. • Environmentally safe. • Low noise pollution. • Low energy consumption.	• Requires high pressure. • Requires trained staff.
Berstoff's method	• Dust size particles. • Steel removing, first cutting. • Further downsizing of the particles in ribbed rolling mills. • Twin screw extruders.	• Low humidity content in particles. • Large specific area.	

3.2.3.3 Rubber reclaiming or devulcanization

In addition to reuse of whole WTT and grinding them, another common type of material recovery technology exists which is devulcanization and reclaiming [14]. Prior to the description of devulcanization and reclaiming, the brief outline of the vulcanization process is given below.

The vulcanization process is used to cross-link polymer chains that have been formed in the desired shape, in our case the shape of the tire, to get an elastic and at the same time a final product resistant to physical impacts. The most common material used in vulcanization is sulfur. Utilization of sulfur helps to create a bridge between large chains of the polymer, linking them together in a fixed pattern [17].

The necessity for reclaiming natural rubber was caused by the scarcity and price of the natural rubber. Any rubber products including ground tire rubber (GTR) can be used as a source for reclaiming and devulcanization [10]. Devulcanization and reclamation degrade the properties of GTR, therefore, the quality of devulcanized and reclaimed rubber, in general, is lower than of a virgin material [24], however, there are some advantages of using reclaimed and devulcanized rubber: lower energy consumption, lower heat generation, shorter mixing time, faster extrusion, and reduced variable costs [10].

Reclamation is decomposition of carbon-carbon bonds to reduce the total molecular weight and to achieve plasticity of the rubber. Devulcanization is breaking down of sulfur-sulfur and carbon-sulfur bonds of the three-dimensional structure formed during the vulcanization process. Scission of the main chain and crosslink bonds happens on the surface; therefore, the core remains three dimensional. The schematic picture of the process is shown in Figure 5 [11].

During the reactions, it is impossible to specify which bond you want to cleave, and always these two reactions occur simultaneously.

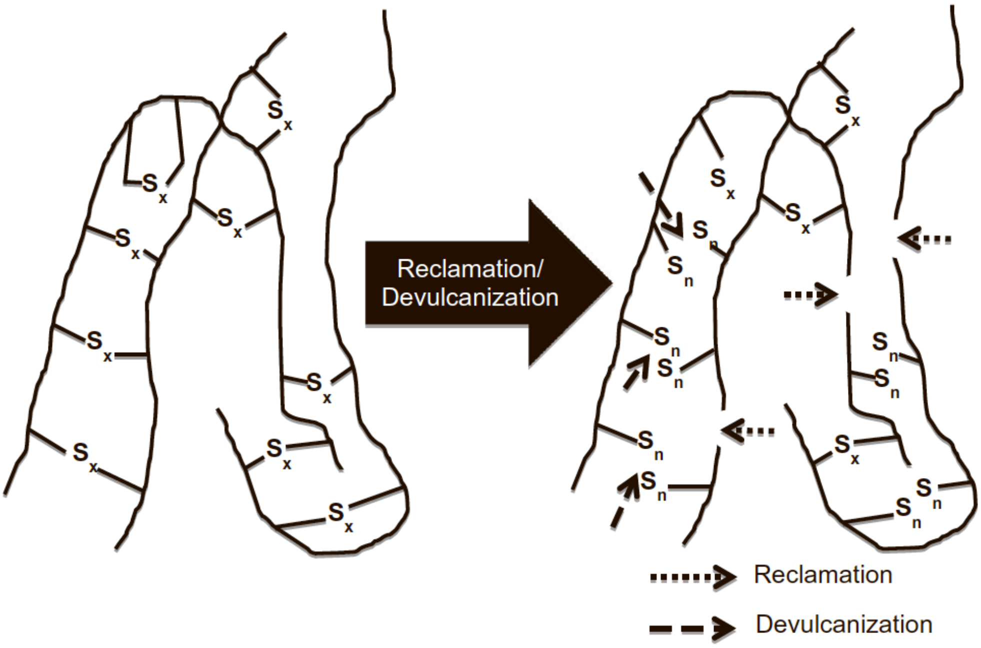

Figure 5. Schematic representation of reclamation and devulcanization

The energy needed for the reactions is shown in Table 7. As can be noticed from the table, the energy required for the reclamation is higher than for the vulcanization.

Table 7. The energy required for cleaving carbon and sulfur bonds [11] [23]

Type of bond	Energy required for cleavage (kJ/mol)
C-C (reclamation)	348
C-S-C (devulcanization)	273
C-S-S-C (devulcanization)	227
C-Sx-C (devulcanization)	251

In total there are four processes of reclaiming and devulcanization. All of them are shown in Figure 6 [11].

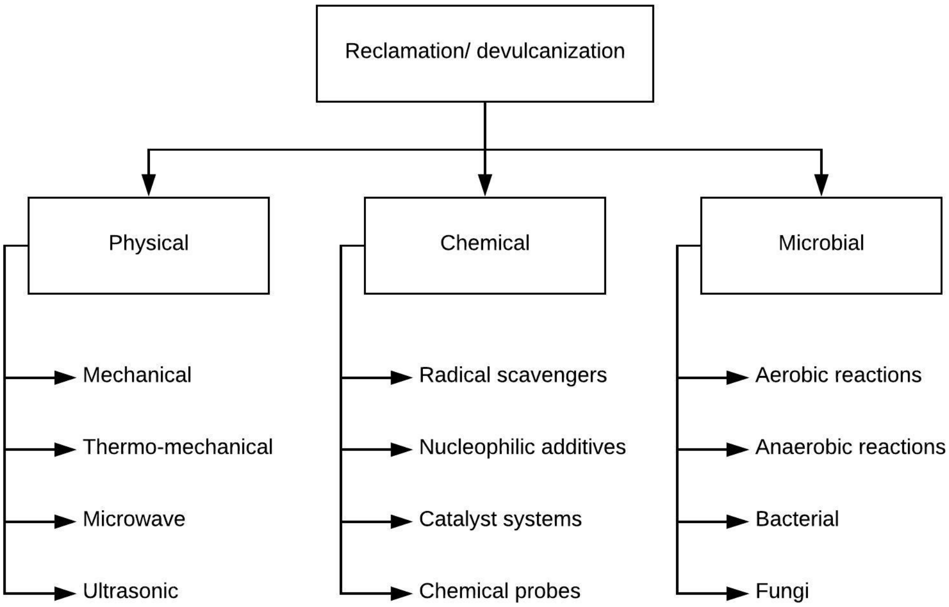

Figure 6. Overview of rubber reclaiming and devulcanization processes.

3.2.4 Thermochemical conversion processes and energy recovery

These processes are used to produce chemicals or to recover energy from WTT feedstock. Thermochemical conversion and energy recovery can be divided into combustion (incineration), hydrothermal liquefaction (HTL), pyrolysis and gasification [10].

3.2.4.1 Combustion (incineration)

Due to the high heating value of 32.6 MJ/kg, which is higher than coal (30 MJ/kg), waste tires could be used as a fuel in the incinerators, especially for high energy-consuming industries such as cement, and power generation.

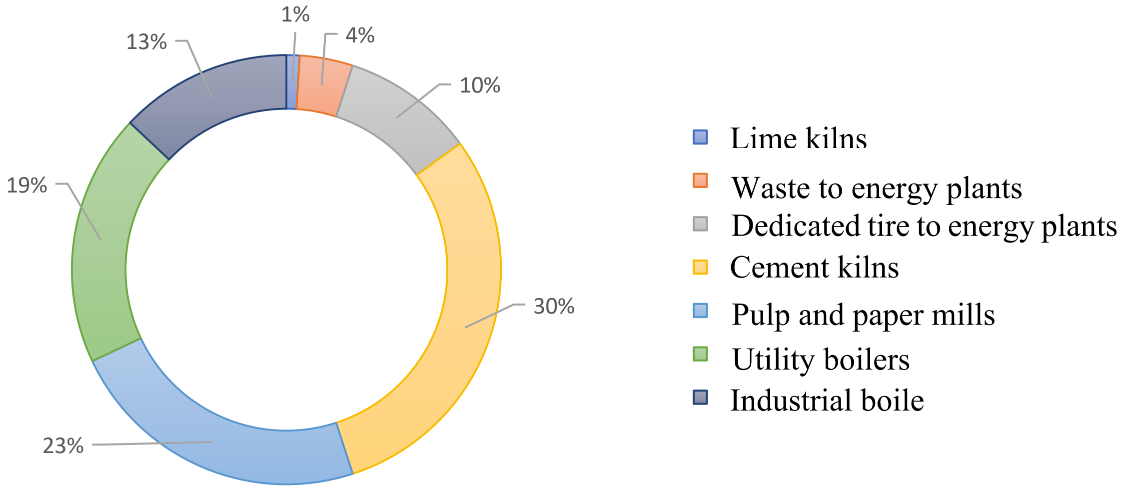

Figure 7. The market distribution of TDF (use of tires as a direct energy source) in the USA for the year 1996

In incineration, shredded tires as well as full-size tires can be used, for example in cement kilns [10], [11]. Use of the whole tire requires a temperature above 1200°C to ensure the complete combustion [11]. Besides the cement industry ST incineration can be used in industrial and utility boilers, lime kilns, pulp and paper mills, and waste-to-energy[25]. Figure 7 shows the use of tires as a direct energy source in the USA in 1996 [15].

The burning of tires instead of coal is more environmentally friendly, and it emits less pollutions [14]. Among disadvantages of waste tires combustion are a large capital investment, necessity for flue-gas cleaning, and relatively high operating cost [14]. Moreover, according to [24] energy recovery through scrap tires combustion is not the most desirable option because only 30-38% of the energy that was initially invested in the tire production could be recovered. In Table 8 the energy balance for different stages of tires’ life cycle is demonstrated.

Table 8. The energy needed at different stages of tires life cycle [24]

Stage of the life cycle	Amount of energy required
Amount of energy required to produce a tire	87-115 MJ/kg
Amount of energy required to produce rubber goods	80-90 MJ/kg
Amount of energy obtained from the combustion of tires	32 MJ/kg
Amount of energy needed to grind tires to grain size < 1.5 mm	1.8-4.3 MJ/kg

One option for waste tire incineration is co-combustion with coal, which not only helps to utilize scrap tires and recover energy stored in tires but also to reduce air pollution and increase the thermal efficiency of boilers and furnaces [10]. The co-firing of coal with tire rubber in [26] in a pilot plant with the total capacity of 80kW showed pollution reduction up to 80% including reduction of NOx.

Examples of co-incineration of coal and scrap tires.

1. South Africa. The total percentage of recycled rubber is about 6% [27].
2. The cement manufacturing company Pretoria Portland Cement Limited (PPC Ltd). Partial use of ST in their plant in De Hoek in the Western Cape (PPC Ltd, 2014) [27].

The relatively small use of ST in the co-combustion process creates the necessity to find other ways to utilize ST, conversion into high-value chemicals for instance.

3.2.4.2 Hydrothermal liquefaction (HTL)

The final product of HTL is bio-oil. The process is usually carried out at subcritical water conditions and high pressure around 200-300 bar [28]. The favorable feedstock is wet or lignocellulosic material [5]. The maximum amount of oil obtained during HTL of scrap tires using a stainless-steel batch reactor was 52.73 wt % with a heating value of approximately 45 MJ/kg at 400 °C [29].

Advantages:

1. There is no necessity to dry the feedstock before.
2. Relatively high yields of liquid fuel [10].

Disadvantages:

1. Poor quality of final oil for transportation compared to diesel. The fuel can be improved by application of upgrading technologies such as separation, hydrogenation/hydrotreating, catalytic cracking, and hybrid processes.
2. The process requires expensive equipment because of high pressure [10].
3. Even though in [29] was shown that scrap tires could be effectively converted into liquid fuel in sub- and supercritical water without catalysts, a limited number of research in this area makes it high risk for implementation on a real project like "Region 42” [10].

3.2.4.3 Gasification

Gasification is reduced air combustion of carbonaceous materials into a mixture of combustible gases called syngas (CH4, C2 H6, H2, CO, CO2, O2), tar, chars. Gasification is not a common technology to deal with scrap tires, and therefore just a few studies have been done using scrap tires gasification [10]. Reactors that can be used in gasification are fixed bed, fluidized bed, and entrained bed reactors. In general, yield increases with increasing the process temperature. The quality and amount of syngas depend on other parameters of the process. Among these parameters are the equivalence ratio (ER), tire feed rate, feedstock properties, particle size, type of oxidizer, gasifier, and steam/ tire ration [10].

In Table 9 some examples of different gasification technologies to recycle ST are demonstrated.

Table 9. Gasification conditions and products

Gasifier type	Initial conditions	Results
Fluidized bed reactor	Particles size: 3 mm diameter and 5 mm length. Temperature: 900–1060 K with steam.	The increase in the temperature caused an increase in gas yield and decrease of syngas heating value — the highest gas yield among other reactors. Heating value (HV) range: 39.6 to 22.2 MJ/m3. Yield range: 0.21 to 0.76 m3/ kg [30].
	Particles size: tire powder with diameters 0.4, 0.9, and 2.1 mm. Temperature range: 350-900°C.	Operational parameters of the reactor and particle size the most important parameters to increase the gas yield. HV of syngas was 6MJ/m3 under the highest yield rate of 11 m3/h. Products: gas mainly contained CO, H2, CH4, C2H6, and longer chain hydrocarbon. Char yield: 24-37%. Oil yield: 0-37% [31].
	Particles size: 0.3 mm. Temperature range: 400-800°C. Equivalence ratio (ER): 0.2–0.6	The yield of syngas and heating value increased with temperature increase and ER increase. Gas yield at 700°C was 5.5% higher when ER value was increased from 0.2 to 0.6, and the amount of carbon black decreased from 600 to 450 g/kg.

Table 9. cont.

Gasifier type	Initial conditions	Results
Fluidized bed reactor	Particles size: 0.3 mm. Temperature range: 400-800°C. Equivalence ratio (ER): 0.2–0.6	The yield of carbon black decreased with the increase of temperature or ER. The most suitable conditions for tire gasification: ER – 0.2-0.4; temperature – 650-700 °C. In this case, yield was 1.8–3.7 Nm3/kg, HV was 4000–9000 kJ/Nm3 [32].
	Particles size: 2 mm in diameter. Bottom heater temperature: 790 and 820 °C. Top heater temperature: 720 and 740 °C.	The heating value of the syngas depends on the agent one use during the process. The HV air/CO2, air/steam and steam agents were 9.59, 7.34 and 15.21 MJ/Nm3, respectively.[33]
	Particles size: 0.25-1.2 mm Sample weight: 0.3 – 2.0 g Temperature range: 850-1000°C. CO2 pressure range: 0.3-1.0 atm.	The reaction is independent of char sizes less than 0.65 mm and mass less than 1.0g. [34]
	Particle size: 2 mm.	Syngas had high H2, CH4 and C2H6 content [35].
Thermobalance reactor	Particle size: 1–2 cm from cold mechanical grinding	Increasing of ER increased CO and H2 content in syngas [36]

Table 9. cont.

Gasifier type	Initial conditions	Results
Thermobalance reactor	Mass flow rate: 3 kg/ hour. Temperature: 850 °C.	
Rotary Kiln	Particle size: 2 mm.	Syngas had high H2, CH4 and C2H6 content [35].
	Particle size: 1–2 cm from cold mechanical grinding Mass flow rate: 3 kg/ hour. Temperature: 850 °C.	Increasing of ER increased CO and H2 content in syngas [36]

3.2.4.4 Pyrolysis

According to [14], pyrolysis has a promising future compared to other available recycling options. It is also considered as an environmentally friendly process of ST recycling [37]. Pyrolysis is the process of decomposing the rubber component in the presence of heat and the absence of oxygen [11]. Pyrolysis breaks down the scrap tires into liquid products, solid products, and gas [38]. The generalized scheme of the pyrolysis process is shown in Figure 8.

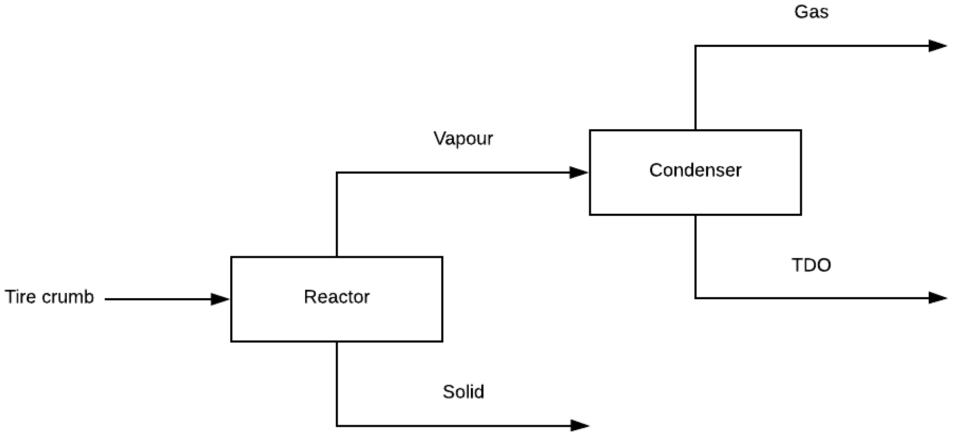

Figure 8. Generalized scheme of pyrolysis

Pyrolysis gas

Pyrolysis gas or pyrogas is the gas remaining after liquid recovery [27] [39]. Pyrogas is generally composed of paraffin and olefin compounds with carbon from one to four [39][40]. The most typical compounds are methane (CH4), ethane (C2H6), ethene(C2H4), propane(C3H8), propene(C3H6), butane (C4H10), butenes (C4H8) and butadiene(C4H6), low concentrations of sulfur(H2S, SO2, COS,CS2), nitrogen (NH3), and some CO, CO2 [41]. The calorific value of the gas might vary from 29.9 to 42.1 MJ/m3 [27] to very high (68-84 MJ/m3) [41]. Such a big difference in calorific values can be explained by the presence of heavier hydrocarbons in the number of experiments. The calorific value of the gas depends on pyrolysis conditions and the initial feedstock [27]. Pyrogas is mostly used as fuel to provide the heat for the pyrolysis [40].

Pyrolytic liquid

The liquid product or tire derived oil (TDO) is a complex mixture consisting of complex organic compounds with carbon from 5 to 20. TDO is a dark brown colored product similar to petroleum fractions, has a sulfur/aromatic smell due to the presence of sulfur-containing compounds and high medium viscosity [41]. The relative proportions of aromatics and aliphatic compounds depends on pyrolytic conditions, including temperature, pressure, volatile residence time, and the quality of rubber particulates [39]. The calorific value of the TDO in general is higher than the calorific value of waste tire itself and the value is around 42 - 44MJ/kg depending on tire composition and pyrolysis conditions [12] [39] [41].

The boiling point of the TDO is in range 50°C to above 350°C. TDO can be used as a fuel if it is blended in small proportions with diesel in order not to affect the performance of the engine and not to increase total pollution level. Due to the high content of sulfur and high viscosity the TDO should be upgraded before use. Pure TDO can be used only in diesel engines that can work with the fuel of less quality or/and have less stringent pollution regulation, such as, stationary engines and marine propulsion engines [5].

Solid products

The composition and characteristics of the pyrolytic char also depends on pyrolysis conditions and the composition of tires [39]. According to [2], the amount of pyrolytic char varies from 22 to 49 wt.%, with a typical range of 38-40 wt.%.There are two main components of pyrolytic char: the inorganic matter of the tire (ash, zinc oxide, steel, silicates, etc.) and the non-volatile carbon black added during tire manufacture.

The carbon content in char is up to 90 wt.%. The ash content is in a range between 8.27 and 15.33 wt.% due to additives during tire manufacturing and dirt material found with the WT [2]. Also, pyrolytic char from WT is rich in sulphur (1.9 – 2.7 wt.%) resulting from use of sulphur in vulcanization process [2]. In general recycled and recovered char from WT can be used in production of activated carbon, as a reinforcing filler for low-value rubber goods, as a filler in road pavement, as a printing ink pigment or blended with bitumen in order to improve its rheological properties [39].

As has been mentioned earlier, the quality of char depends on pyrolytic conditions. In [39] the author mentioned that only vacuum pyrolysis gives char with similar concentration of carbon as in virgin carbon black and the quality of char also can be compared to commercial of the N300 series.

It is worthwhile to mention that pyrolytic char is a heterogeneous material regarding to particle size, impurities, absorption properties, structure and both surface chemistry and activity because of use various carbon black grades during tire's manufacturing. The pyrolysis process itself also changes the initial characteristics of the virgin rubber. Most of the time, use of pure pyrolytic char in manufacturing without further upgrading is impossible [39].

Higher value products from waste tire pyrolysis

Chemicals from tire pyrolysis oil

There is limited direct use of TDO due to its low quality making the selling price of TDO low. Also, the process of recycling might be not economically viable. Due to these reasons, further processing of TDO and its use as a chemical feedstock is considered as a more favorable option [2] [42].

In [2] the author showed that TDO composition could be very complex with a wide range of different chemicals in it. The total number of compound in oil can be up to 132 [43], with the concentration of the most compounds generally less than 1%. However, the concentrations of valuable chemicals such as, benzene, toluene, xylenes or BTX, styrene and limonene are in significant amount.

The possible application of each of these chemicals is shown in Table 10.

Table 10. TDO compounds and its possible further application [2]

Name of the compound	Possible application
Benzene	Production of derivatives such as ethylbenzene, cyclohexane and cumene which are used for the production of plastics, resins, fibres, surfactants, dyestuffs and pharmaceuticals
Toluene	
Xylenes	Plastics industry – production of plasticisers, polyester resins and fibres and for use in the dyes and pigments industries.
Styrene	Production of plastic materials and is also used to make synthetic rubber and other polymers
Limonene	Production of industrial solvents, resins and adhesives and for the production of fragrances and flavourings

The yields of chemicals mentioned in Table 10 depend on reactor design, pyrolysis conditions, and raw material. Different studies used different brands and types of tires. Tables 11 -Table 13 show the yields of valuable chemicals, such as benzene, toluene, xylenes, styrene, and limonene from different literature sources.

The demand for BTX, especially for xylene, is constantly growing due to its use in plastic/polymer industry [44]. According to the studies, the concentration of dipentene (or limonene) for low temperatures pyrolysis is predominant [44] [3].

Dipentene consists of d- and l-limonene. Dipentene is a monoterpene which is a dimer of two isoprene units. Dipentene can be obtained from polyisoprene tire content which in its term can be natural or synthetic. Limonene is very unstable in high temperatures. The common yield of limonene for low temperatures pyrolysis is in a range 2.5-5 wt.% on the steel-free tire basis and can be as high as 27.97% (Tables 11 -Table 13). D-limonene has an orange smell, l-limonene smells like pine. Limonene has wide industrial application and the current constantly growing demand for it is mainly supplied by citrus-derived limonene [3] [45]. Islam in his works [46], [47]showed that amount of obtained limonene from WTT is highest among other types of tires.

Further details concerning economic aspect of limonene or other valuable chemicals production will be discussed in chapter dedicated to economic analysis.

Table 11. Dipentene yields from truck tires in different literature sources. CSBR, conical spouted bed reactor; FR, feeding rate; HR, heating rate; p, pressure; MBR, moving bed reactor; SBR, sliding blade reactor; SS, sample size; T, temperature; TDO, tire-derived oil; XBR, fixed bed reactor; XBR-FT, fixed bed reactor with fire tubes.

Ref.	Particle size	FR (kg/h) SS (kg)	Reactor type	T (ºC)	HR (ºC min $^{-1}$)	P (kPa)	Carrier gas	Flow (L/min)	TDO (wt.%))	Dipentene (wt. %)
[48]	2000 mm^3	1	XBR, 15 L	500	15	1	-	-	62.2	5.0
	2000 mm^3	1	XBR, 15 L	500	15	6	-	-	61.7	4.2
[4]	<3800 mm^3	42	MBR, 850 L	500	Fast	13	-	-	56.5	1.6
	<3800 mm^3	25	MBR, 850 L	540	Fast	10	-	-	40.9	0.8
	<3800 mm^3	33	MBR, 850 L	451	Fast	12	-	-	53.7	3.6
	<3800 mm^3	0.2	XBR, 1 L	480	Not mentioned	1	-	-	60.0	3.3
	<3800 mm^3	0.2	XBR, 1 L	440	Not mentioned	1	-	-	43.4	3.3
	<3800 mm^3	0.2	XBR, 1 L	480	Not mentioned	1	-	-	Not mentioned	2.8

Table 11. cont.

Ref.	Particle size	FR (kg/h) SS (kg)	Reactor type	T (ºC)	HR (ºC min $^{-1}$)	P (kPa)	Carrier gas	Flow (L/min)	TDO (wt.%))	Dipentene (wt. %)
[12]	1.5-2 mm	0.13	XBR, 0.6 L	650	7	101	N2	0.025	56	16.12
[49]	<10 mm	0.18	CSBR	425	Fast	101	N2	9.5	62.8	12.75
	<10 mm	0.18	CSBR	500	Fast	101	N2	9.5	60.9	11.00
	<10 mm	0.18	CSBR	600	Fast	101	N2	9.5	54.9	0.95
[38]	4000 mm ^{3}	0.75	XBR-FT, 2.1 L	475	Fast	101	N2	8	55.0	27.97
[12]		1.5-2.0	XBR, 2.1 L	650		101	N2	25	56	28.78

Table 12. Yield of valuable chemicals in pyrolysis process

Name of the compound	Yield from tire feed (wt.%)					
	Source - [43]. Raw material - commercial car tire (Firestone 155R13, F-570).			Source - [40]. Conical spouted bed reactor. Raw material is not specified.		
	500 ºC	600 ºC	700 ºC	Thermal pyrolysis, 500 ºC	HZSM-5 Catalyst, 500 ºC	HY Catalyst, 500 ºC
Benzene	0.98	0.52	0.29	0.21	3.64	0.39
Toluene	4.4	2.81	2.09	0.78	7.39	1.04
Xylenes	3.48	2.05	1.49	1.23	9.00	2.09
Styrene	2.45	1.94	1.44	2.17	0.82	0.17
Limonene	5.12	3.19	3.29	26.8	8.34	3.86

Table 13. Yield of valuable chemicals in pyrolysis process (continue)

Name of the compound	Yield from tire feed (wt.%)				
	Source - [44]. Spouted bed reactor. Raw material is steel-free rubber crumb, brand is unknown.			Source - [4]. Used car and truck tires. Vacuum and in a continuous feed reactor.	Source - [50]. The pilot-scale pyrolysis of scrap tires in rotary kiln reactor.
	425 ºC	500 ºC	600 ºC	480 ºC	500 ºC
Benzene	0.14	0.27	0.76		2.09
Toluene	0.74	1.51	2.5		7.24
Xylenes	1.27	1.53	2.11		2.13
Styrene	4.49	6.08	4.22		
Limonene	20.4	10.29	0.94	3.6	5.44

Hydrogen from waste tires

Another way to use TDO is to produce hydrogen from it. In [51] the author showed that 1 kg of steel and fiber-free crumb tire can be converted into 0.158 kg of hydrogen. The amount of obtained hydrogen is higher than the amount of hydrogen originally present in the tire due to the additional hydrogen from the water gas shift reaction of steam. The generalized scheme of the process is represented below (Figure 9). Also, in [52] the authors investigated the correlation between rubber type using in tire manufacturing and amount of hydrogen produced from it. Although, hydrogen production from WT is an interesting way to supply the possible future hydrogen infrastructure, for now this process is not economically feasible [51] and therefore will not be considered in this study further.

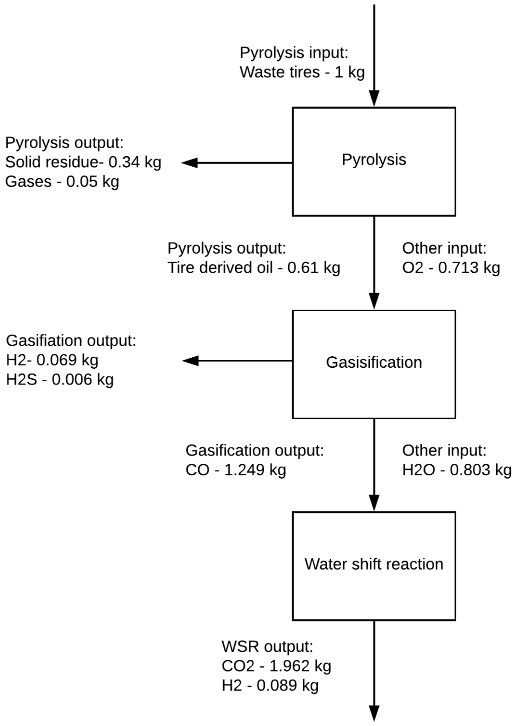

Figure 9. Mass balance for the hydrogen production process from WT

Pyrolysis conditions

In [53] the author mentioned that the main characteristics that influence the pyrolysis of WT and the by-product of the process are temperature, pressure, residence time and heating rate.

Pressure

The pyrolysis of WTT in different literature sources was carried out at pressures from 1 kPa to normal atmospheric pressure 101 kPa (). Lopez in [42] investigated the pyrolysis of tire material free of steel, carcass, and textiles under vacuum (25 and 50 kPa) and atmospheric pressure at 425°C and 500°C. He discovered that the reduction of pressure leads to an increase in the yield of tar with C_{11}^{+} and reduction of C_5^{+} - C_{10}^{+} (both aromatics and aliphatic compounds) fraction and slight increase of gas yield. The amount of char in vacuum has not changed [44] while the quality of char, mainly composed of carbon black, is higher. Zhang in [54] showed that despite the high ash content CB under pyrolytic conditions has a surface area close to commercial, CB used in tire manufacturing. Also, Roy noticed in [48] that oil yield under vacuum condition is higher than under atmospheric conditions and when the amount of limonene has been increased. All of these can be explained as the residence time of volatiles in vacuum is shorter and the occurrence of secondary reactions is limited, but still can appear [39]. As result, the formation of carbonaceous deposits on the surface of the char are minimized, thereby improving the surface area and increasing the number of active sites. From the limonene perspective, lower vacuum pyrolysis temperatures and faster removal of volatiles from the reaction zone prevent the secondary cracking reaction which degrades limonene by so increasing the limonene content in the TDO. However, Lopez in his works [42] showed that pyrolysis under close to vacuum conditions (25-50kPa) actually decreased the total limonene yield.

Temperature

The reactor temperature is an important parameter. The optimum temperature for WT pyrolysis in atmospheric pressure to achieve total conversion of the tire is 500ºC [39]. Yield, heating value, and compounds of pyrolytic gas are sensitive to thermal cracking. When the temperature increases the secondary reaction such as thermal cracking occurs which leads to decrease of long chain hydrocarbons in favor of lighter hydrocarbon $C_1 – C_4$ and H_2 in the gas fraction. The heating value of the gas fraction decreases when the temperature increases due to the decreasing concentration of heavy hydrocarbons. The gas HV might drop from 50 to 36 MJ/m^3 [39]. Simultaneously, the total yield of gas fraction is increasing with higher temperature as a consequence of cracking reaction [39].

According to [44], an increase of pyrolysis temperature does not have an important effect on the yield of adulterated carbon black in the 400 – 600°C. In [41] the authors reported a decrease of solid fracture with increase of temperature from 300 – 500°C and almost equivalent solid yield at 500-700°C even when they elongated the reaction time. Gonzalez [53] also noticed that the solid fracture in his experiment was rapidly decreasing from 350°C to 500°C, and was relatively stable at temperatures in the range of 500-700°C. Simultaneously, the ash content was increasing from 350°C to 500°C while the volatiles content was decreasing at the same temperature range. Both ash content and volatiles content reached their equilibrium at temperatures 500-700°C.

A decrease of solid yield with temperature also mentioned by Martinez in [39]. Authors explained this as at 500°C tire decomposition is complete while at lower temperatures one can observe heterogonous structure of rubber tire made of SBR, BR, and NR.

Ucar in his experiments on WTT showed that the ash content and fixed carbon content did not change at temperature from 550°C to 800°C. The ash content was 13.5-14.8 wt.% and fixed carbon content equaled 82.4 – 84.3 wt.%. The total solid fraction was about 33.2-33.8 wt.% [12].

As Martinez mentioned in [39] the occurrence of secondary cracking reactions promotes a decrease of liquid fraction, or TDO. It means an increase of gas yield resulting in a decrease of oil yield. This correlation between the increase of gas and decrease of oil yield with temperature increase is mentioned by Gonzalez in his research [53] when the oil yield decreased from 55.2% at 450°C to 36.6% at 700°C while the gas fraction increased from 4.5% at 450°C to 26.7% at 700°C. The same trend was observed by Choi in his paper [55]. The author pyrolyzed steel and fiber free waste tire rubber (WTR) in a fixed bed reactor. He showed that with temperature increase from 500°C to 800°C the char yield remained fairly constant (about 37 wt.%), liquid yield decreased from 38.29 wt.% to 29.78 wt.%, and gas yield increased from 22.59 wt.% to 30.08 wt.%. Choi also pointed at that not only the amount of liquid fraction changed but also the composition. The concentration of the aliphatic fraction decreased from 15.1 wt.% to 6.1 wt.%, whereas the aromatic fraction increased from 65.3 wt.% to 79.3. wt.% with temperature increase. The explanation for this phenomenon is that temperatures higher than 600°C favors formation of aromatics and as a consequence it causes the decomposition of aliphatic compounds, including limonene.

At the same time in [12] Ucar, did not notice a relationship between temperature changes and oil/gas yields fluctuations. In his case the liquid yield from WTT was 55.1-56.0 wt.% and gas yield was 7.6 – 8.8 wt.% with a temperature change from 550°C to 800°C. However, in his research he mentioned that it is more common in other works to find such relationship as decrease in TDO yield and increase of gas yield with increase of temperature.

The effect of temperature change on oil from WTT is represented below in Table 14Table 15.

Table 14. Liquid fraction from pyrolysis of WTT under different temperatures [12]

Temperature, °C	550	650	800
Reaction products, wt.%			
Gas	7.6±2.8	7.6±2.4	8.8±2.7
Oil	55.6±1.3	56.0±1.8	55.1±2.0
Water	3.0±0.5	2.6±1.1	2.9±0.9
Carbon black	33.8±2.8	33.8±2.8	33.2±2.7
Effect of temperature on the hydrocarbon types in the pyrolytic oils, vol.%			
Tempereature, °C	550	650	800
Aroamtics	15.41	15.29	15.22
Paraffins	64.12	64.31	64.45
Olefins	20.47	20.40	20.33

Table 15. Effect on reactor operating temperature on the product yields [47]

Temperature, °C	375	425	475	525	575
Reaction products, wt.%					
Gas	7.5±1.0	8.0±1.1	9.0±1.6	12.5±1.5	18.0±2.0
Oil	47.5±3	53.0±2.2	55.0±1.5	52.21±2.1	47±3.0
Solid char	45.0±2.0	39.0±2.6	36.0±1.8	35.5±1.6	35.0±1.5

Temperature also affects the share of valuable chemicals in pyrolytic oils. Limonene, for instance, is very unstable at temperature above 500°C and breaks down into trimethylbenzene, m-cymene and indane [4].

Volatile residence time

Volatile residence time is connected with carrier gas flow rate and reactor type [39]. According to Martinez, an increase of carrier gas flow rate causes the decrease of volatile residence time due to the faster removal of volatiles and vice versa. Longer volatile residence time favors the secondary cracking reactions which in its turn can increase the gas fraction at the expanse of the oil fraction [56]. Pakdel in [4] said that with a high reactor temperature (above 450°C) or/and long residence time the limonene will degrade via secondary reaction.

Heating rate

According to Martinez [39] heating rate is one of the key pyrolysis variables that determines the temperature profile within the particles and reaction rate. The increase of the heating rate leads to higher pyrolysis temperature, increase degradation rate and encourages secondary reactions which in its turn enhances the gas yield at the expense of liquid yield [39]. In order to minimize secondary reactions at a higher heating rate, the residence time should be decreased. This means that higher heating rate can be used for limonene production but faster removal of primary volatiles is important in order to avoid secondary reactions. The effect of heating rate on limonene yield was also described in [3], Danon mentioned that the highest limonene yield was obtained with the lower heating rate.

According to the information in the chapter, pyrolysis and grinding are the most applicable technologies. Considering the desire of the company to look closer at the conversion of WTT into oil, gas, and char, pyrolysis process was chosen to recycle scrap tires.

CHAPTER IV: PROCESS DEVELOPMENT

Overview

The design basis for the project is shown below in Table 16 and discussed further in this chapter. The initial conditions include a description of the raw material used in the research, a tire feed rate of the future facility, the main product of the recycling process, mode of the operation, and plant location.

Table 16. The design basis

Parameter	Value	Motivation
Raw material	Truck tire. Steel content – 15-25% (base case – 20%)	Average steel content in waste truck tires
Tire feed rate	30 ton per day	Flow rate for commercial recycle facility. In [46] Islam mentioned that small private recycling facilities are typically in a range from 26 ton/day to 30 ton/day. In this study, 30 ton/day was used.
Main product	Technical grade limonene	Valuable chemical with the highest price. Amount of limonene from STT is the highest among other types of tires [46], [47]. Due to the market standard of technical limonene, the purity of limonene should be 95%[45].

Table 16.cont.

Parameter	Value	Motivation
Mode of operation, operating hours	24-hour continuous 8000 hours/ year.	In [57] Sinnott and Towler mentioned that continuous plants usually have 90-95% availability which approximately 7884 – 8332 hours per year. In the framework of the study I used 8000 hours/year as a nominal value.
Plant location	Close to the company	All trucks of the company once in a while come back to a company's maintenance facility. These trucks could provide a constant flow of a raw material for the recycling facility and at the same time eliminate logistics cost associated with a delivery of raw material.

Raw materials and production capacity

The raw material for the process in this study is scrap truck tires (STT) with steel content of 20% wt.%. All tires are assumed to be supplied from the company's warehouses or delivered by the trucks from the strip mines with which the company works. For a simplification of the future model and inability to gather the data about composition and amount of particular tire of a specific brand, the average value for steel content in TT was used for this study. The steel content of 15 wt.% to 27 wt.% is commonly used in literature for waste truck tires studies and conceptual processes [2], [6], [13]. In this model 20 wt.% steel content is used as the average value.

A feed rate of tires in the study equals 30 ton/day which is the average value for the feed rate among other studies. Islam [46] made a comparative techno-economic assessment for three different sizes of the plant: medium commercial scale (144 tons/day), small commercial scale (36 tons/day), and pilot scale (3.6 tons/day). He noticed that the most feasible facility was of a medium commercial scale. Also, Islam mentioned in his article [46] that there a number of researches used a feed rate of 24-30 ton/day in their works. A flow rate of 30 tons/day was also used in the economic analysis for a scrap tires recycling facility by Pilusa in [58] and by Mulaudzi in [27]. 30 ton/day was chosen as the initial scrap truck tires feed rate for their work to ensure sustainability and to perform a realistic economic feasibility evaluation. The significant volume of published research for a small commercial plant allowed validation of the economic model.

The company does not track number of waste tires they have at their warehouse. Therefore, scrap truck tires feed rate of 30 tons/day for the next 10-15 years would be more feasible and realistic for the private company than 100-140 tons/day.

Main product

Recovery of valuable chemicals makes the pyrolysis process more economically feasible, as the price of valuable chemicals is usually higher than the price of raw tire derived oil. Technical grade limonene of 95% purity is the targeted product from the pyrolysis of waste truck tires as this level of purity complies with market requirements [45]. Limonene concentration in pyrolytic oil derived from truck tires is the highest among other types of tires due to the significant content of natural rubber in the raw material [38]. A yield of limonene from truck tires ranges from 0.8 wt.% to 28.78 wt.% on the steel-free basis [2]. In this research, it was assumed that the yield of limonene is

5 wt.% on the steel free basis. Other targeted products that can be sold include steel, pyrolytic char, and tire-derived oil.

Operation time

The plant operating time was adopted from [57]. Towler mentioned that continuous processes are usually more economical due to less labor and operating costs compared to the batch processes. Operation time for continuous processes is assumed to be 24 hours a day, 7 days a week, throughout the year. However, because of the necessity to carry out maintenance work and/or catalyst regeneration, the operating time for the continuous process is 90-95% of the available hours per year, or the total operating time of 7884 to 8322 hours per year. A common design basis would assume 8000 working hours per year [57].

Plant location

In this study, the possible location of the plant is a company property or nearby. This location would allow the future recycling facility to have continuous access to the raw material due to several reasons. First, all of the company's trucks are going through maintenance in the territory of the company. Trucks can bring tires that were dumped into strip mines on the way back to the company. Secondly, there is a truck tire stockpile near the territory of the company that creates an extra flow of raw material without extra costs.

Structure of the recycling process

A simplified input-output scheme of pyrolysis is shown in Figure 10.

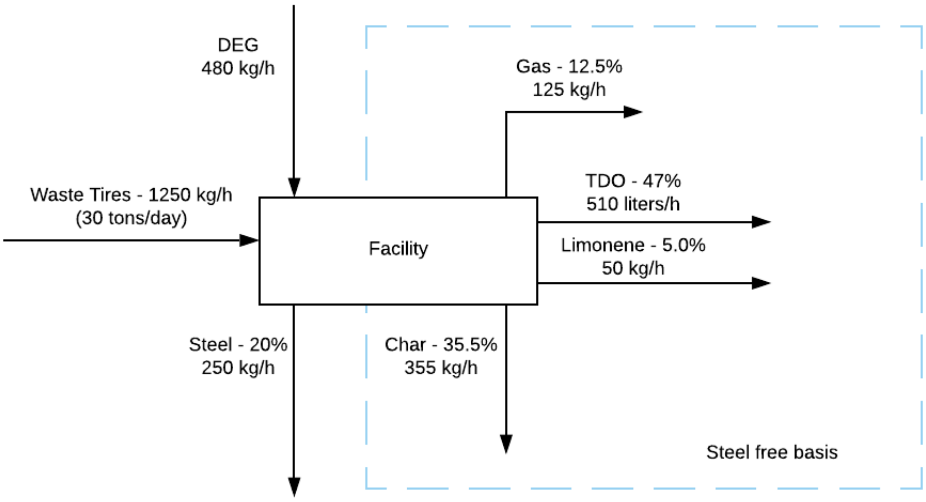

Figure 10. Input-output structure of the scrap truck tires

Compounds that make up the feed and the by-products of the process at various stages were adopted from Islam [57], Danon [3], and Mulaudzi [27]. Islam work was used as the base for the by-products values distribution. The amount of TDO, gas, and char were chosen from [57] for pyrolysis process at 525°C for scrap truck tires and equaled 52 wt.%, 12.5 wt.%, and 35.5 wt.% respectively on the steel-free basis. The limonene yield criterion was adopted from Danon [3] (). In [3] the yield of limonene from STT varies from 0.8wt.% to 28.78 wt.%. For this particular study, the limonene rate production of 5.0 wt.% (or almost 10% of total TDO) was chosen for the initial calculations.

Studies by Mulaudzi [27] and Ngwetjana [59] were used as the base literature sources to develop a recycling process itself and for the further estimation of pre-treatment process, pyrolysis, and limonene recovery. Figure 11 shows the final process flow diagram (PFD) for recycling of waste tires to limonene made by Mulaudzi in [27].

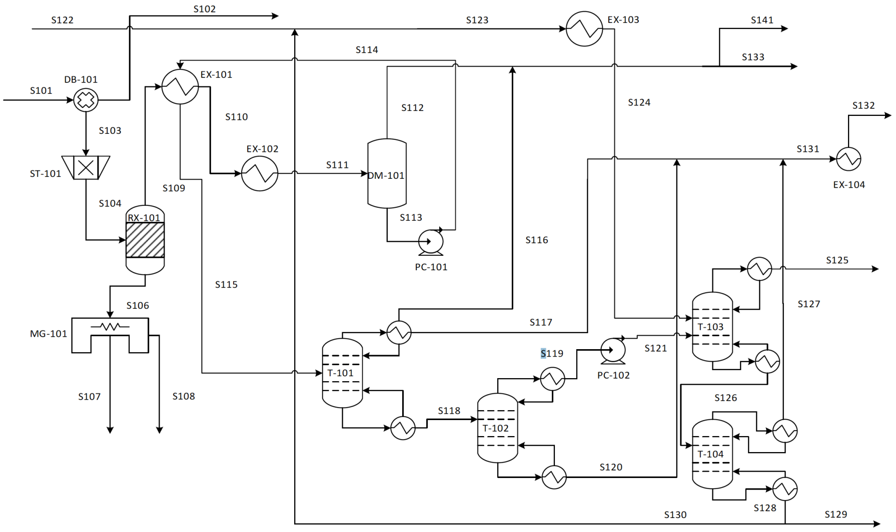

Figure 11. Process flow diagram for recycling of waste truck tires into limonene [27]

Table 17 shows all streams of the waste tires recycling process into limonene in Figure 11. Streams S112, S116, S133-134, S136-140 belong to the energy recovery system in Figure 12. The energy recovery system also was adopted from the research by Mulaudzi [27].

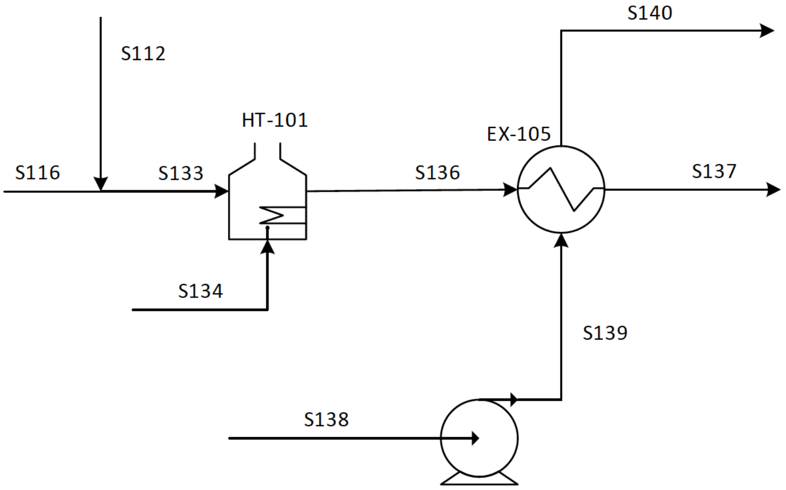

Figure 12. Energy recovery system for waste tires recycling into limonene process [27]

Table 17. Stream names of waste truck tires recycling into limonene [27]

Stream name	Description	Stream name	Description
S101	Tire feed	S123	Hot DEG feed
S102	Bed wire steel	S124	Cool DEG feed
S103	Whole tires	S125	Limonene product
S104	Tire chips	S126	DEG-rich stream
S105	Pyrolysis reactor product	S127	Aromatics product
S106	Char and steel	S128	DEG product
S107	Char product	S129	DEG purge
S108	Steel	S130	DEG recycle
S109	Reactor volatiles	S131	Hot TDO product
S110	Slightly cooled volatile product	S130	Cool TDO product
S111	Condensed volatiles	S131	Flue gas to RX-101
S112	Pyrolysis gas	S132	Cool TDO product
S113	Pressured pyrolysis oil	S133	Fuel gas to RX-101

Table 17.cont.

Stream name	Description	Stream name	Description
S114	Pressured pyrolysis oil	S134	Combustion air
S115	Warm pyrolysis oil feed	S135	Hot flue gas
S116	T-101 vapor distillate	S136	Hot flue gas
S117	T-101 liquid distillate	S137	Flue gas discharge
S118	T-101 bottom product	S138	Boiler feed water
S119	Limonene-rich stream	S139	Pressurized boiler feed water
S120	T-102 bottom product	S140	High pressure steam
S121	Pressurized limonene-rich stream	S141	Flue gas to flare
S122	DEG make-up		

Table 18 shows what kind of equipment the recycling and energy recovery systems use [27].

Table 18. Equipment

Equipment name	Description	Equipment name	Description
DB-101	Tire de-beader	EX-105	Steam generator
ST-101	Tire shredder	DM-101	Volatiles condenser knockout drum
RX-101	Pyrolysis reactor	PC-101	Lights remover feed pump
MG-101	Magnetic separator	PC-102	Limonene column feed pump
EX-000	Tube side of EX-101	PC-103	Boiler feed water pump
EX-001	RX-101 heating	T-101	Light hydrocarbon remover
EX-002	EX-105 shell side	T-102	Limonene-rich cut purifier
EX-101	T-101 feed preheater	T-103	Limonene recovery column

Table 18. Cont.

Equipment name	Description	Equipment name	Description
EX-102	Reactor volatiles condenser	T-104	DEG regeneration column
EX-103	DEG cooler	HT-101	RX-101 combustion chamber
EX-104	TDP cooler		

Pre-treatment system

The pre-treatment system consists of tire de-beader (DB-101) and tire shredder (ST-101). A tire de-beader is necessary to extract the reinforcement high tensile steel (stream S102) which will be later sold as a by-product of the recycling process. Free of reinforcement steel WTT then go to the tire shredder. Tire chips stream (S104) then flows to the pyrolysis reactor (RX-101).

Pre-treatment of the tire is the most energy consuming process in recycling. The total energy consumption during tire grinding can reach up to 83% of the complete overall process requirements. The most power consuming process in tire pretreatment is shredding. Tire's shredding accounts for almost 86% of total energy use in the pre-treatment process [27],[58].

Pyrolysis system

The pyrolysis system consists of the pyrolysis reactor (RX-101), a magnetic separator (MG-101), feed preheater (EX-101), reactor volatiles condenser (EX-102), volatiles condenser knockout drum (DM-101). The final streams of the pyrolysis system are char product (S107), steel (S108), pyrolysis gas (S112), and pyrolysis oil (S113). Values for char (S107), steel (S102+S108), gas (S112), and oil (S113) are 355 kg/h, 250 kg/h, 125 kg/h, and 520 kg/h respectively [38] (Table 19).

Table 19. Stream table for pyrolysis and pre-treatment processes [27]

Stream number	S101	S102+S108	S107	S112	S113
Mass flow (kg/h)	1250	250	355	125	520

The reactor operating conditions were adopted from Islam [57]. Islam conducted his research for the temperature in the range from 375°C to 575°C. A temperature of 525°C, was chosen for this work, as this represents the temperature when the total conversion of WT occurs. The temperature favors limonene production [39] at a pressure of 100 kPa (atmospheric pressure). The total energy used for the pyrolytic reactor accounts for 70-73% (approximately 468-544 kW for pyrolysis of 30 ton/day) of the total energy needed for a pyrolysis process [27], [60].

The truck tire chips after the shredder go to a pyrolysis reactor where they are transformed into volatiles (stream S109) and a solid product (stream S106). When the pyrolysis process is completed the magnetic separator (MG-101) divides solids (S106) into steel (S108) and char (S107). Volatiles stream (S109) flows to a volatiles condenser knockout drum (DM-101) where separation into pyrolytic gas (S112) and pyrolytic oil (S113) occurs.

Separation system

The purpose of the separation system is to recover valuable chemicals out of raw TDO. The valuable chemical for this study is limonene of 95%-99% purity as this is the quality of market standard. The system was adopted from Mulaudzi study [27]. The separation system consists of 4 distillation columns (T-101-104), pump (PC-102), and heat exchangers (EX-103,104). The main streams of the recovery system are warm pyrolysis oil feed (S115), DEG make-up (S122), DEG recycle (S130), limonene product (S125), cool TDO product (S132), DEG purge (S129).

Distillation column T-101

T-101 removes compounds lighter than a limonene-rich fraction. Distillation column T-101 operates in atmospheric pressure. The input to T-101 is pre-heated oil stream S115. The output of T-101 is bottom product stream or limonene-rich fraction (S118) and two distillate streams which are vapor (S116) and liquid distillates (S117) [27]. Vapor distillate stream (S116) flows to the heat recovery where it combines with pyrolysis gas stream (S112). The blue rectangle in Figure 13 demonstrates the joining of S112 and S116. The liquid distillate stream (S117) combines with output streams from distillation columns T-102 (S120) and T-104 (S127). The two orange rectangles in Figure 13 show the location of streams' connections. Limonene rich-fraction or T-101 bottom products (S118) goes to further limonene enrichment in distillation column T-102. The concertation of limonene in S118 is 10%.

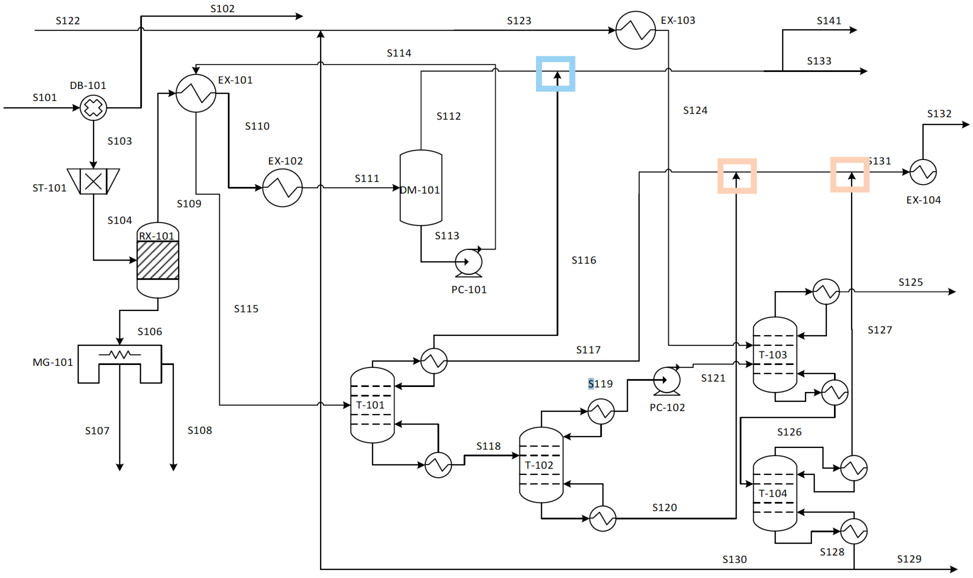

Figure 13. Junction of gas by-products S112 and S116; junction of liquid by-products S117, S120, and S127

Distillation column T-102

T-102 is a packed distillation column that removes compounds heavier than limonene. T-102 operates under atmospheric pressure with 50 Pa pressure drop at each stage. The input to T-102 is bottom products from T-101. The output of the column T-102 is bottom stream S120 and limonene-rich fraction (S119).

Stream S120 combines with liquid distillate from T-101 and T-104 to make final hot TDO stream (S131). Limonene- rich fraction S119 has an approximate concentration of limonene about 39%. After the column T-102, S119 is pressurized in limonene column feed pump (PC-102) and flows to the final limonene recovery column T-103.

Distillation column T-103

Distillation column T-103 is also a packed column with 50 Pa pressure drop per stage. The inputs of T-103 are a pressurized limonene-rich stream (S121) and cool DEG stream (S124). The outputs of the system are 95% limonene product (S125) at a rate of 50 kg/h and a solvent rich stream or a DEG-rich stream (S126). Limonene can be sold as a by-product. DEG-rich stream after the column T-103 flows to the column T-104 (Figure 11).

Distillation column T-104

Distillation column T-104 regenerates DEG used in limonene production by filtering entrained impurities in the DEG-rich stream (S126). The input to the T-104 is a solvent-rich stream (S126). The output of the T-104 is aromatics products (S127) and DEG product (S128). The distillate aromatics products (S127) combine with liquid distillate products from T-101 (S117) and T-102 (S120) into hot TDO product (S131). The combined hot TDO product stream goes to the TDO cooler (EX-104) where it is cooled. The final cool TDO stream (S132) at a rate of 510 liters/h and a temperature of 35°C can be sold as a by-product.

Recovered DEG product (S128) is separated into DEG recycle (S130) and DEG purge (S129) streams. The total DEG purge stream (S129) accounts for 1% of the solvent stream. The recycled solvent or DEG recycle stream (S130) after the separation combines solvent make-up stream (S122) and forms hot DEG stream (S123). Hot solvent stream (S123) in its turn flows to the solvent cooler (EX-103) where it is cooled down to 100°C and forms cool DEG feed stream (S124) that later is going to be used in the final stage of limonene recovery.

Mulaudzi in his research [27] showed that the minimum number of stages to achieve 95% limonene purity with the lowest annualized cost is 50. The total flow of solvent diethylene glycol (DEG) is 460-500 kg/h when the total number of stages is 50 or above. In the framework of this study, 480 kg/h is used.

Table 20 shows the final characteristics of the distillation column for this study adopted from [27].

Table 20. Parameters of the distillation columns [27]

	Value			
Parameter	T-101	T-102	T-103	T-104
Number of stages	65	50	50	10
Reflux ratio	2.3	5	1	1.73
Feed stage	38	24	-	5
Oil feed stage	-	-	30	-
DEG feed stage	-	-	2	-

Table 21 summarizes the power requirement for the equipment in the system.

Table 21. The power requirement of the equipment [27]

Equipment name	Power requirements
DB-101 tire de-beader	11 kW
RX-101	544 kW = 73% of the total heat required
ST-101 tire shredder	95 kW = 89% of power needed for pre-treatment

Table 21. cont.

Equipment name	Power requirements
T-101 distillate condenser	91 kW = 63% of the cooling requirements for all 4-columns or 42% of the whole separation system
T-101 reboiler	103 kW of heat input from high-pressure steam = 51% of steam requirements in the separation section
T-102 distillate condenser	36 kW
T-102 reboiler	37 kW. Low heat requirements because input stream S118 is already of a high temperature of approximately 200°C.
T-103 distillate condenser	2 kW = 2% of total cooling requirements for 4 columns
T-103 reboiler	29 kW = 14% of the total steam usage in the separation system
T-104 distillate condenser	13 kW = 6% of the cooling requirements for all 4-columns or 3% of the overall cooling requirements
T-104 reboiler	31 kW = 16% of the steam usage or 4% of the overall steam requirements
EX-000	19 kW
EX-101	19 kW which is provided by contact with the hot reactor volatiles
EX-102	235 kW = 100% requirements for pyrolysis cooling or 52% of the total cooling requirements

Table 21. cont.

Equipment name	Power requirements
EX-103	42 kW = 19% of the cooling requirements for the separation system or 9% of the overall cooling requirements. The energy usage is so high because the recycled DEG stream (S130) has a temperature of approximately 240°C when the solvent has to be 100°C for proper extraction in T-103
EX-104	28 kW to cool down hot TDO product stream (S131) = 13% of cooling requirements in the separation system or 6% of the overall cooling process

Table 22 demonstrates the total power requirements for different processes and the system itself.

Table 22. Summary of power requirement [27]

Name	Power requirement
Cooling requirement for four distillation columns	145 kW
Cooling requirements for the separation system	217 kW
Cooling requirements for the whole system	467 kW
Heat needed for the separation system	201 kW
Heat needed for the pyrolysis process	544 kW
Heat needed for the system in total	775 kW

Energy recovery system

In various works dedicated to pyrolysis the most common way to use pyrolytic gas is to use it for a reactor heating while the excess gas is burned. The idea of an energy recovery system (Figure 12) is to generate steam using the pyrolytic gas left after the reactor heating requirements. The input to the energy recovery system is the rest of the fuel gas to the reactor RX-101 (S133) and combustion air (S134). The output of the system is flue gas discharge and high-pressure steam (S140) that might be sold as high-pressure steam. The final decision on the implementation of the energy recovery system is made in the economic analysis section.

CHAPTER V: ECONOMIC ANALYSIS

Overview

An economic analysis of the future recycling facility follows the algorithm presented below (Figure 14).

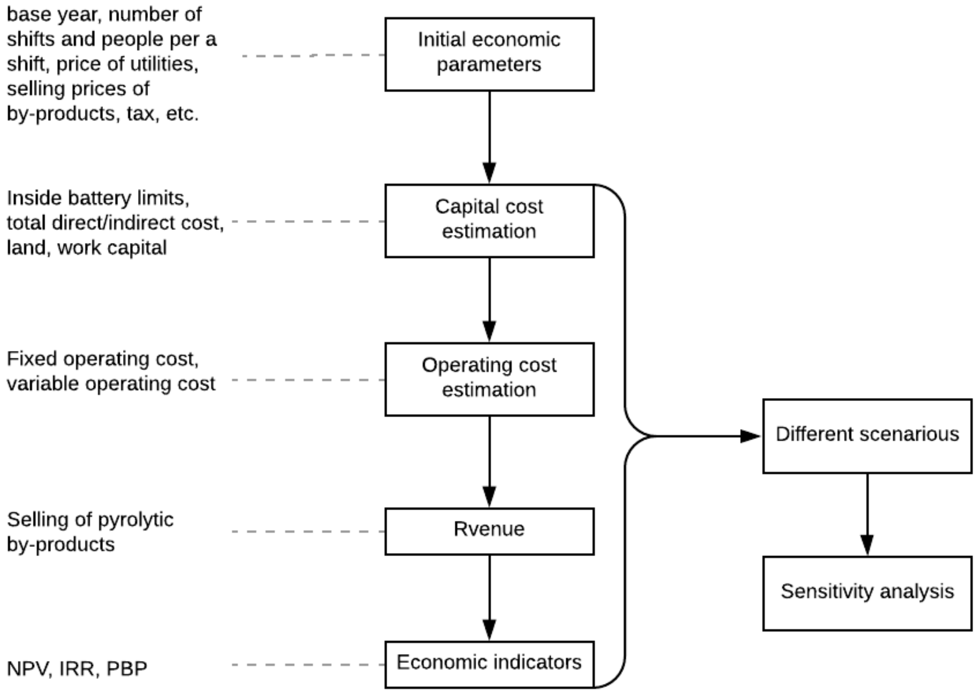

Figure 14. Algorithm for the estimation of economics for recycling facility

All components of the algorithms are discussed in the respective subsections. Each of the subsections represents an important step in the overall process of the economic evaluation.

Initial economic parameters

Discounted cash flow rate of return (DCFRR) method is used to make an economic analysis in this research [61], [62] as it considers the effect of time and gives a more precise idea about the profitability of the project. Key economic indicators used for DCFRR are payback period, internal rate of return, and net present value.

Net present value (NPV) is a cumulative discounted cash position at the end of the project. At the end of each year of a project lifetime, the cash flow is discounted at a specific discount rate and summed up [61].

$$NPV = -P_{init} + \sum_{year=1}^{lifetime} \frac{P_{ann}}{(1+i)^{year}}, \quad 1$$

where P_{init} is a total capital investment, P_{ann} is a cumulative effect of annuity.

Payback period (PBP) shows the minimum time necessary to recover the original capital investment in the form of cash flow [63]. Shorter PBP is better, especially for such a high-risk project as a recycling facility where the payout period should not exceed 2-4 years [61]. PBP can be calculated using equation 2 [64].

$$PBP = (year - 1) + \frac{|NPV_{year-1}|}{(NPV_{year} - NPV_{year-1})} \quad 2$$

The internal rate of return (IRR) is a discount rate at which net present value equals zero. Optimum IRR value depends on the maturity of a technology. For example, IRR of 12% is for a mature technology and up to 40% for very new technology [61]. In this study, optimal value for IRR starts from 25%.

The base year for all calculations is 2018. Adjustment of all costs of a different year was made by using the Chemical Engineering plant cost index (CEPCI) [65] [61] (equation 3).

$$Corrected\ Equipment\ cost = old\ equipment\ cost * \frac{2018\ cost\ Index\ Value}{old\ index\ value} \quad 3$$

The average annual CEPCI in 2018 was 603.1 (www.chemengonline.com).

In cases when the equipment should be adjusted in size, the exponential scaling was applied (equation 4).

$$Scale-up\ equipment\ cost = base\ cost * \left(\frac{Scale-up\ capacity}{Base\ capacity}\right)^{n}, \quad 4$$

where n is a scaling exponent that typically belongs to the range of 0.6 to 0.7 [27], [66].

A possible lifetime of the future chemical facility was adopted from [61] and equaled 10,12, and 15 years. The initial calculation is done for the shortest lifetime to get an idea about the least optimistic result. The operation time of the facility equals 8000 hours/year [57]. Straight-line depreciation over 10 years is used in calculations with zero salvage value of the pyrolysis equipment at the last year [61], [62]. The project is fully financed by the company itself; no loans have been considered in the calculations. The conversion rate of R65/1USD is used where it is necessary. The currency value was obtained from the Central Bank of Russia (2018).

Capital cost estimation

According to [63], the capital cost estimation may vary from a predesign estimation to a very detailed estimation which includes all specifications and complete drawings of all systems. In total there are five different levels of accuracy:

1) Order of magnitude (OOM). Used by project managers to estimate a future project at the very beginning when information is limited, and everything can change. Accuracy is about ±30%. OOM estimation uses historical project data with analogous mathematics [63].

2) Study estimate. Accuracy is about ±30%. SE uses knowledge of major items of equipment such as pumps, compressors, columns, and vessels, etc. [63]. Equipment is roughly sized to satisfy the chosen capacity of the future facility.
3) Preliminary estimate. Accuracy is ±20% [63].

These first three levels of accuracy are significant for the further consideration of the project [63]. The following two levels of estimation are used for a more detailed evaluation

4) Definitive estimate. Accuracy is ±10%. Estimation is based on almost complete data, but still, there is no explicit specification and drawings [63].
5) Detailed estimate. Accuracy is ±5%. Estimation is based on complete engineering drawing, specifications, survey, and other information that is available about the project [63].

In this study, OOM and study accuracies are used for a capital cost estimation. Muluadzi used the same accuracy in his research for economic evaluation of scrap tires pyrolysis in South Africa [27] and by Wright for economic analysis of biomass fast pyrolysis [67].

Seider in [62] mentioned that total capital investment or TCI of a chemical facility is a one-time expense for the design, construction, and startup of a new plant or modification/modernization of an existing one. Formula 5 shows how to calculate TCI.

$$TCI = TFCI + land + working\ capital \qquad 5$$

where TFCI is a total fixed capital cost, land is a price of land, and working capital is the working capital of the company.

In [66] Dutta calculated total fixed capital cost or TFCI as a sum of total direct cost (TDC) and total indirect cost (TIC) (equation 6).

$$TFCI = TDC + TIC \tag{6}$$

Total direct cost is a sum of all installed equipment in the main manufacturing process also called installed battery limits (ISBL) and other direct costs such as a warehouse, site development, and additional piping (equation 7) [66].

$$TDC = ISBL + other\ direct\ cost \tag{7}$$

Other direct costs can be calculated as a percentage of ISBL [66]. The whole warehouse, site development, and additional piping expenses are 4%, 10%, and 4.5% of ISBL (equations 8-10).

$$warehouse = 4\% * ISBL \tag{8}$$

$$site\ development = 10\% * ISBL \tag{9}$$

$$additional\ piping = 4.5\% * ISBL \tag{10}$$

shows all components used in the calculation of the inside battery limits for a base scenario of WTT recycling into limonene. ISBL includes necessary pre-treatment equipment, pyrolysis system, separation system. Prices of the machines were adopted from the study of Mulaudzi [27]. CEPCI of 2016 is 556.8. Installed costs of heat exchangers, pumps, drums, and columns Mulaudzi calculated in [27] using Aspen Plus® Economic Analyzer.

The installed cost of the pre-treatment system and pyrolysis reactor were calculated using formula 11 [66].

$$Installed\ cost = f_{installation} * Purchased\ cost, \tag{11}$$

where $f_{installation}$ is an installation factor that equals 3.02 and 3.0 for pre-treatment system and pyrolysis reactor respectively [68].

Mulaudzi obtained the purchased cost of pre-treatment equipment from Jiangyin Xinda Machinery (2016) and for pyrolysis reactor he used Pyrocrat Systems LLP (2016). I adjusted the prices of the equipment using formula 3 and chemical engineering plant cost indexes for 2016 and 2018 for all pieces of equipment used in the process (Table 23) [27].

Table 23. Individual equipment cost

Equipment item	Installation factor	Total scaled installed cost in 2016	Total scaled installed cost in 2018
Pre-treatment system			
Single hook de-beader	3.02	24,160	26,169
Tire conveyor	3.02	14,496	15,701
Tire shredder	3.02	157,644	170,753
Tire chip conveyor	3.02	10,872	11,776
		Total:	224,399
Reactor system			
Pyrolysis reactor	3.00	1,159,909	1,256,359
Magnetic separator	3.00	96,000	103,983
Reactor volatile condenser	6.3	86,764	93,979
Volatiles condenser knockout drum	6.9	108,455	117,473
		Total:	1,571,794
Separation			
Lights remover feed pump	7.00	26,108	28,279

Table 23. cont.

Equipment item	Installation factor	Total scaled installed cost in 2016	Total scaled installed cost in 2018
Limonene column feed pump	7.2	26,991	29,235
T-101 reflux pump	6.3	26,598	28,809
T-102 reflux pump	6.5	27,482	29,767
T-103 reflux pump	6.5	27,482	29,767
T-104 reflux pump	6.5	27,482	29,767
T-101 feed preheater	6.1	55,258	59,852
DEG cooler	5.3	53,688	58,152
HFO cooler	7.4	78,617	85,154
T-101 condenser	6.7	80,090	86,749
T-102 condenser	5.7	52,412	56,770
T-103 condenser	5.9	7,253	7,856
T-104 condenser	4.8	16,592	17,971
T-101 reboiler	4.3	78,323	84,835
T-102 reboiler	4.3	70,078	75,905
T-103 reboiler	5.4	64,975	70,377
T-104 reboiler	3.7	73,710	79,839
T-101 condenser accumulator	6.3	97,658	105,778
T-102 condenser accumulator	6.9	106,492	115,347
T-103 condenser accumulator	6.9	106,492	115,347
T-104 condenser accumulator	6.9	106,492	115,347

Table 23. cont.

Equipment item	Installation factor	Total scaled installed cost in 2016	Total scaled installed cost in 2018
Light hydrocarbon remover	7.8	318,310	344,7785
Limonene-rich cut purifier	7.8	255,331	276,562
Limonene column	7.8	255,331	276,562
DEG regeneration column	8.2	76,087	82,413
		Total:	2,291,218
		Total for three blocks:	4,087,411

Table 24. ISBL of the base scenario

Equipment item	Installed cost, MM$	Percentage of total ISBL, %
Pre-treatment system	0.23	5.6
Reactor system	1.36	33.3
Heat exchangers	0.29	7.1
Pumps	0.057	1.4
Drums	0.12	2.9
Columns	2.02	49.5
Total:	4.08	100

As can be seen from Table 24, the most significant contribution to the total ISBL belongs to distillation columns used in the separation process (approximately 50%) and to the pyrolytic reactor (34%).

According to [27], installed cost of the distillation columns includes not only the price of columns itself, but also associated with columns equipment such as condensers, reboilers, reflux pumps, and condenser accumulators. The power requirement of the associated equipment is shown in Table 21.

Table 25 shows calculated results for the additional components of total direct cost such as site-development, extra piping, and warehouse.

Table 25. Other direct costs

Component	Percentage of ISBL, %	Installed cost, MM$
Site-development	10	0.41
Additional piping	4.5	0.184
Warehouse	4	0.163
Total other direct costs:		0.76
Total direct costs:		4.84

Summing the results from Table 25, the total direct cost for the base scenario is 4.84 MM$.

Total direct cost is used to calculate the total indirect cost (TIC). TIC represents a non-constructional cost. Total indirect costs represent expenses on such services as management and engineering, procurement, and construction (EPC) services [66]. TIC includes five components which are prorated expenses, home office and construction fees, field expenses, project contingency, and other costs. Each of these components is calculated as a percentage of the total direct cost. Table 26 shows what portion of total direct cost is used to calculate each of the five parts. The total indirect cost is 2.9 MM$ (Table 26).

Table 26. Total indirect cost

Component	Percentage of ISBL, %	Cost, MM$
Prorated expenses	10	0.48
Home office and construction fees	20	0.97
Field expenses	10	0.48
Project contingency	10	0.48
Other costs (start-up and permits)	10	0.48
Total indirect cost:	60	2.9

The total indirect cost and the total direct cost are then used to find total fixed capital investment (TFCI). Formula 6 shows the way how to find TFCI. Total fixed capital investment equals approximately 7.73 MM$.

Working capital (WC) and land expenses can be calculated as a percentage of TFCI (formulas 12-13) [62],[68]. WC and land expenses can be recovered at the end of the project lifetime.

$$Working\ capital = 2\%\ * total\ fixed\ capital\ investment \tag{12}$$

$$Land = 5\%\ * total\ fixed\ capital\ investment \tag{13}$$

Table 27. WC and land expenses

Component	Percentage of TFCI, %	Cost, MM$
Working capital	2	0.15
Land	10	0.39
Total working capital and land	12	0.54
Total capital investment		8.3

Using formula 5 and summarizing working capital, land expenses, and the total fixed capital investment, the total capital investment for the base scenario is 8.3 MM$.

Operating cost estimation

In [61] Turton defines operating costs (OC) as the costs associated with the day-to-day operation of a chemical facility and maintenance of the facility [66]. Wright mentioned in [67] that there are two types of operating costs: variable operating costs (VOC) and fixed operating costs (FOC). The VOC relates to the production rate, whereas FOC is irrespective to the production rate or in our case recycling rate.

The total operating cost can be calculated as

$$operating\ cost = variable\ oerating\ cost + fixed\ operating\ cost \tag{14}$$

Fixed operating cost

Dutta showed in [66] that fixed operating costs include employee salaries and benefits, overhead, plant maintenance costs, insurance, and taxes (formula 15). The value of fixed operating costs does not depend on whether a facility works at full producing capacity or not.

$$\begin{gathered} FIC = salary + supervisory + maintanence + \\ + operating\ supply + lab\ charges + \ insurance \end{gathered} \tag{15}$$

Salary

A number of people working at the facility was adopted from [27]. Muluadzi mentioned in his study that an operational pyrolysis facility could provide work for 20 people by having 5 shifts with 4 people per shift. Generally, in Russia the number of shifts per day equals 3 and each of them is 8-hour shift. However, Seider mentioned that 5 shifts are necessary to consider leave, sick leave, and working hours [62]. The cost of operating labor in this study is obtained as the average salary of the plant operator from russia.trud.com (2018) and equals 80,000 RUB per month.

Direct supervisory

Peters and Timmerhaus in [63] emphasized that a direct supervisory is always required. A number of people depends on the total number of operating labors. The total expenses for the supervisory are no more than 15% of total operating labor expense.

Maintenance and repair

Another important fixed operating cost is maintenance. Maintenance is necessary to keep the facility in efficient operating conditions. The expense includes the cost for labor, materials, and supervision.

Annual expenses for the maintenance are in the range from 2% of the equipment costs or TFCI and up to 20% in case of severe operating conditions [63]. In [68] James used 3% of TFCI for the pyrolysis facility to estimate maintenance. The same number of 3% is used in the current research. Possible expenses were adopted from [63] and equal 3% of TFCI.

Operating supply

Among FIC Peters and Timmerhaus in [63] also emphasized operating supply costs that cannot be considered as a raw material but still essential for the process. Operating supply costs is 15% of the total maintenance and repair cost and include items such as charts, lubricants, test chemicals, custodial supplies, and similar supplies.

Laboratory Charges

Laboratory charges allow to regularly check the quality of the pyrolytic by-product. The possible value of the laboratory charges is in a range of 10% to 20% of the total operating labor. In the framework of my study, the average number of 15% was used [63].

Property insurance and tax

The total amount that should be paid for the property insurance and tax was obtained from [68]. The percentage for property insurance and tax is 0.7% of the TFCI.

Table 28 shows different components of the fixed operating costs.

Table 28. Fixed operating costs

Component	Value, $/year
Operating labor (OL)	80,000 RUB per month ≈ 14,770 $/year per one operator
Supervisory	15% of the total OL
Maintenance and repair	6% of the TFCI
Operating supply	15% of maintenance and repair
Laboratory charges	15% of the total OL
Property insurance and tax	0.7% of the TFCI

Table 29 shows the actual FIC for the recycling WTT facility where the largest share belongs to the maintenance and repair (48%) and to the operating labor (30%).

Table 29. Actual fixed operating costs for the recycling facility

Component	Total cost, \$/year	Percentage of total FOC, %
Operating labor (OL)	295,400	30
Supervisory	44,310	5
Maintenance and repair	463,800	48
Operating supply	69,750	6
Laboratory charges	44,310	5
Property insurance and tax	54,110	6
Total fixed operating cost:	971,499	100

Variable operating cost

The variable operating costs (VOC) in the framework of this study include the total price of utilities needed for the pyrolysis, separation, and shredding processes, and the total cost of the solvent (diethylene glycol) necessary for the separation process. The price of WTT transportation is zero as the company's trucks on the way to the maintenance facility can bring WTT. Trucks provide a constant flow of the raw material to the future recycling facility for free.

In calculations, I considered the following utilities: cooling water, steam, electricity, and boiler feed water for energy recovery (formula 16). Prices of utilities were adopted from the business tariffs (tarify-zhkh.ru) for Kemerovo region.

$$VOC = utilities + DEG \quad 16$$

Table 30 shows the unit cost of each utility.

Table 30. Unit cost of utilities and DEG

Utility	Unit	Unit price, $
Cooling water	m^3	18.38 RUB*1.2 ≈ 0.34$
Boiling water	Ton	88.41 RUB*1.2 ≈ 1.63$
HP steam	Ton	12.1$
Electricity	kWh	2.21RUB*1.2 ≈ 0.041
DEG	Kg	130 RUB ≈ 2$

Table 31 shows the annual cost of each utility for the base case scenario.

Table 31. Annual cost of variable expenses for base case scenario

Utility	Total number of units per year	Total cost, $/year	Percentage of total VOC, %
Cooling water	206,900 m^3/year	70,346	24
Boiling water	-	-	-
HP steam	2,062 tons/year	24,950	9
Electricity	1,064,480 kWh	43,644	15
DEG	480+2%*480*8,000=77,280 kg/year	154,560	53
Total variable operating cost:		293,500	100

The total operating cost is 1,264,999 $ per year (formula 14).

Revenue

Revenue is generated from selling the by-products of the pyrolytic process. In the base case scenario, the by-products are limonene, steel, char, and TDO. The average Russian prices of char, steel, and TDO were used in the revenue calculations. The price of limonene used in the calculation of the revenue is the average selling price of technical limonene of 95% purity. Table 32 shows the product selling prices.

Table 32. Product selling price

Product name	Unit	Unit price, $
Char	kg	0.037 [27]
Steel	kg	16,300 RUB per ton ≈ 0.25$/ kg (sdaymetall.ru)
TDO	liter	18 RUB ≈ 0.28$ (rtut-arb.ru)
Steam	Ton	10.1 [62]
Limonene	kg	455 RUB ≈ 7$ (rusabs.ru)

Table 33 shows a breakdown of revenue generated in the base case scenario.

Table 33. Revenue for the base case scenario

Product name	Total number of units per year	Revenue generated, $/year	Percentage of total revenue, %
Char	2,840,000	105,080	2
Steel	2,000,000	94,000	2
TDO	4,080,000	1,101,600	24
Steam	-	-	-
Limonene	400,000	3,200,000	71
Total revenue:	-	4,500,680	100

Table 33 shows that limonene is the primary source of revenue (71%) even though the total production of limonene is only 4.3% among all products for selling. This can be explained by the high price of the limonene. Also, such a significant share of limonene in the total revenue makes the whole process highly dependent on the limonene quality, purity, and limonene demand on the market.

The second largest contributor to the total revenue is TDO (24%). This can be explained by the high production of TDO which is approximately 44% of the full products produced during the process.

Char and steel contribute only 4% of the total revenue when the total share of these products in the total production is nearly 52%.

Profitability analysis

In this study, the prime interest rate of 8% is adopted as a minimum discount used in DCFRR method for estimation of the economic feasibility of the project. Prime interest rate of 8%, as well as a business tax rate of 20%, were obtained from the Central Bank of Russia website (www.cbr.ru). However, to encourage an owner of the company to invest in such a high-risk project as recycling, the final IRR should be more than the prime interest rate. An IRR of 25% is used in this study as the minimum IRR to make the project attractive for the owner [61]. The NPV is evaluated using DCFRR method where the discount is in a range of 8% to 25%. The results are represented below in

Table 34. The flowchart of the base case scenario for WTT is in Figure 15.

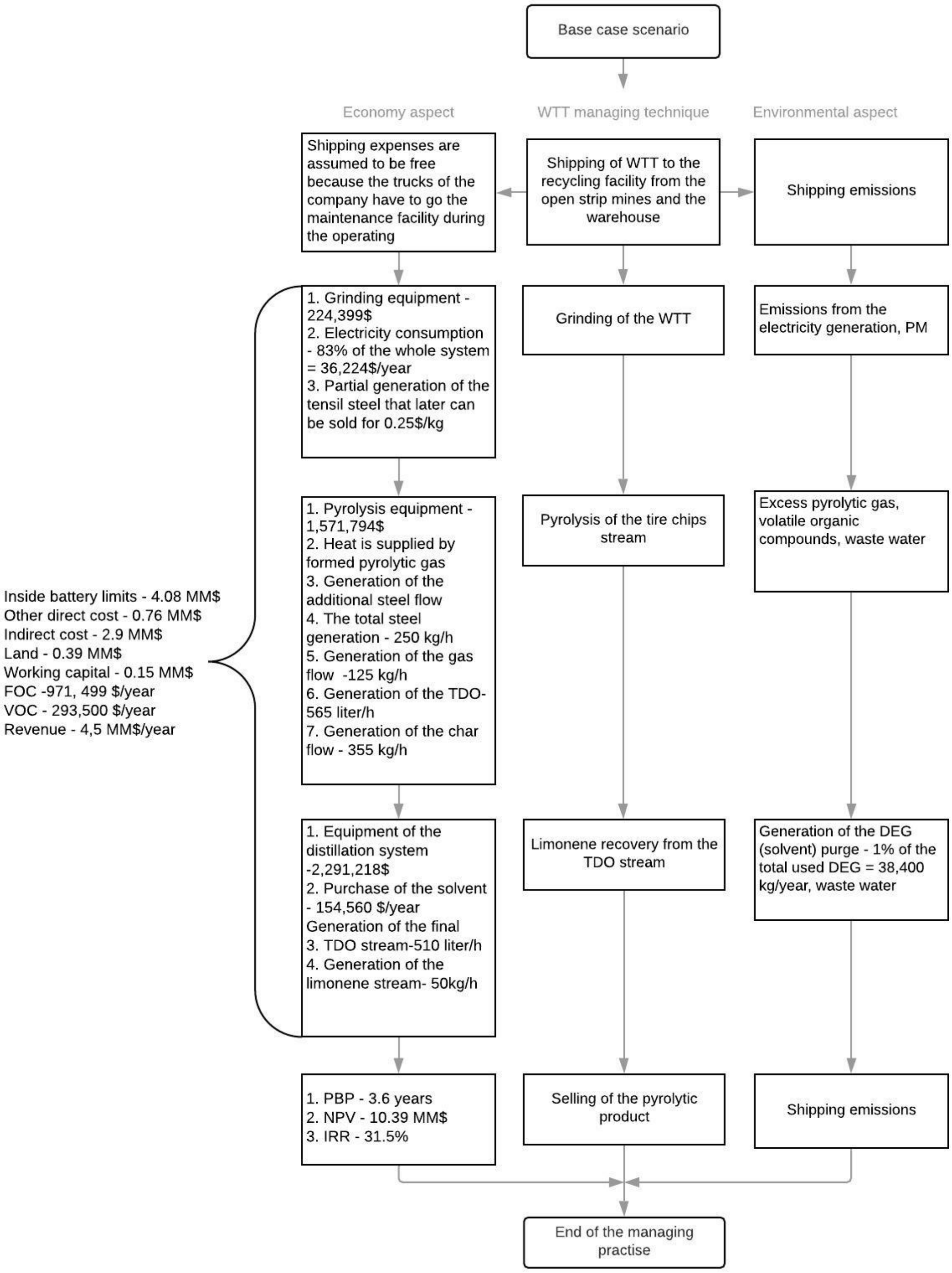

Figure 15. Flowchart of the base case scenario

Table 34. Key economic indicators for the base case scenario

Discount, %	Net present value, (MM$)	Payback period, years
8	10.39	3.6
10	8.79	3.77
12	7.4	4.0
14	6.18	4.2
16	5.11	4.46
18	4.16	4.74
20	3.32	5.07
22	2.56	5.5
24	1.89	5.98
25	1.58	6.3
IRR	31.0	

The results in

Table 34 show that the base case scenario of the WTT recycling facility into limonene is economically feasible and attractive. The payback period of the project using the prime interest rate is 3.6 years which is in the range of acceptable payback period length.

According to the results in

Table 34, the critical role in defining the attractiveness of the project belongs to the limonene sell due to the high price of the chemical. But at the same time, such a high contribution of the limonene in the total project revenue makes the feasibility and attractiveness of the recycling process extremely correlated to the limonene market and the limonene price. Due to these reasons, the analysis of the recycling process without limonene production is necessary. The study of different scenarios based on Mulaudzi [27] and shown in the next paragraph.

Scenario analysis and comparison

The additional scenarios adopted from [27] are the adding of the energy recovery section, implementing of the better pre-treatment system to get better rubber granulate, crumb purchase scenario, and scenario of tire-derived oil production without further recovery of valuable chemicals. Payback period, internal rate of return, and net present value are the key parameters to compare scenarios with each other.

Energy recovery scenario

The idea and structure of the energy recovery system were described earlier in the research in the section "Structure of the recycling process". The additional equipment in this scenario is the item necessary for steam generation (EX-105 in), a combustion chamber (HT-101), and boiler feed water pump (PC-103).

Extra revenue in energy recovery scenario is from the selling of excess steam. The rate of generated steam is approximately 2881 kg/h, where only 258 kg/h is necessary for the boiler and the rest 2623 kg/h can be sold [27]. Table 35 the calculations of the total capital investment (TCI) for the energy recovery scenario. TCI for the energy recovery scenario is 8% higher than for the base case scenario.

Table 35. TCI for the energy recovery scenario

Equipment item	Installed cost, MM$	Percentage of total ISBL, %
Pre-treatment system	0.23	5.2
Reactor system	1.36	30.8
Heat exchangers	0.29	4.1
Pumps	0.057	1.3
Drums	0.12	2.9

Table 35. cont.

Equipment item	Installed cost, MM$	Percentage of total ISBL, %
Pre-treatment system	0.23	5.2
Reactor system	1.36	30.8
Heat exchangers	0.29	4.1
Pumps	0.057	1.3
Drums	0.12	2.9
Columns	2.02	45.7
Additional equipment	0.34	7.7
Total:	4.413	100
Other direct costs		
Site-development	0.44	10
Additional piping	0.2	4.5
Warehouse	0.18	4
Total other direct costs:	0.82	
Total direct costs:	5.23	
Indirect costs		
Prorated expenses	0.53	10

Home office and construction fees	1.05	20
Field expenses	0.53	10
Project contingency	0.53	10
Other costs (start-up and permits)	0.53	10
Total indirect cost:	3.14	60
Total fixed capital investment	8.4	

Table 35. cont.

Equipment item	Installed cost, MM$	Percentage of total ISBL, %
Working capital and land expenses		
		Percentage of TFCI, %
Working capital	0.17	2
Land	0.42	10
Total working capital and land	0.59	12
Total capital investment	8.95	

Table 36 shows the total operating costs for the energy recovery scenario that includes variable operating costs and fixed operating costs.

Table 36. Operating costs

Type of the costs	Amount, $/year
Total fixed operating costs	1,019,916
Total variable operating costs	330,242
Total operating costs	1,350,158

As you can see from Table 36, the total operating costs are 6.7% higher than for the base case scenario due to the extra cost for electricity (approximately 7%) and use of boiler feed water. The total revenue for the energy recovery scenario is 4.7 MM$ which is 4.5% higher than for the base case scenario due to the extra revenue from selling steam.

Profitability analysis for the energy recovery scenario was done the same way as for the base case scenario using DCFRR method where the discount is in a range of 8% to 25%. The results are represented below in Table 37.

Table 37. Key economic indicators for the energy recovery scenario

Discount, %	Net present value, (MM$)	Payback period, years
8	10.4	3.77
10	8.78	3.96
12	7.3	4.18
14	6.06	4.4
16	5.11	4.72
18	3.96	5.04
20	3.09	5.45
22	2.3	5.92
24	1.6	6.55
25	1.28	6.91
IRR	29.0	

The flowchart of the energy recovery scenario for WTT is in Figure 16.

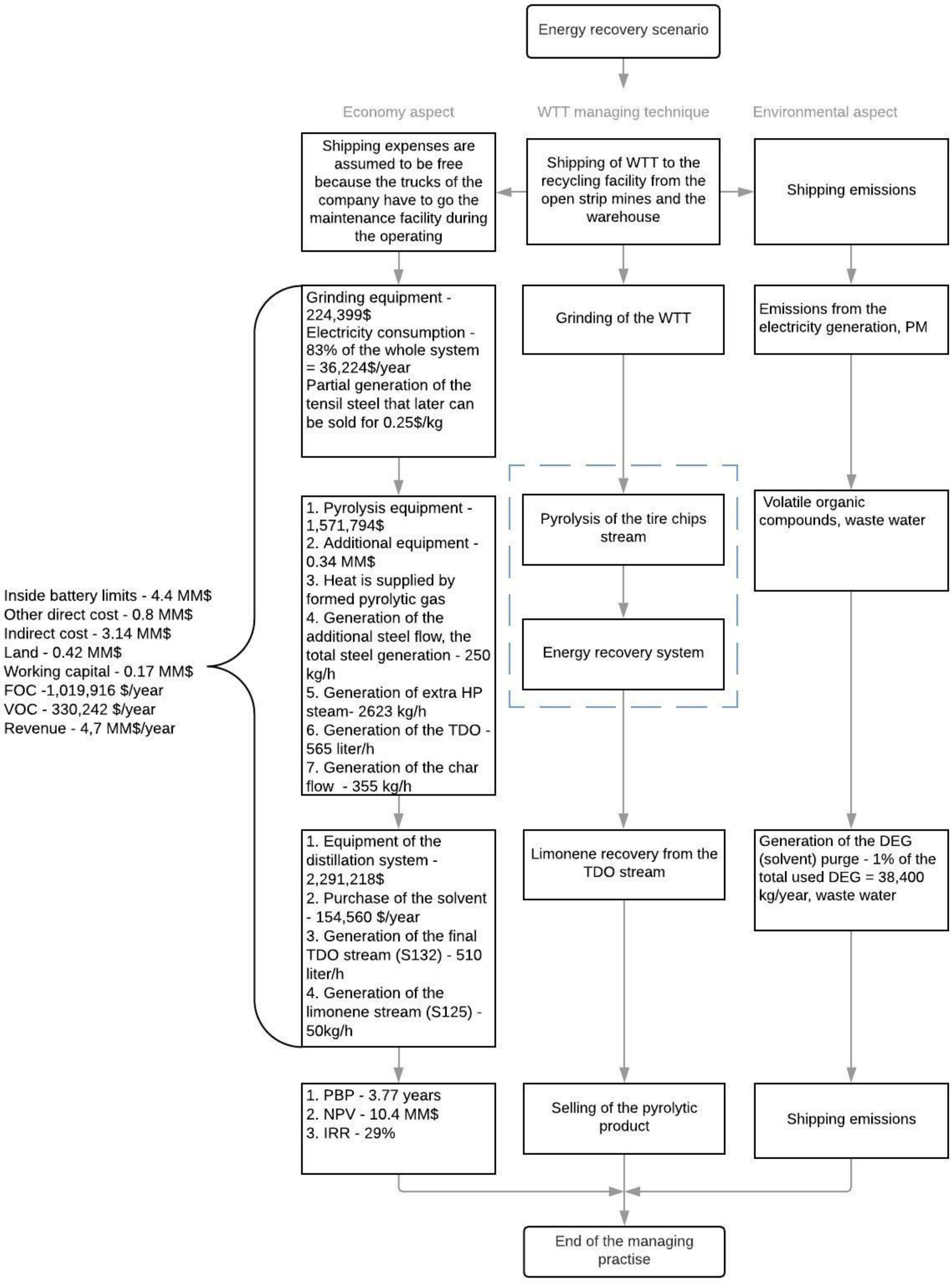

Figure 16. Flowchart of the energy recovery scenario

The results in Table 37 also show that the energy recovery scenario of the WTT recycling facility into limonene is economically feasible and attractive. The payback period of the project with the prime interest rate is 3.77 years which is in the range of acceptable payback period length, but the value is bigger than in the base case scenario where the payback period is only 3.6 years. IRR in the energy recovery scenario is more than 25% which complies with IRR of a high-risk project, but at the time IRR value for the energy recovery is smaller than for the base case.

Additional pre-treatment

The additional equipment in the pre-treatment scenario would help to reduce the tire chips to crumb size. Table 38 shows the total capital investment by the category. The total capital investment of the pre-treatment scenario is almost 21% higher due to the implementation of additional grinding units.

Table 38. TCI for the pre-treatment scenario

Equipment item	Installed cost, MM$	Percentage of total ISBL, %
Pre-treatment system	0.23	4.7
Reactor system	1.36	27.8
Heat exchangers	0.29	5.9
Pumps	0.057	1.16
Drums	0.12	2.45
Columns	2.02	41.3
Additional equipment	0.81	16.6
Total:	4.887	100

Table 38. Cont.

Equipment item	Installed cost, MM$	Percentage of total ISBL, %
Other direct costs		
Site-development	0.49	10
Additional piping	0.22	4.5
Warehouse	0.2	4
Total other direct costs:	0.9	
Total direct costs:	5.8	
Indirect costs		
Prorated expenses	0.58	10
Home office and construction fees	1.16	20
Field expenses	0.58	10
Project contingency	0.58	10
Other costs (start-up and permits)	0.58	10
Total indirect cost:	3.47	60
Total fixed capital investment	9.26	
Working capital and land expenses		
		Percentage of TFCI, %
Working capital	0.1852	2
Land	0.4633	10
Total working capital and land	0.6486	12
Total capital investment	9.91	

Table 39 shows the total operating costs for the pre-treatment scenario. The operating costs of the pre-treatment scenario are 22% higher than the total operating expenses for the base case scenario because of the extra electricity that

Table 39. Operating costs

Type of the costs	Amount, $/year
Total fixed operating costs	1,088,217
Total variable operating costs	450,260
Total operating costs	1,538, 477

The total revenue for the pre-treatment scenario is the same as in the base case scenario 4.5 MM$.

Profitability analysis for the pre-treatment scenario was done the same way as for the base case and the energy recovery scenarios using DCFRR method where the discount is in a range of 8% to 25%. The results are represented below in Table 40.

The flowchart of the pre-treatment scenario for WTT is in Figure 17.

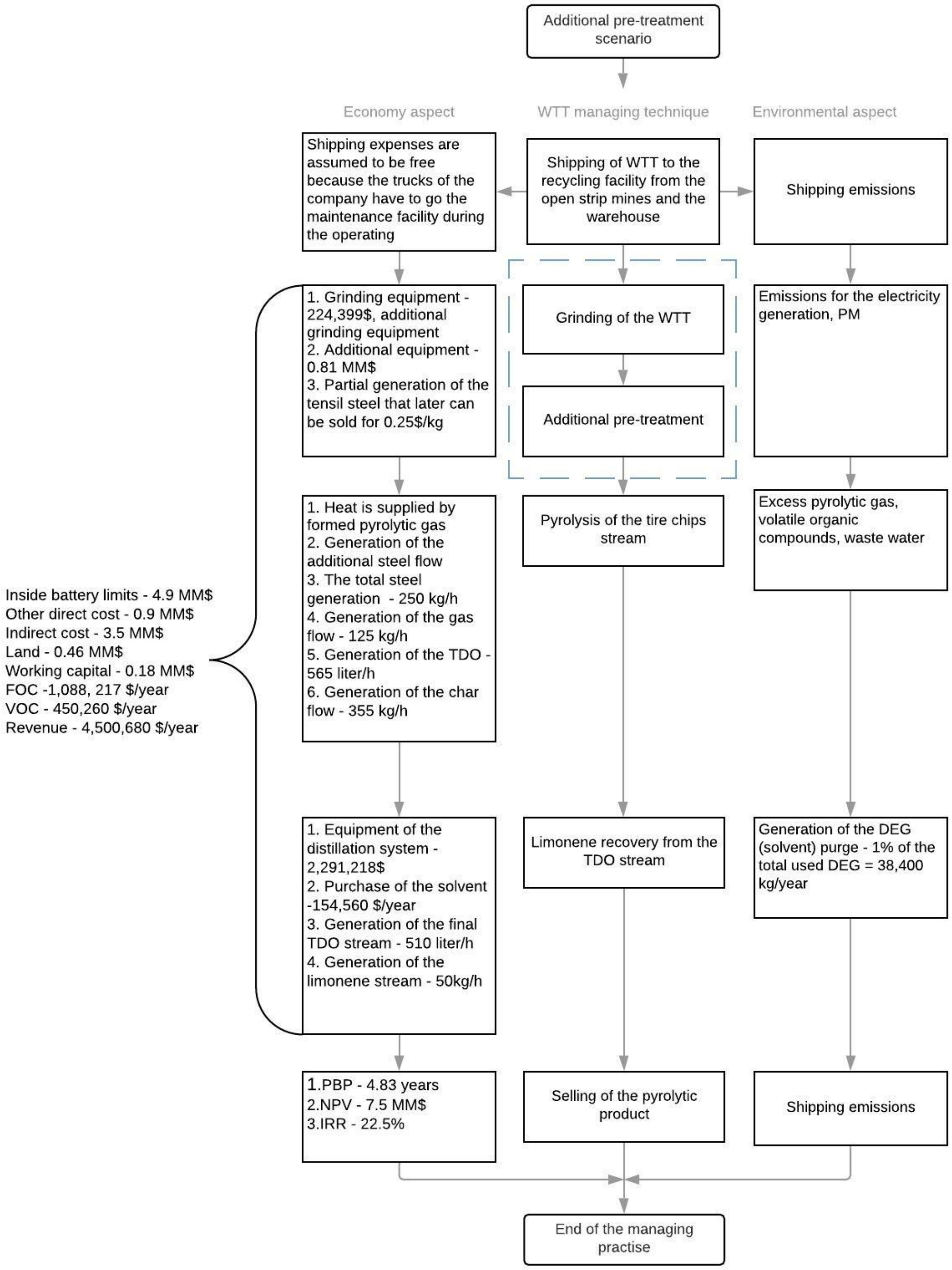

Figure 17. Flowchart of the pre-treatment scenario

Table 40. Key economic indicators for the pre-treatment scenario

Discount, %	Net present value, (MM$)	Payback period, years
8	7.5	4.83
10	6.03	5.16
12	4.7	5.54
14	3. 6	5.98
16	2.6	6.55
18	1.7	7.26
20	0.9	8.22
22	0.2	9.55
24	-	-
25	-	-
IRR	22.5	

The results show that the pre-treatment scenario of the WTT recycling facility into limonene is not economically attractive because of the high payback period (4.83 years) and low IRR value (22.5%).

Crumb purchase scenario

In this scenario, I assumed purchasing of necessary rubber material (30 ton/day) instead of recycling of WTT. This assumption allows for reducing the total capital investment by illuminating grinding equipment. Purchasing of crumb increases the yield of the main valuable chemical limonene, as the purchased crumb is steel-free material and instead of 24 ton/day as in the base case scenario, there are 30 ton/day of the steel-free material. Figure 18 shows the generalized input-output structure of the crumb purchase scenario. Products' distribution is adopted from Islam [57].

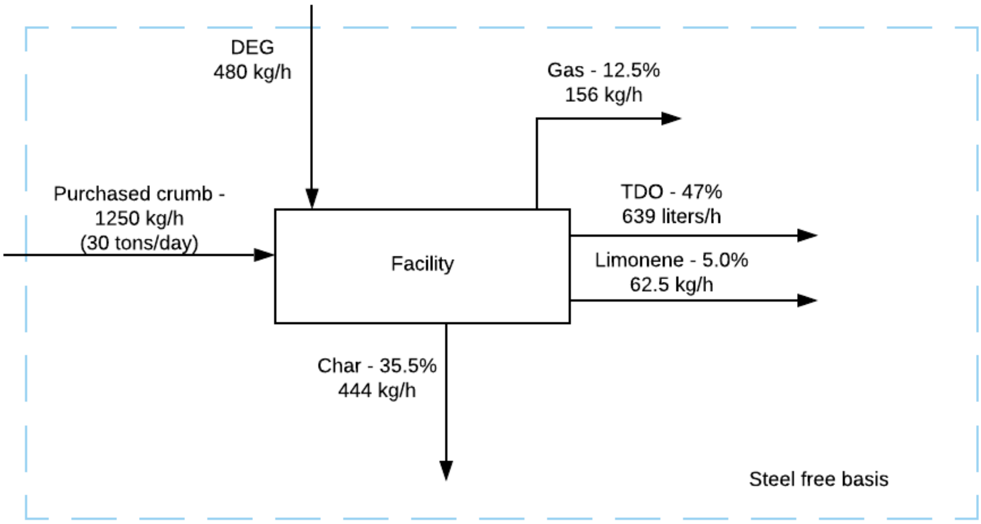

Figure 18. Input-output structure of the crumb purchase scenario

Table 41 shows the total capital investment for the crumb-purchase scenario. The ISBL of the crumb purchase scenario is 6% lower than in the base case. In total, the total capital investment of the crumb purchase scenario is 6% lower than in the base case scenario due to the absence of the pre-treatment system.

Table 41. TCI for the crumb purchase scenario

Equipment item	Installed cost, MM$	Percentage of total ISBL, %
Pre-treatment system	0.0	-
Reactor system	1.36	35.4
Heat exchangers	0.29	7.55
Pumps	0.057	1.5
Drums	0.12	3.1
Columns	2.02	52.6
Additional equipment	0.0	-
Total:	3.84	100

Table 41. Cont.

Other direct costs		
Site-development	0.38	10
Additional piping	0.17	4.5
Warehouse	0.15	4
Total other direct costs:	0.7	
Total direct costs:	4.55	
Indirect costs		
Prorated expenses	0.46	10
Home office and construction fees	0.91	20
Field expenses	0.46	10
Project contingency	0.46	10
Other costs (start-up and permits)	0.46	10
Total indirect cost:	2.73	60
Total fixed capital investment	7.29	
Working capital and land expenses		
		Percentage of TFCI, %
Working capital	0.15	2
Land	0.36	10
Total working capital and land	0.51	12
Total capital investment	7.8	

In the crumb purchase scenario, two factors differ the total operating cost of this scenario and the base scenario.

1. Electricity. The crumb purchase reduces electricity consumption by 83% due to the lack of grinding process.

2. Crumb purchase. The price of the crumb is 14RUB/kg ≈0.22$/kg (shinopererabotka.ru). The total amount of crumb needed is 10,9 ton/year which equals 2.4 MM$ of additional variable operating cost per year. The crumb purchase is responsible for 89% of the total variable operating expensses and for 66% of the total operating costs.

Table 42 demonstrates the total operating costs per year for the crumb purchase scenario. The total operating costs of the base case are almost 3 times less than in the crumb purchase scenario. The flowchart of the crumb purchase scenario for WTT is in Figure 19.

The primary revenue sources in this scenario are char, limonene, and TDO. The total revenue is 5.5 MM$ which is 22% higher than in the base case. Extra limonene is the main reason for the revenue increase. The total contribution of selling the additional limonene in the overall revenue increase is 78%.

Table 42. Operating costs of the crumb purchase scenario

Type of the costs	Amount, $/year
Total fixed operating costs	938,357
Total variable operating costs	2,700,482
Total operating costs	3,638,840

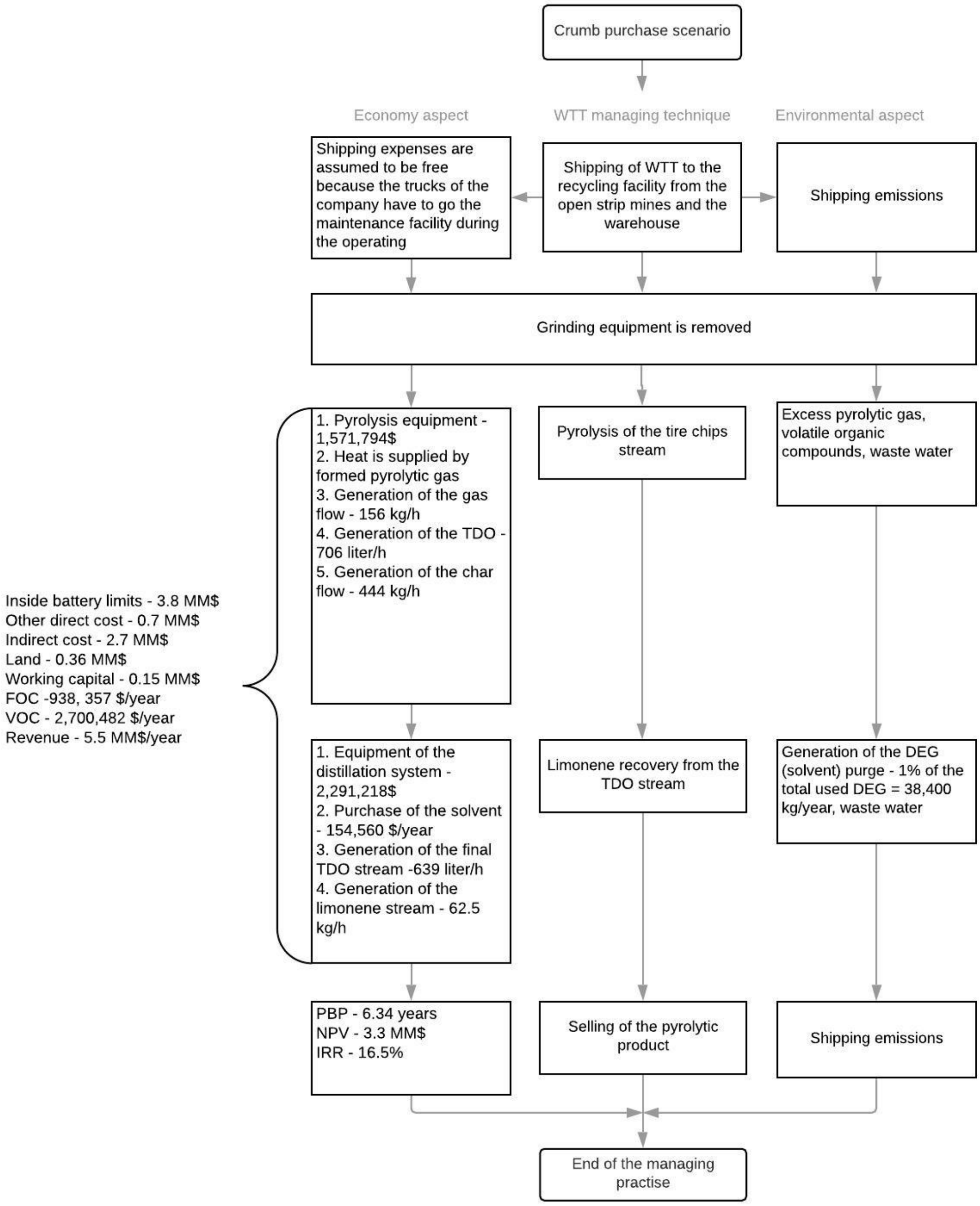

Figure 19. Flowchart of the crumb purchase scenario

Profitability analysis for this scenario has been done the same way as for the base case, energy recovery, and pre-treatment scenarios using DCFFR method where the discount is in a range of 8% to 25%. The results are represented below in Table 43.

Table 43. Key economic indicators for the crumb purchase scenario

Discount, %	Net present value, (MM$)	Payback period, years
8	3.3	6.34
10	2.3	6.91
12	1.5	7.64
14	0.78	8.6
16	0.13	9.72
18	-	-
20	-	-
22	-	-
24	-	-
25	-	-
IRR	16.5	

Low IRR value (16.5%), the high payback period for the prime interest rate (8%) of 6.34 years make the crumb purchase scenario not feasible and economically attractive for further consideration.

TDO production

The main idea of this scenario is to illuminate the most expensive equipment which in this case is the limonene recovery system. The share of the distillation columns in the total ISBL for the base scenario is 49.5%. After the illumination of the distillation columns, the recycling process products are steel, char, and TDO (Figure 20).

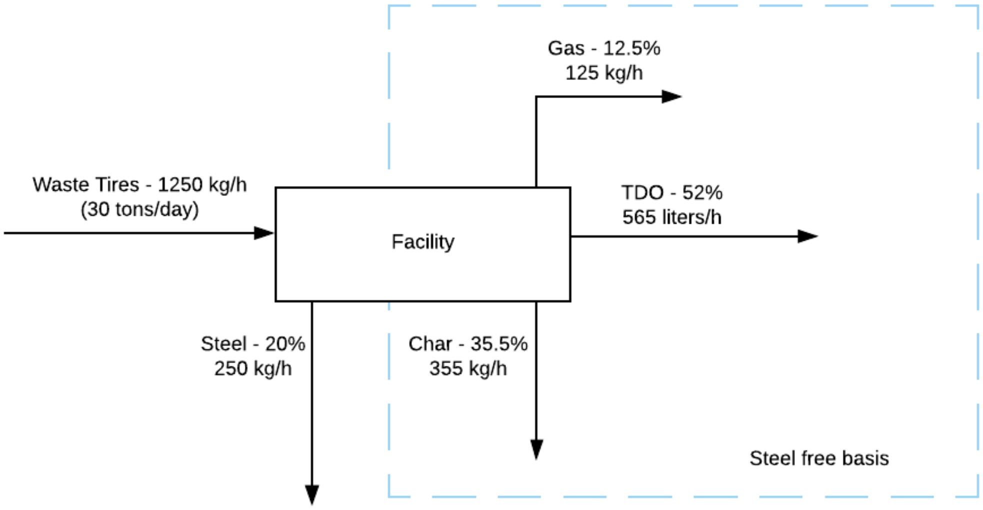

Figure 20. Generalized input-output structure for the TDO production scenario

Table 44 shows the total capital investment for the TDO production scenario. The ISBL of the crumb purchase scenario is 50.2% lower than in the base case due to illumination of the distillation columns. The total capital investment of the crumb purchase scenario is two times less than in the base case scenario.

Table 44. TCI for the TDO production scenario

Equipment item	Installed cost, MM$	Percentage of total ISBL, %
Pre-treatment system	0.23	11.2
Reactor system	1.36	66.3
Heat exchangers	0.29	14.1
Pumps	0.057	2.8
Drums	0.12	5.8
Columns	0.0	-
Additional equipment	0.0	-
Total:	2.05	100

Table 44. Cont.

Other direct costs		
Site-development	0.2	10
Additional piping	0.09	4.5
Warehouse	0.09	4
Total other direct costs:	0.38	
Total direct costs:	2.43	
Indirect costs		
Prorated expenses	0.24	10
Home office and construction fees	0.49	20
Field expenses	0.24	10
Project contingency	0.24	10
Other costs (start-up and permits)	0.24	10
Total indirect cost:	1.46	60
Total fixed capital investment	3.9	
Working capital and land expenses		
		Percentage of TFCI, %
Working capital	0.08	2
Land	0.19	10
Total working capital and land	0.27	12
Total capital investment	4.17	

The total operating costs for the TDO production scenario are 38% less than for the base due to the less amount of equipment. Even though the production of tire-derived oil increased by 11% compared to the base case, the price of TDO is still low.

As a result, the total revenue is only 1.4 MM$ which is 3.2 times or 69% less than in the base scenario.

Table 45. Operating costs of the TDO production scenario

Type of the costs	Amount, $/year
Total fixed operating costs	680,425
Total variable operating costs	103,874
Total operating costs	784,299

Table 46 shows the results of profitability analysis for the TDO production scenario using DCFFR method with a discount in a range of 8% to 25%. As can be noticed from Table 46, the recycling process of the WTT to TDO without further separation is not economically attractive and feasible. The flowchart of the TDO production scenario for WTT is in Figure 21.

Table 46. Key economic indicators for the TDO production scenario

Discount, %	Net present value, (MM$)	Payback period, years
8	-1.1	-
IRR	5.0	

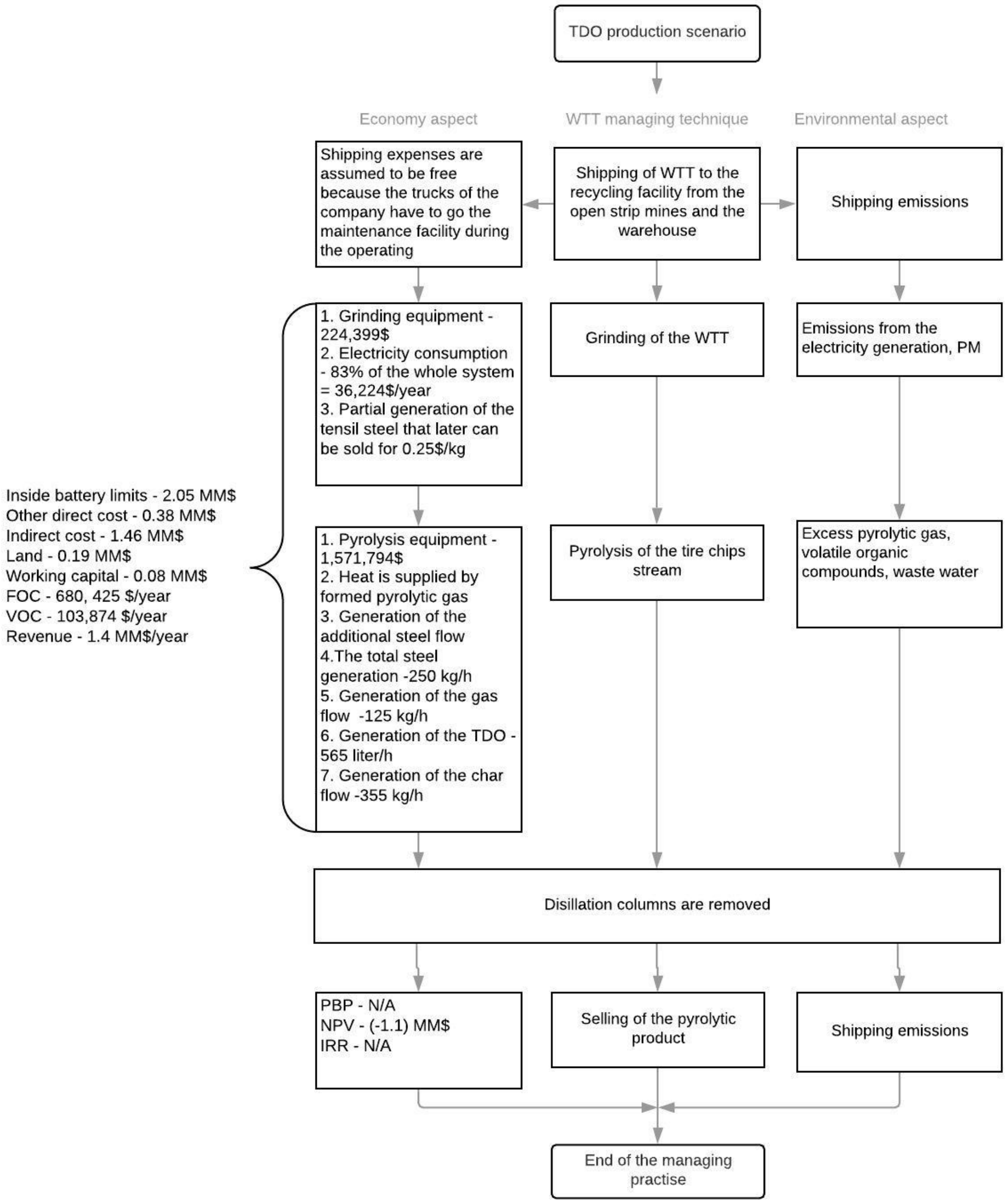

Figure 21. Flowchart of the TDO production scenario

Considering the results of DCFFR for different scenarios, the base case and the energy recovery scenarios are the most attractive and feasible due to the small payback period and high IRR. Among these two options, the base case scenario is better due to the higher values of the key economic parameters. The sensitivity analysis of the base case scenario is done in the next paragraph.

The least attractive scenario is the TDO production scenario. Table 47 demonstrates cash flows for all five scenarios (base case, energy recovery, pre-treatment, crumb purchase, and TDO production).

Sensitivity analysis

Sensitivity analysis helps to identify how the fluctuation of the particular parameter affects the key economic indicators of the process [66], [68]. In the framework of this study, the first-order sensitivity analysis is used [61]. This type of sensitivity analysis was used by Dutta [66] in the design of the pyrolytic process for the conversion of lignocellulosic biomass to hydrocarbon fuels, by James [68] in his research of the biomass conversion into hydrocarbon fuels, and by Mulaudzi [27] in his study of the waste tire conversion. In [66], [68] the authors used minimum fuel selling price (MFSP) as the critical parameter of the sensitivity analysis. In this study, the key economic indicators that are used as the measure of the project profitability remain the same as in the economic evaluation (NPV, IRR, and PBP) [61].

Table 48. Cash flow analysis for different scenarios

Base case scenario

Year	Fixed capital	Working capital	Land	Operating costs	Revenue	Depreciation	Tax	Net income	Cash flow	Discounted cash flow (8%)	Cumulative discounted cash flow (8%)	Discounted cash flow (25%)	Cumulative discounted cash flow (25%)
0	-7,729,992	-154,600	-386,500						-8,271,091	-8,271,091	-8,271,091	-8,271,091	-8,271,091
1				-1,264,999	4,500,680	772,999	492,536	2,743,144	2,743,144	2,539,948	-5,731,142	2,194,515	-6,076,575
2				-1,264,999	4,500,680	772,999	492,536	2,743,144	2,743,144	2,351,804	-3,379,338	1,755,612	-4,320,963
3				-1,264,999	4,500,680	772,999	492,536	2,743,144	2,743,144	2,177,596	-1,201,742	1,404,489	-2,916,473
4				-1,264,999	4,500,680	772,999	492,536	2,743,144	2,743,144	2,016,293	814,550	1,123,591	-1,792,881
5				-1,264,999	4,500,680	772,999	492,536	2,743,144	2,743,144	1,866,938	2,681,488	898,873	-894,008
6				-1,264,999	4,500,680	772,999	492,536	2,743,144	2,743,144	1,728,646	4,410,135	719,098	-174,909
7				-1,264,999	4,500,680	772,999	492,536	2,743,144	2,743,144	1,600,598	6,010,733	575,279	400,369
8				-1,264,999	4,500,680	772,999	492,536	2,743,144	2,743,144	1,482,035	7,492,769	460,223	860,593
9				-1,264,999	4,500,680	772,999	492,536	2,743,144	2,743,144	1,372,255	8,865,024	368,178	1,228,771
10		154,600	386,500	-1,264,999	4,500,680	772,999	492,536	2,743,144	3,284,243	1,521,240	10,386,264	352,642	1,581,414

Energy recovery scenario

Year	Fixed capital	Working capital	Land	Operating costs	Revenue	Depreciation	Tax	Net income	Cash flow	Discounted cash flow (8%)	Cumulative discounted cash flow (8%)	Discounted cash flow (25%)	Cumulative discounted cash flow (25%)
0	-8,952,741	-167,300	-418,400						-8,952,741	-8,952,741	-8,952,741	-8,952,741	-8,952,741
1				-1,350,158	4,702,680	836,705	503,164	2,012,653	2,849,358	2,638,295	-6,314,446	2279486	-6,673,254
2				-1,350,158	4,702,680	836,705	503,164	2,012,653	2,849,358	2,442,865	-3,871,580	1823589	-4,849,664
3				-1,350,158	4,702,680	836,705	503,164	2,012,653	2,849,358	2,261,912	-1,609,667	1458871	-3,390,793
4				-1,350,158	4,702,680	836,705	503,164	2,012,653	2,849,358	2,094,363	484,695	1167097	-2,223,695
5				-1,350,158	4,702,680	836,705	503,164	2,012,653	2,849,358	1.939,225	2,423,921	933,677	-1,290,018

Table 47. cont.

6				-1,350,158	4,702,680	836,705	503,164	2,012,653	2,849,358	1,795,579	4,219,500	746,942	-543,075
7				-1,350,158	4,702,680	836,705	503,164	2,012,653	2,849,358	1,662,573	5,882,074	597,553	54,477
8				-1,350,158	4,702,680	836,705	503,164	2,012,653	2,849,358	1,539,419	7,421,493	478,043	532,520
9				-1,350,158	4,702,680	836,705	503,164	2,012,653	2,849,358	1,425,388	8,846,882	382,434	914,955
10		167,300	418,400	-1,350,158	4,702,680	836,705	503,164	2,012,653	3,435,058	1,591,038	10,437,976	368,835	1,283,791

Pre-treatment

Year	Fixed capital	Working capital	Land	Operating costs	Revenue	Depreciation	Tax	Net income	Cash flow	Discounted cash flow (8%)	Cumulative discounted cash flow (8%)	Discounted cash flow (25%)	Cumulative discounted cash flow (25%)
0	-9,914,354	-185,300	-463,300						-9,914,354	-9,914,354	-9,914,354	-9,914,354	-9,914,354
1				-1,538,477	4,500,680	926,575	407,125	1,628,502	2,555,077	2,365,812	-7,548,542	-	-
2				-1,538,477	4,500,680	926,575	407,125	1,628,502	2,555,077	2,190,567	-5,357,975	-	-
3				-1,538,477	4,500,680	926,575	407,125	1,628,502	2,555,077	2,028,302	-3,329,672	-	-
4				-1,538,477	4,500,680	926,575	407,125	1,628,502	2,555,077	1,878,058	-1,451,614	-	-
5				-1,538,477	4,500,680	926,575	407,125	1,628,502	2,555,077	1,738,942	287,328	-	-
6				-1,538,477	4,500,680	926,575	407,125	1,628,502	2,555,077	1,610,132	1,897,460	-	-
7				-1,538,477	4,500,680	926,575	407,125	1,628,502	2,555,077	1,490,863	3,388,323	-	-
8				-1,538,477	4,500,680	926,575	407,125	1,628,502	2,555,077	1,380,428	4,768,752	-	-
9				-1,538,477	4,500,680	926,575	407,125	1,628,502	2,555,077	1,278,174	6,046,927	-	-
10		185,300	463,300	-1,538,477	4,500,680	926,575	407,125	1,628,502	3,203,608	1,483,923	7,530,851	-	-

Crumb purchase

Year	Fixed capital	Working capital	Land	Operating costs	Revenue	Depreciation	Tax	Net income	Cash flow	Discounted cash flow (8%)	Cumulative discounted cash flow (8%)	Discounted cash flow (25%)	Cumulative discounted cash flow (25%)
0	-7,804,485	-145,900	-364,700						-7,804,485	-7,804,485	-7,804,485	-7,804,485	-7,804,485

Table 47. cont.

1				-3,638,840	5,479,664	729,391	222,286	889,146	1,618,537	1,498,645	-6,305,839	-	-
2				-3,638,840	5,479,664	729,391	222,286	889,146	1,618,537	1,387,635	-4,918,204	-	-
3				-3,638,840	5,479,664	729,391	222,286	889,146	1,618,537	1,284,847	-3,633,357	-	-
4				-3,638,840	5,479,664	729,391	222,286	889,146	1,618,537	1,189,673	-2,443,683	-	-
5				-3,638,840	5,479,664	729,391	222,286	889,146	1,618,537	1,101,549	-1, 342,134	-	-
6				-3,638,840	5,479,664	729,391	222,286	889,146	1,618,537	1,019,953	-322,180	-	-
7				-3,638,840	5,479,664	729,391	222,286	889,146	1,618,537	944,401	622,220	-	-
8				-3,638,840	5,479,664	729,391	222,286	889,146	1,618,537	874,445	1,496,665	-	-
9				-3,638,840	5,479,664	729,391	222,286	889,146	1,618,537	809,671	2,306,337	-	-
10		145,900	364,700	-3,638,840	5,479,664	729,391	222,286	889,146	2,129,11	986,190	3,292,528	-	-

Crumb purchase

Year	Fixed capital	Working capital	Land	Operating costs	Revenue	Depreciation	Tax	Net income	Cash flow	Discounted cash flow (8%)	Cumulative discounted cash flow (8%)	Discounted cash flow (25%)	Cumulative discounted cash flow (25%)
0	-4,173,100	-78,000	-195,000						-4,173,100	-4,173,100	-4,173,100	-4,173,100	-4,173,100
1				-784,299	1,419,480	390,007	49,034	196,138	586,146	542,727	-3,630,349	-	-
2				-784,299	1,419,480	390,007	49,034	196,138	586,146	502,525	-3,127,823	-	-
3				-784,299	1,419,480	390,007	49,034	196,138	586,146	465,301	-2,662,521	-	-
4				-784,299	1,419,480	390,007	49,034	196,138	586,146	430,834	-2,231,686	-	-
5				-784,299	1,419,480	390,007	49,034	196,138	586,146	398,921	-1,832,765	-	-
6				-784,299	1,419,480	390,007	49,034	196,138	586,146	369,371	-1,463,394	-	-
7				-784,299	1,419,480	390,007	49,034	196,138	586,146	342,010	-1,121,383	-	-
8				-784,299	1,419,480	390,007	49,034	196,138	586,146	316,676	-804,707	-	-
9				-784,299	1,419,480	390,007	49,034	196,138	586,146	293,218	-511,488	-	-
10		78,000	195,000	-784,299	1,419,480	390,007	49,034	196,138	859,151	397,953	-113,535	-	-

The main idea of this sensitivity method is to check how the chosen profitability indicators are affected by the various parameters. In mathematical terms this can be expressed by equation 17.

$$Sn = \left(\frac{\partial(economic\ indicator)}{\partial(xn)}\right), \qquad 17$$

Where ∂ (xn) is a change of an affecting economic parameter, n is the total number of modifying parameters, and Sn is the sensitivity coefficient of the n affecting parameter.

As has been mentioned in the previous paragraph, the base scenario was chosen for the sensitivity analysis. The selected impact parameters are the installed cost of the reactor system, distillation columns, the total price of operating labor, limonene price per kg, and limonene yield.

The possible range of parameters variation is shown below in Table 48. The prices of the reactor system and distillation columns are used as the most significant contributors to the total capital investment of the system. The total operating labor is used as another parameter to change because this item has the highest contribution to the total operating costs. Finally, the price and yield of limonene are used as the last two parameters to change in sensitivity analysis as the contribution of the limonene to the total revenue is the highest. It is worthwhile to mention that the change of limonene yield also influences the total yield of TDO what can be seen from Table 51.

Table 48. The range of parameters variation in sensitivity analysis

Name of the parameter	Original value	Min value	Max value
Reactor system	1.36 MM$	0.95 MM$ (-30%)	1.77 MM$ (+30%)
Distillation column	2.02 MM$	1.4 MM$ (-30%)	2.6 MM$ (+30%)
Operating labor	14,770 $/year	11,076 $/ year (-25%)	18,463 $/year (+25%)
Limonene yield	5% on steel-free basis	3% on steel-free basis	15% on steel-free basis
Limonene price	8 $/kg	3$/kg (-58%)	12 $/kg (+715)

The effect of each parameter on the NPV, PBP, and IRR is shown in Tables 49-53. From Tables 49-53 it is evident that the economic feasibility and attractiveness of the recycling project highly depends on the limonene price and its production volume. Just 2% less of the total limonene production volume in Table 53 made the project not feasible. The overall drop of NPV is almost 64% and decrease in IRR value to 17.5% compared with the base case values.

However, the high sensitivity of the process to the total limonene production volume makes the recycling facility highly attractive with the slightest increase of the total limonene yield. Just 2% of extra produced limonene increased the NPV by 64% compared the base value, decreased the payback to 2.55 years, and increased the IRR by 13% (44.5%).

The effect of changing the highest operating cost item (the total operating labor) on the fluctuation of the key economic indicators is negligible. The IRR of the process altered by ±1%. The change of NPV is ±5%. The payback period remained almost the same. This means that there is no reason for the company to change the salary of employees to make the process feasible as it does not affect the key economic indicators at all. The fluctuation of the price of the most expensive equipment has changed the key parameters more than the total operating labor, but still, the lowest IRR values have acceptable values of more than 25%. However, the payback in both cases for the highest value of the parameter is more than 4 years (4.06 years with the highest installed cost of the reactor system and 4.31 years with the highest installed cost of the distillation columns). Figure 22 shows how the change of the economic parameters affects the NPV values compared to the base case scenario.

Table 49. Sensitivity analysis for the base scenario by changing the price of the reactor system

reactor system change	reactor system price, MM$	NPV, MM$	PBP, year	IRR, %
-30	0.95	11.4	3.14	35.5
-25	1.02	11.23	3.22	34.5
-20	1.09	11.06	3.29	34.5
-15	1.16	10.89	3.37	33.5
-10	1.22	10.72	3.44	32.5
-5	1.29	10.56	3.52	31.5
0	1.36	10.39	3.6	31.5
5	1.43	10.22	3.67	30.5
10	1.5	10.05	3.75	29.5
15	1.56	9.88	3.83	29.5
20	1.63	9.71	3.9	28.5
25	1.7	9.54	3.98	27.5
30	1.77	9.37	4.06	27.5

Table 49. Sensitivity analysis for the base scenario by changing the price of the distillation columns

Distillation column change	distillation column price, MM$	NPV, MM$	PBP, year	IRR, %
-30	1.42	11.89	2.93	38.5
-25	1.52	11.64	3.04	36.5
-20	1.62	11.39	3.15	35.5
-15	1.72	11.14	3.26	34.5
-10	1.82	10.89	3.37	33.5
-5	1.92	10.64	3.48	32.5
0	2.02	10.39	3.6	31.5
5	2.12	10.14	3.71	30.5
10	2.22	9.88	3.82	29.5
15	2.32	9.63	3.94	28.5
20	2.42	9.38	4.06	27.5
25	2.52	9.13	4.18	26.5
30	2.63	8.88	4.31	25.5

Table 51. Sensitivity analysis for the base scenario by changing the price of the operating labor

Operating labor change	Operating labor value, $	NPV, MM$	PBP, year	IRR, %
-25	11078	10.9	3.48	32.5
-20	11816	10.8	3.51	31.5
-15	12554	10.7	3.53	31.5
-10	13293	10.59	3.55	31.5
-5	14032	10.49	3.57	31.5
0	14770	10.39	3.6	31.5
5	15508	10.28	3.62	30.5
10	16247	10.18	3.64	30.5

Table 51. cont.

Operating labor change	Operating labor value, $	NPV, MM$	PBP, year	IRR, %
15	16986	10.08	3.67	30.5
20	17724	9.97	3.69	30.5
25	18462	9.87	3.71	30.5

Table 50. Sensitivity analysis for the base scenario by changing the price of limonene

Limonene price change	Revenue from limonene, $/year	NPV, MM$	PBP, year	IRR, %
5$	2000000	3.94	6.03	17.5
6$	2400000	6.09	4.91	22.5
7$	2800000	8.24	4.15	26.5
8$ the base price	3200000	10.39	3.6	31.5
9$	36000000	12.53	3.17	35.5
10$	4000000	14.68	2.83	39.5
11$	4400000	16.83	2.57	43.5
12$	4800000	18.98	2.34	47.5

Table 53. Sensitivity analysis for the base scenario by changing the yield of limonene

Limonene yield on steel free basis	Limonene yield per hour, kg/h	Percentage of limonene from TDO, %	TDO yield per hour, l/h	NPV, MM$	PBP, year	IRR, %
3%	30	5.8	533	3.78	6.14	17.5
4%	40	7.7	522	7.09	4.53	24.5

Table 53. cont.

Limonene yield on steel free basis	Limonene yield per hour, kg/h	Percentage of limonene from TDO, %	TDO yield per hour, l/h	NPV, MM$	PBP, year	IRR, %
5% the base	50	9.6	511	10.39	3.6	31.5
6%	60	11.5	500	13.71	2.97	37.5
7%	70	13.5	489	17.01	2.55	44.5
8%	80	15.4	478	20.32	2.22	50.5
9%	90	17.3	467	23.63	1.97	-
10%	100	19.2	457	26.95	1.77	-

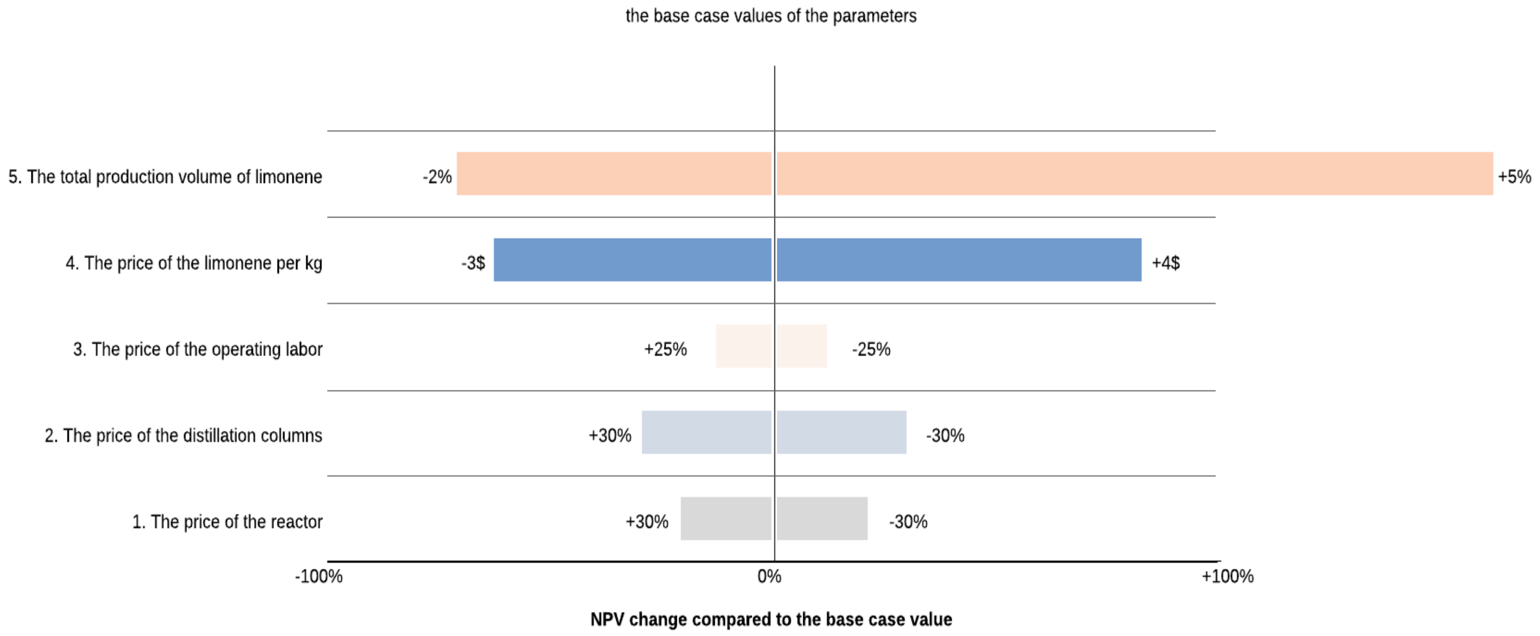

Figure 22. Effect of variation of key parameters on NPV at 8% prime interest rate

CHAPTER VI: CONCLUSION AND RECOMMENDATIONS

The aim of this study was to discover the possibility of recycling the waste truck tires accumulating by Siberian coal transportation company “SibTreid NK” and evaluate the economic feasibility of the most attractive option. As mentioned in the first chapter, the goal was set out to be achieved through addressing the following objectives:

Objective 1: Description of the company and the location, including general characteristics of Kemerovo region, status of coal mining industry for Kuzbass, and company’s profile

In order to develop a project for a certain company, it is important to know not only the initial data or conditions, but also take into account the specifics of the location. It was demonstrated that the region, where the company “SibTreidNK” is located, is one of the major coal regions of Russia. The mining industry of the region has been dramatically increased over last 26 years and is still growing. It was mentioned that the industry plays a crucial role in economic development of the Kemerovo region overall. The company “SibTreidNK” is one of the biggest companies related to coal industry. The company is responsible for three different activities including the transportation of coal. Currently the company uses trucks of three different carrying capacities: 50-, 12-, and 220-ton. Nowadays, the company goes through the replacement of trucks with small carrying capacity to a big one due to the increased demand in transportation. The geography of the company’s coal transportation activity was illustrated in the first chapter.

Objective 2: Characterization of tires' disposal problem in the company, analysis of WTT life cycle within and outside the company and description of the composition of WTT.

It was shown, that all waste truck tires produced by the company either stockpiled or dumped into the open strip mines where the company is working. The rate of tires disposal was reduced after the implementation of the retreading facility on the territory of the company. The approximate rate of truck tires accumulation/dumping is 2 truck tires per day of the unknown size. According to the company, the total number of dumped and stockpiled tires is many thousands, but the exact number is unknown. The generalized scheme of the truck tires lifecycle within the company is shown in the first chapter.

The company uses three brands of tires, but the number and the model of each brand is also unknown. The truck tire composition was adapted from studies done specially for this type of waste.

Objective 3: Investigation of current technologies and methods for waste tire management.

A deep literature review of various methods and technologies for dealing with scrap tires was conducted in this research. The investigation included the description and analysis of advantages and disadvantages of current practices used by the company, which are stockpiling, dumping, and retreading. Also, it contained the information about other methods such as material recovery practices, which includes the use of tires as whole, grinding, vulcanization, and reclaiming, and about thermochemical conversion of the waste such as incineration, hydrothermal liquefaction, gasification, and pyrolysis. The most attractive technology from the maturity and company perspectives was the pyrolysis treatment of the waste tires, in particular with recovery of valuable chemicals to make the process more feasible. As truck tires have the highest content of natural rubber among other types, the most profitable chemical to recover is limonene of a high purity.

Objective 4: Development of models/simulations for the scenarios with targeted byproducts and economic evaluation of scenarios.

In this part of the research, I analyzed possible operating conditions of the future recycling facility based on the same study done in different research. The operating conditions include the total number of operating hours, total number of people, targeted product, appropriate feed rate for the future facility, lifetime, composition of the raw material. The plant location was chosen as the one to provide free and constant flow of the raw material. The structure and the byproducts of the process were adopted from literature sources.

For economic analysis, 2018 was chosen as the base year. In the economic evaluation I used Russian economic parameters such as the prime interest rate (8%), tax (20%), and currency course (65RUB = 1$). Also, I was using some indicators special only for the Kemerovo region like the cost of utilities, the selling prices, the average salary of operating labor that are shown in the fifth chapter.

For economic evaluation of the project discounted cash flow rate of return method was used with 8% as the discount. The depreciation was assumed to be linear during the minimum possible lifetime of the chemical facility which is 10 years. The accuracy that was used in the study was the order of magnitude or ±30%. The economic parameters to show the profitability of the project were the net present value, payback period (2-4 years), and the internal rate of return that should be higher than 25% for such a high-risk project as recycling.

Five different scenarios were compared in this study:

1) The base case scenario of conversion the waste tires into limonene.
2) The energy recovery scenario. It has additional energy recovery equipment to deal with excess gas produced during the pyrolysis.
3) The additional pre-treatment scenario. This scenario implies the additional module of equipment to get better rubber granulate.
4) The crumb purchase scenario. The raw material free of steel was assumed to be supplied by the third company.
5) The TDO production scenario. In this scenario no further recovery of tire-derived oil into valuable chemicals was assumed.

During economic evaluation of these five scenarios, the most feasible and economically attractive was the base case scenario. The final distribution of the process products is the following: 50kg/h for limonene, 510 l/h of TDO, 250 kg/h of steel, and 355 kg/h of char. The payback period of this option is 3.6 years, NPV by the end of the lifetime is 10.39 MM$, and the internal rate of return is 31.5%.

The least favorable option was the TDO production scenario. In this case, the project had negative NPV value by the end of lifetime using DCFRR with the prime interest rate as a discount.

Objective 5: Carry out sensitivity analysis for the most attractive scenarios.

The sensitivity analysis was done only for the most attractive scenario which was the base case scenario. In the framework of this study, the first-order sensitivity analysis was used. The critical parameters for the methods were the key economic indicators. The selected impact parameters were the installed cost of the reactor system, distillation columns, the total price of operating labor, limonene price per kg, and limonene yield.

According to the results, the most influencing parameters were the limonene price and the total limonene yield. Even the slight change of these two parameters affected the critical economic indicators. The impact parameters with the least influence on NPV, PBP, and IRR was the cost of operating labor.

Objective 6: Write a list of recommendations for the company.

1. The current practices of dealing with WTT which are stockpiling and dumping into open mines are not environmentally friendly, as well as economically beneficial for the company. The tire is a valuable raw material that can be used to produce extra revenue for the company. Also implementing the first truck tires recycling facility in the private company would somehow improve the reputation of the company among public.

2. The most attractive process to deal with scrap truck tires is pyrolysis with further recovery of the limonene. Considering the feeding rate for the future facility of 30 ton/day, 20 as the total number of people, the current course of ruble, economic parameters of Russia and the Kemerovo region, NPV, PBP, and IRR were 10.39 MM$, 3.6 years, and 31.5% respectively. The selling prices of the products were 8$ per 1 kg of limonene, 0.037$ per 1 kg of char, 0.25$ per 1 kg of steel, and 0.28$ per 1 liter of TDO. The final yields of the products were 50kg/h for limonene, 510 l/h of TDO, 250 kg/h of steel, and 355 kg/h of char. The slight decrease of limonene yield, for example to 30 kg/hour caused the decrease of NPV by 64%. The same situation was observed when the price of limonene was 5$ instead of 8$. The NPV dropped by 62%. I would

suggest with such high dependency of the project feasibility on the limonene price and yield, to find a buyer of the product before making the decision to build the facility.

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