May 2019

Analysis of a Garment-oriented Textile Recycling System via Simulation Approach

Reyhaneh Yavari
yavarir@uwindsor.ca

Analysis of a Garment-oriented Textile Recycling System via Simulation Approach

By

Reyhaneh Yavari

A Major Research Paper
Submitted to the Faculty of Graduate Studies
through the Industrial Engineering Graduate Program
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science
at the University of Windsor

Windsor, Ontario, Canada

2019

Analysis of a Garment-Oriented Textile Recycling System via Simulation Approach

By

Reyhaneh Yavari

APPROVED BY:

____

L. Miller-Branovacki

Department of Mechanical, Automotive and Materials Engineering

____

Z. Pasek, Advisor

Department of Mechanical, Automotive and Materials Engineering

April 16, 2019

DECLARATION OF ORIGINALITY

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication.

I certify that, to the best of my knowledge, my thesis does not infringe upon anyone's copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices. Furthermore, to the extent that I have included copyrighted material that surpasses the bounds of fair dealing within the meaning of the Canada Copyright Act, I certify that I have obtained a written permission from the copyright owner(s) to include such material(s) in my thesis and have included copies of such copyright clearances to my appendix.

I declare that this is a true copy of my thesis, including any final revisions, as approved by my thesis committee and the Graduate Studies office, and that this thesis has not been submitted for a higher degree to any other University or Institution.

ABSTRACT

The textile industry is one of the polluting industries on the planet. Public awareness has increased manufacturers responsibility and forced them to shift from linear to the circular production line to reduce the amount of environmental impact such as; energy and freshwater consumption, toxic and fertilizer usage and cutting down the use of raw material. Also, some new business strategies like fast fashion which is a recent trend in the fashion industry by offering fast changing trend and inexpensive designs accelerate the process of purchasing new clothes that end up in landfills. Recycling, remanufacturing and reusing are some practices that can be done to minimize the environmental impact and to keep used clothes out of the landfills. One of these preventive actions is textiles recycling which involves so many uncertainties, such as quality, quantity, and type of the used materials. To address this problem, a discrete event simulation model is proposed to study the changes in the recycling process. The main focus of the model is on the interaction between different components in a textile recycling system to increase the number of recycled materials to return them into the supplier. Moreover, the performance of the servers is studied in order to run different scenarios. These scenarios are proposed and have been chosen based on the Welch method.

Key words: Fashion Industry, Second Hand Clothing, Textile, Textile Recycling, Remanufacturing, Supply Chain, Simulation, Enterprise Dynamics.

DEDICATION

Dedicated to

My beloved father, mother, and brother.

ACKNOWLEDGEMENTS

First of all, I would like to express my special thanks to my supervisor, Dr. Z. Pasek for his detailed guidance and all his support and mentorship to complete my program. Also, deeply I am grateful to him for giving me the opportunity to start my M.Sc. under his supervision. I would also like to thank Dr. L. Miller; it was an honor to have her in my committee.

Furthermore, I would also like to acknowledge with much appreciation to Ms. Angela Haskell for providing me continuous encouragement throughout my years of study.

TABLE OF CONTENTS

DECLARATION OF ORIGINALITY iii

ABSTRACT iv

DEDICATION..v

ACKNOWLEDGEMENTS...vi

LIST OF TABLES xi

LIST OF FIGURES..xii

LIST OF APPENDICES xv

LIST OF ACRONYMS...xvi

CHAPTER 1: INTRODUCTION..1

1.1 Introduction to textile recycling..1

1.2 Clothing recycling..4

1.3 Apparel industry...5

1.3.1 Fast Fashion..5

1.4 Textile waste...7

1.5 Closed loop fashion system 9

1.6 Mechanisms to recover the value of used products 10

1.6.1 Repair and reuse..11

1.6.2 Remanufacturing and upcycling 11

1.6.3 Recycling..13

1.6.4 Reasons to do recycling..15

1.6.5 Disposing 16

1.6.6 Landfill Disposal..17

1. 7 Share of different material in clothing 19

1.8 Problem statement..23

1.9 Contribution of this research 24

1.10 The objective of the study 24

1.11 Proposed approach 25

1.12 Research outline..26

CHAPTER 2: LITERATURE REVIEW 27

2.1 Relevant literature review..27

2.2 Gap in the literature and plan of work..33

CHAPTER 3: SOLUTION APPROACHED AND WORKING ASSUMPTIONS..34

3.1 Simulation models...35

3.1.1 Discrete-event simulation...35

3.2 Modeling for simulation..36

3.2.1 Model architecture 37

3.2.2 Sub-system 1: Product generation 37

3.2.3 Sub-system 2: After use phase..37

3.3 The main framework of the model...38

3.4 Simulation process 43

3.5 Description of the recycling process 43

3.6 Notations and assumptions 47

3.6.1 Notations...47

3.6.2 Assumptions 48

3.6.3 System performance..49

3.6.4 Labeling..49

CHAPTER 4: METHODOLOGY 51
4.1 Model description 51
4.2 Different components of the simulation model 52
4.3 Key factors in the simulation of the recycling process 53
4.3.1 Inter-arrival time in source atom (for disposed materials) 53
4.3.2 Distributor atom 54
4.3.3 Connecting channels 54
4.4 Breakdown time 54
4.5 System timing 54
4.6 Sorting and inspection station 55
4.7 Spinning 56
4.8 Queue capacity 56
4.9 Warm up time period...57
4.10 Data collection for the simulation model 60
4.11 Determining the minimum numbers of replications 64
4.12 Results of the base model and improved scenarios..................................65
4.12.1 Base model (current setup) 65
4.13 The first improvement model 69
4.14 The second improvement scenario 70
4.14.1 Introducing a novel separation method and a different process flow 70
4.15 Analyzing the scenarios 74
Table 7. The average content of each improvement scenarios output 74
4.16 Selecting one of the alternatives as an improvement scenario 74
4.17 Results 76
4.18 Verification and validation of the model...77

CHAPTER 5: CONCLUDING REMARKS 79
5.1 Conclusion 79
5.2 Future work 79
REFERENCES/BIBLIOGRAPHY 80
APPENDICES 83
Appendices 1. Analysis 83
Appendices 2. Discussion 88
Appendices 3. Environmental aspects of textile waste 89
Appendices 4. Pricing analysis 89
Appendices 5. Related figures and tables 92
VITA AUCTORIS 119

LIST OF TABLES

Table 1. Different applications of low quality recycled cotton............................ 40
Table 2. Price of virgin and recycled fibers adapted from [45] 42
Table 3. The results of 316 replications.. 65
Table 4. Results of running the first improvement scenario 70
Table 5. The production plan for different types of material............................... 73
Table 6. Results of running the first and second improvement scenarios 73
Table 7. The average content of each improvement scenarios output 74
Table 8. Average and standard deviation of alternatives..................................... 76
Table 9. Summary results 76
Table 10. Table Costs of production of raw cotton in Australia (2011)................ 84
Table 11. Pricing analysis.. 90
Table 12. The results of 316 replications from the base model 93
Table 13. Queue capacities 108
Table 14. Data used in the simulation model and range of input parameters.......109
Table 15. 4D Script syntax of input parameters..110
Table 16. The capacity of each machine..110

LIST OF FIGURES

Figure 1. Municipal Solid Waste Generation Rates, 1960-2012 [8] 2
Figure 2. Total MSW Generation (by Material), 2013 3
Figure 3. The Closed-looped supply chain network for textile manufacturing adapted from [26] 9
Figure 4. The share of sub-sectors of the textile industry.................................... 10
Figure 5. Textile waste management in the US from 1960 to 2015 [8] 14
Figure 6. Textile closed-loop network [12] 16
Figure 7. Businesses involved in the textile industry 18
Figure 8. Classification of fibers 19
Figure 9. The share of different fibers in clothing in 2010 20
Figure 10. Energy consumption for production of 10000 cotton T-shirts 20
Figure 11. The carbon footprint for production of 10000 cotton T-shirts 21
Figure 12. The comparison of energy consumption for cotton and recycled T-shirts 21
Figure 13. The comparison of the carbon footprint for cotton and recycled T-shirt 22
Figure 14. The comparison of consumption for cotton and recycled and polyester T-shirt 22
Figure 15. The comparison of the carbon footprint for virgin cotton, and recycled cotton, and polyester T-shirt 23
Figure 16.Textile Flow (in tons) in Denmark, 2010 [28] 32
Figure 17. Subsystem 1: the introduction of material to the system 39
Figure 18. Subsystem 2: products arrival to the system 39
Figure 19. The processes involved in the textile reusing system 41
Figure 20. Differences between recovered and conventional production method of cotton adapted from [40]... 45
Figure 21. The existing system operations 46
Figure 22. Textile after use phase diagram 50
Figure 23. Batch rule 55
Figure 24. Inspecting different products in the sorting station 56

Figure 25. Experimentation with separate runs.. 57
Figure 26. Warm up diagram for the simulation model 58
Figure 27. Simulation process flow chart 59
Figure 28. Flowchart for basic simulation programming [1]................................ 61
Figure 29. Flowchart for arrival routine, queuing model adapted and modified from [1] 62
Figure 30. Textile recycling processes 63
Figure 31. The performance of the twisting machine after 8 hours simulation run 66
Figure 32. The performance of the spinning machine after 8 hours simulation run 66
Figure 33. 2D view of the base model after 8 hours of run 68
Figure 34. 3D view of the proposed system in the first improvement scenario 69
Figure 35. The proposed process for mechanical recycling of cotton fibers 72
Figure 36. Comparison of the base and proposed systems 77
Figure 37. Cost of cotton production in Australia from 2000 to 2012. 84
Figure 38. The amount of donated clothes collected from the weekly collection for a recycling plant in the UK 85
Figure 39. Determining the distribution of clothing donation (figure 36)............. 86
Figure 40. The cotton loss in different stages of production 87
Figure 41. Potential reasons which can have an effect on textile waste adapted and modified from [58] 88
Figure 42. Different factors involved in T-shirt pricing 90
Figure 43. Recovered textile price [7] 91
Figure 44. Environmental impacts of a cotton T-shirt (0.3kg) and a recovers T-shirt [40]... 92
Figure 45. Main steps to produce recycled cotton [40]. 92
Figure 46. Mechanical textile recycling for cotton fibers is presented with the simulation approach.. 94
Figure 47. Recycling process model 95
Figure 48. Details in the recycling process model (1).. 96
Figure 49. Details in the recycling process model (2).. 97

Figure 50. Details in the recycling process model (3) 98
Figure 51. Summary report after running the base model for 16 hours 99
Figure 52. Proposed model after using the new sorting system and using a new process flow for different types of materials 100
Figure 53. 3D view of the new inspection and sorting system 101
Figure 54. The 3D view of improvement model (The inventory behind cutting machine)..102
Figure 55. 2D view of sorting and inspection stations for the proposed model ...102
Figure 56. Cycle time for cutting machine for the first type of material.............103
Figure 57. Cutting machine cycle time for the second type of material..............104
Figure 58. Inspection time for 70% of initial products.......................................105
Figure 59. Inspection time for 20 percent of materials.......................................106
Figure 60. Inspection time for 10% of the material 107
Figure 61. Screenshot of the model after 7 hours of run 110
Figure 62. The performance of sorting, cutting and shredding server 111
Figure 63. Performance of Cutting, Blending and Spinning machine 111
Figure 64. Sorting time 112
Figure 65. Cutting machine cycle time 113
Figure 66. Inspection time 114
Figure 67. Separation of different type of material based on their label 114
Figure 68. Cycle time for cutting type 1 products..115
Figure 69. Cycle time for cutting type 2products...115
Figure 70. The cycle time of pulling machine 116
Figure 71. The cycle time of final twisting..116
Figure 72. The cycle time of the first pulling process 117
Figure 73. The results of 5 replications in kilograms 117
Figure 74. Run length for 5 replications 118
Figure 75. The average number of final products (kilogram) for 5 replications...118

LIST OF APPENDICES

Appendices 1. Analysis.. 83
Appendices 2. Discussion 88
Appendices 3. Environmental aspects of textile waste....................................... 89
Appendices 4. Pricing analysis... 89

LIST OF ACRONYMS

CO Cotton

SC Supply Chain

CV Viscose

ED Enterprise Dynamics

EPA Environmental Protection Agency

FF Fast Fashion

GHGs Green House Gases

GRI Global Reporting Initiative

LB Lower Bound

LP Linear Programming

MIP Mixed Integer Programming

MSW Municipal Solid Waste

PES Polyester

SCM Supply Chain Management

SHC Second Hand Clothes

UB Upper Bound

DA's NOP Department of Agriculture's National Organic Program

WO Wool

CHAPTER 1: INTRODUCTION

1.1 Introduction to textile recycling

The global population growth and rise in the living standards are increasing the use of apparel. Consumption of natural resources and textile disposal are increasing continuously [2]. Based on the global fiber production for the garment industry in 2014 approximately 90 million metric tonnes of apparel were consumed. Among textiles, cotton is the most popular fiber among available materials used in the garment industry (30% of total fiber production worldwide); therefore, more attention is given to recycling cotton products [3]. By deploying a recycling system the amount of textile which goes to the landfill can be reduced, for instance, one Ontario study found that 85 percent of discarded textiles end up in the landfill [4] even though 95% can be reused and recycled [5] so, there is a need to change this trend. Figure 1 shows the increase in total municipal solid waste (MSW) from 1960 to 2013 (this data includes textiles as well). As it is illustrated, the MSW has an increasing rate which means the generation rate is going to increase in the future.

This study aims to propose improvements to textile recycling process to reuse or recover second hand and disposed clothes. A simulation-based model is proposed for the textile recycling process to represent a variety of scenarios according to the input parameters which are provided for the model. The model is divided into two different sections, use, and post-use phase. Generally, post-use phase contains four sub-models (recycling, remanufacturing, upcycling and reusing). The main focus of this study would be on modeling the recycling process by introducing different production methods for the proposed scenarios.

Studies in the UK show that [6], around 650,000 tonnes of clothing is collected annually for reuse and recycling but about 450,000 tonnes are dumped in bins and are suitable for recycling [5], and this number is expected to multiply in the USA due to it's larger population (around 5 times more than the UK population) [6]. Based on a 2017 survey some of the reasons that people do not recycle all of their used clothes are as follow:

- 49% said they did not think they could recycle clothing that was worn out or dirty
- 16% said they did not have time to visit a charity shop or simply could not be bothered to sort items, and finally
- 6% did not know that clothing could be recycled [7]

Therefore, one of the main problems in recycling process is that people think just perfect clothes can be donated or collected while even worn out clothes should be used for other purposes such as insulation or manufacturing certain types of paper or for agriculture purposes, for instance, in Canada organizations like Salvation Army collects used products and puts them into huge bales (450 kg) and sells them to private companies to be used in different industries [7]. Figure 1 shows the amount of municipal solid waste generated in the US from 1960 to 2012. The amount of generated MSW in 2012 was approximately 251 million tons in which textiles are part of this amount [8].

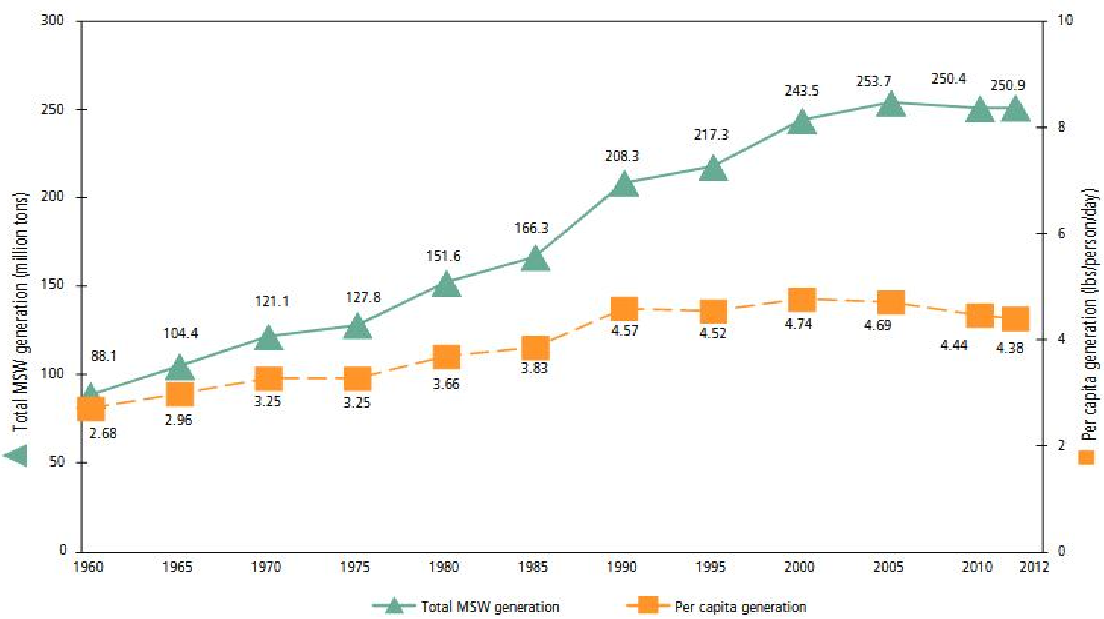


Figure 1. Municipal Solid Waste Generation Rates, 1960-2012 [8]

According to the United States Environmental Protection Agency (EPA), 2.6 million tons of textiles are currently recycled annually. The EPA likewise, reports that present clothing and textile recycling significantly affects diminishing greenhouse gases than the recycling of yard waste, glass, and plastic. Reuse and recycling of clothing and textiles are equal to removing 1.3 million cars and their CO2 emission from America's highways [8]. So, if a typical vehicle emits approximately 4.6 metric tons of CO_2 per year by textile recycling, it is possible to reduce 5.9 metric tons of carbon dioxide [9]. This is a noticeable number by knowing that 270.4 million cars are on the US roads [10].

In the US each person throws away about 36.741 kg of textiles annually [11]. Generally, 95% of the used clothing and textiles have the potential to be reused and recycled, but only 15% of the total amount goes to the recycling process [11]. The United States Environmental Protection Agency announced that in 2013 from 16,030 thousand tons only 2,450 thousand tons were recycled. Figure 2 illustrates the share of each sector in municipal solid waste in 2013 in the US in which the share of textiles, leather, and rubber is 9% [10].

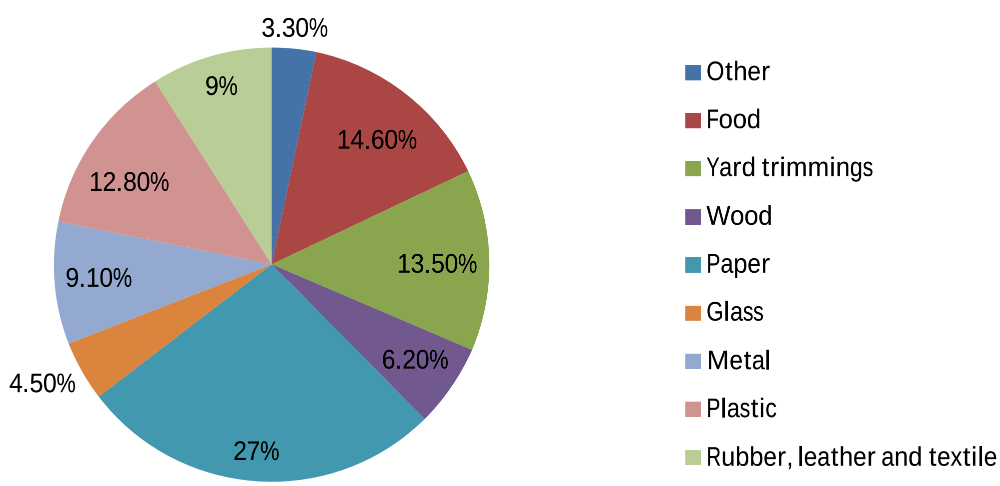


Figure 2. Total MSW Generation (by Material), 2013

1.2 Clothing recycling

Processes such as, for example, recycling and recovery textile, have considerable abilities to reuse a variety of discarded clothes. Although the trend to benefit from recycling garment is increasing in the textile industry, there has not been enough attention in the literature to the performance of such systems. Cue and Vidovic [12] provided a mathematical model for textile recovery process which considers the cost of reverse logistics in the garment recovery process. Due to the limitations in mathematical modeling, it is not possible to consider some critical parameters such as machine repair time or machine failure rate as random. In this thesis, random parameters are considered for modeling, and the aim is to enhance the productivity of the recycling system by proposing various improvement scenarios.

Depending on the factory priorities and their customer needs, the types of machines and procedures used in recycling may vary considerably in each textile recycling facility. Due to the limited available resources, the recycling process of two big European companies and a sustainable fashion brand are used for the simulation model which is proposed in this research. In the textile recycling process, the machine cycle time and failure rate are critical because this industry trends to rely more on machines than labor. Moreover, the quality and variety of incoming products are outstanding because it directly affects the inspection and sorting time. Therefore, system timing and type of material used should also be considered as a vital factor in the simulation model. The final product from the recycling process can be used for secondary applications, or it can be used in the same supply chain (fashion supply chain). The simulation model which is proposed in this work considers different types of cotton shirts as received disposed clothes and also takes into account the total amount of time that each product spends in the system to be turned into the recycled raw material. The objective is to show how to increase the total output of the system by choosing the optimal input parameters and appropriate sequence of the operations. The model is also capable of determining how each component of the system will be affected by the change in the input parameters.

1.3 Apparel industry

Apparel industry has a considerable impact on the world economy. Global apparel exports rose by 48% between 2005 and 2011, to 412 billion US dollars in 2011 [13]. Nowadays, the apparel industry is affected by fast changing trends and growth of mass production, so disposed textile and clothes are growing very fast. Based on recent research [10], in some developed countries like the United Kingdom people throw away 350,000 tonnes of apparel each year [13]. The effect of this growth on the environment and waste management is remarkable due to the amount of fresh water, energy and raw materials which are needed to produce a clothing item, for example, to produce regular cotton T-shirt 2,700 liters of water and 1.808 kWh are required [32]. Considering that the global T-shirt production reaches approximately two billion items it makes the clothes consumption critically impactful.

1.3.1 Fast Fashion

The fashion industry, and specifically Fast Fashion are one of the key textile waste generation industries. Fast Fashion is one of the most critical factors for leading brands, and its focus is to motivate consumers to buy more clothes [14]. Fast fashion is a business strategy that the main purpose is to make fashion products in short, limited series, minimize cycle and lead times to launch new trends into markets as soon as they become available in order to satisfy customer needs. Fast Fashion retailers have their suppliers to produce new items within 3-4 week cycle instead traditional 10 to 15 weeks. Moreover, clothes from fast fashion companies, are affordable, offered in mid-to-low price range with a medium quality [15]. Therefore, customers are attracted to stores due to low prices and latest trends, as products remain on shelves for shorter periods than traditional fashion industries [16]. Customers are aware that if they like an item today, it might not be in store in two weeks anymore so, they develop immediate brain reflexes, even if not having an apparent need. All these changes and new businesses in the fashion industry have had inevitable environmental impacts. In order to reduce environmental problems, fast fashion industries are under pressure to address these issues by, for example adopting sustainable strategies and trying different practices [16]. *H&M*, one of the well-known Fast Fashion brands, located donating boxes in its retail stores so that the customers will receive promotional discount if they put their old clothes to the box to be collected for recycling purposes. Since applying this strategy, they have collected about 89 million T-shirts [17].

Nature of Fast Fashion changed customers' shopping habits by accelerating fashion trends and obsolescence, shortening shopping season duration and shifting customers' attitudes towards disposability of clothes and increased throwaway attitude among consumers. Also, as it was mentioned in section 1.1 and 1.3 fashion consumes excessive amounts of natural resources and generates significant waste, and is therefore not sustainable[13].

Variety of practices can be used in the fashion industry to pursue environmental sustainability. The most important ones used are listed below [18];

- Use of organic fibers (cotton, wool, and hemp) which follow national organic standards for harvesting without the use of toxic, chemical fertilizers and insecticides. In the US, the Department of Agriculture's National Organic Program (USDA's NOP) specifies the standards for growing organic fibers [19]. So by replacing the organic cotton, wool, and silk to the conventional fibers, it is possible to eliminate CO_2 emission and ensure the security of natural resources
- Remanufacturing and recycling discarded clothes
- Reusing second-hand clothes (exporting to the other countries or sell the cheaper in second-hand clothing markets)
- Producing green products with an eco-friendly process and materials
- Green certifications like Global Organic Textile Standards, Eco-label and Global Reporting Initiative (GRI) [15]

On the other hand, the used cotton or wool in the weaving process can have noticeable environmental impacts due to their requirement of water consumption and energy for the production process. Besides, to offer inexpensive products, made in low-cost labor countries such as: China, Bangladesh, or India, in European or US markets, transportation is required [18]. The global usage of textile products is significantly increasing, and predictions show this trend is going to increase due to population growth and economic development [20]. Therefore, GHGs emission, water consumption, toxic chemicals, and waste are the most important environmental issues related to the textile industry and especially cotton cultivation.

1.4 Textile waste

Materials which are thrown away during the fiber and clothes production process and after usage are defined as textile waste. Estimations show that just in 2015, global textile waste was 92 million tons and this number is expected to increase up to about 150 million tons annually by 2030 (63% increase during fifteen years) [21]. On the other hand, based on estimations just 20% of clothing goes to reusing or recycling process, and the rest of them (80%) are incinerated or landfilled [21].

Canada and the United States have a similar solid waste management system which is assigned to the non-profit organizations and textiles are not part of their recycling programs [22]. Data for textile waste generation and diversion towards reuse and recycling are scarce. In the United States, the textile waste rate between 2000 and 2014 is approximately 16% reused and recycled, and the remaining 84% is landfilled [22]. Textile waste in Canada accounts for 5% of the total waste volume annually [23]. Based on a study in 2009, the average American threw away 82 pounds of the garments annually [9]. In Canada, this number is approximately between 30 and 55 pounds of textile per year [23]. Meanwhile, fast-changing trends increase the textile waste amount by attracting consumers to replace old items with new ones at a faster pace. Therefore, this trend will result in irrational consumers to buy more than their need to the point where the average consumer purchases 1.2 clothing items per week [23] [24].

Destination of over 70% of the post-consumer textiles are second-hand markets which even 15% of this amount due to the decrease in demands and their poor quality go to the landfill. Moreover, only 8% of materials passed from the recycling process will be used again in the same industry [12].

There are limited data available to establish a trend line for post-consumer textile waste volume. However, the volume of post-consumer textiles waste in landfills is expected to increase, due to low-cost products. From 1983 to 2013 price of apparel had the minimum fluctuation with a trend to decrease, this leading to a growing trend in consumption and further disposal [23].

The garment industry needs to find an applicable solution to collect and recycle used fibers, the estimated worth possibly 90 billion USD. If implemented, decreasing the use of the raw material in the production process will make the industry less vulnerable to changes in the price of raw material [25].

Forecasts show that the world population is to on its way to reaching 8.5 billion by 2030, and expected apparel production might rise around 63% globally [23]. Thus, there will be an increased need for available land to dispose used material and the energy required for production [23] and need to grow more cotton. That is why there is a need to pay more attention to this issue.

Moreover, most of the fashion trends are produced in a linear system in which extracted materials from the earth are used to manufacture products, and after consumption, they will be disposed. In a linear system, 73% of the manufactured products will end up in the landfill [25] whereas, in a circular production system the aim is to use and recover the used raw material. Currently, in textile circular production system near 15% of clothes are collected for recycling process, and approximately 1% of the material used to produce clothing is recycled into new items [25].

Most fashion products do not take into account recyclability or durability and the textile industry is far away from sustainable used materials and sustainable production processes. It is worthy to invest for the innovative ideas in this area which have a direct impact on the environmental and economic issues, especially considering the population growth and rarity of natural resources [25].

1.5 Closed loop fashion system

Using collection and recycling systems to reuse post-consumer textiles in the same industry or other industries, can be used to make a closed-loop fashion system [25]. Figure3 shows the required steps to change a linear production system to a closed-loop system. Circular production systems have fewer flaws than the liner systems due to the using less raw materials and natural resources.

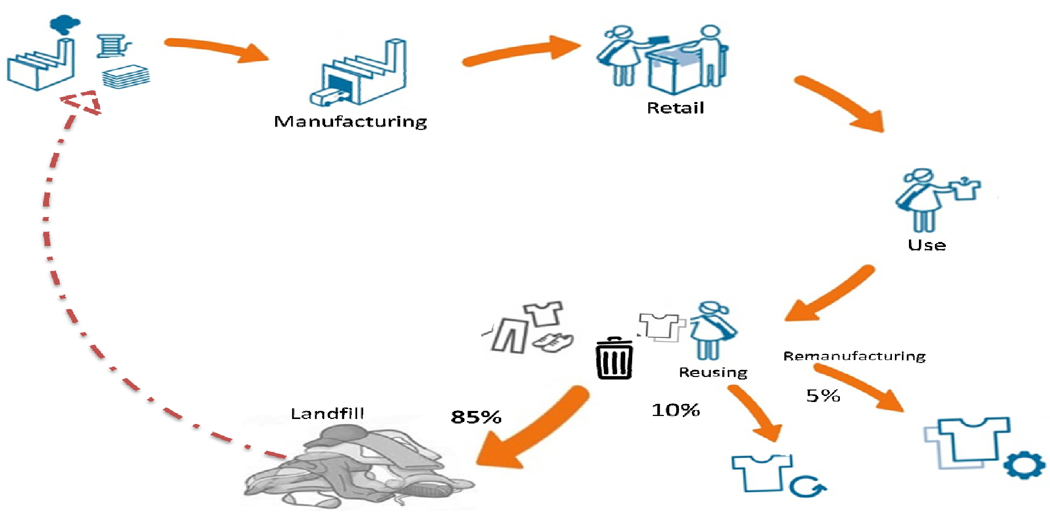


Figure 3. The Closed-looped supply chain network for textile manufacturing adapted from [26]

The environmental impacts of various textiles waste can be divided into multiple categories. Biodegradability, product type, and used materials are some factors can have impact on the environment. In addition, even natural fibers like cotton and wool are included in this list because in the production process these raw materials need to be dyed or bleached.

By recovering and recycling used clothes and get those back to the fashion supply chain to be used again it would be possible to keep them out of the landfill for a longer time. Also, more fresh water can be saved due to the reduction of cotton growing and cultivating, and the soil quality will not decrease. Moreover, considering the reduced purchase of second-hand clothes in the third world countries which were the final destination of these products in the past, there is a need to develop replacement methods. In figure 4 the pie chart presents the shares of sub-sectors of the textile industry where the share of woven material (including clothing) is more than the other sections [31]. So by reusing materials from products such as, for example, a T-shirt or jeans, the impacts would be more significant in the environment.

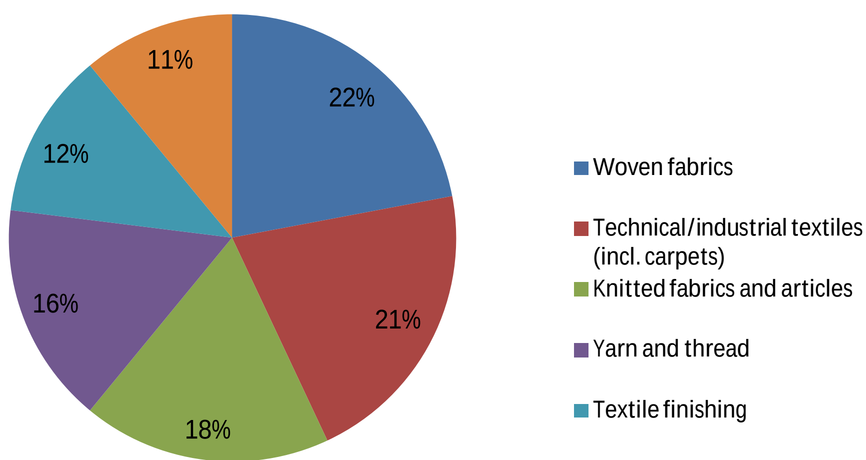


Figure 4. The share of sub-sectors of the textile industry

1.6 Mechanisms to recover the value of used products

Greenhouse gases emission, fresh water consumption and the amount of waste are the most important environmental issues related to the textile industry, especially business strategies like Fast Fashion [27]. From an environmental respective, the replacement of used products is generally detrimental. According to previous studies, there are five ways to recover used items which are listed below;

1.6.1 Repair and reuse

The definition of repair applies to restoration of broken, worn or damaged product to the working order, whereas, recycling is defined as converting the used material to the various items with a different application [28]. Many research papers which focus on clothing waste emphasize the benefits of reusing which repair could be part of it [29].

Reuse process is preferred for recycling as this method provides a more significant environmental benefit even with low substitution factors [28]. On the other hand, there is a concern that most of the clothes for reusing purposes end up being exported to the third world or developing countries, which can undermine the viability of domestic producers in these countries [12]. In addition to the economic impact, most of the exported items especially from North American countries are not suitable for people living in developing countries because the clothes are not the proper size or consumers prefer to purchase from domestic brand to help the economy. Therefore, people are not willing to purchase second-hand clothes as much as in the past causing more waste landfilling. Also, because of some new business strategies like fast fashion, the quality of clothing has fallen, so in some cases, customers of second-hand clothes believe that it is not reasonable anymore to buy SHC.

1.6.2 Remanufacturing and upcycling

Remanufacturing is a process that gets back a product to its useful life cycle by upgrading its quality while the main purpose is cutting down the use of raw materials. Remanufacturing process involves different activities such as; disassembly, inspection, cleaning and finally creating an almost-new product with restored quality. Some of the major concerns with remanufacturing are: the uncertainty in timing and quantity of returns, balancing returns with demand, disassembly, reverse logistics, materials matching requirements, routing uncertainty, and processing time uncertainty.

The concept of remanufacturing formed after the Second World War when there was a short supply of fashion clothing. At that time the UK government started a campaign to encourage people to make a modern style from their old clothes [13]. Recently, in context of sustainability, this idea has been re-considered to minimize fashion wastes which end up in the landfill.

Moreover, upcycling can be used along with other waste avoiding processes. It means that by using upcycling in the designing step it is possible to create or transform an old product in to upgraded one that can have an equal or higher value than the original item. Upcycling can include reuse and remanufacturing processes, and a final item is a new form of old product, for instance, cutting blue jean into a skirt or converting a T-shirt into a tote bag. This concept is an exercise which is acceptable as a sustainable designing method, but it is sometimes expensive as expected due to time spend for designing and sewing [24].

On the other hand, it should be noted that upcycling cannot replace remanufacturing and vice versa due to the differences between design methodology, material process approach, and product final application. The process of upcycling is to build a crafted and unique product which in most cases requires manual activity but, in remanufacturing process, industrial procedures can be used in a manufacturing environment and final products are reproducible [13]. The upcycled products can find a different purpose from their original use, while in remanufacturing the resulting product maintains the same purpose. Therefore, replacing or adding some elements to clothes refreshes their look but, the main issues with the mass production of upcycled fashion items are variety of fabric types making it unfeasible to scale, labor-intensive and time-consuming processes; driving the cost up [30].

The most significant positive impact of remanufacturing and upcycling activities is that it keeps textiles out of the landfill. Woolridge et al. [31] stated that 65 kWh of energy would be saved by just substituting one kilogram of virgin cotton with discarded apparel. As the customer throwaway attitude is becoming more prevalent, implementing different practices is needed to manage garment waste [31].

Textile is one of the fast-growing waste categories across the world especially in countries with rising populations such as the EU countries and the United States since these countries are the major market for fast fashion products. Most of the generated waste will end up into the landfill and are out of use. Disposing clothes into the landfill is wasteful, and processes involved in the cotton growing stage are hazardous for the society. For example, based on the estimation about 99.9% of pesticides used in cotton growing take its toll on the environment and only 0.1% of total amount (is about 150 million tons) reach target pests [32]. The pesticide reminds poison fresh water, air, and soil. Although reuse SHC has smaller environmental impacts, the mentioned methods such as, for example, reuse, cannot be a viable alternative in the near future because the production rate of waste textile is increasing dramatically (the increase rate is shown in figure 5). Thus, there is a need to find new ways of disposing of used clothes.

1.6.3 Recycling

Many studies claim that textile recycling is better than incineration due to its reduced environmental effects [28]. However, some African countries inhibit imports of used textiles by restrictions, and high taxes in order to protect their own textile industries. This motivates some of the textile recycling companies to look for alternative solution. It is inevitable that in the absence of a reuse system SHC will be landfilled [33, 34].

The origins of garment recycling/recovering can be tracked to 2- million old practice in China, where old clothes were shredded and reprocessed by hand to create new material for the production of new textiles [11]. According to Secondary Materials and Recycled Textiles (SMART), textile materials can be brought back to production to be used in new products. Generally, 95% of unwanted textiles can be processed through recycling, and the remaining 5% that do not have the minimum required quality for recycling (wet clothes) can be cut into wiping rags and polishing cloths [24]. In this thesis, the main focus would be on the recycling process of cotton shirts.

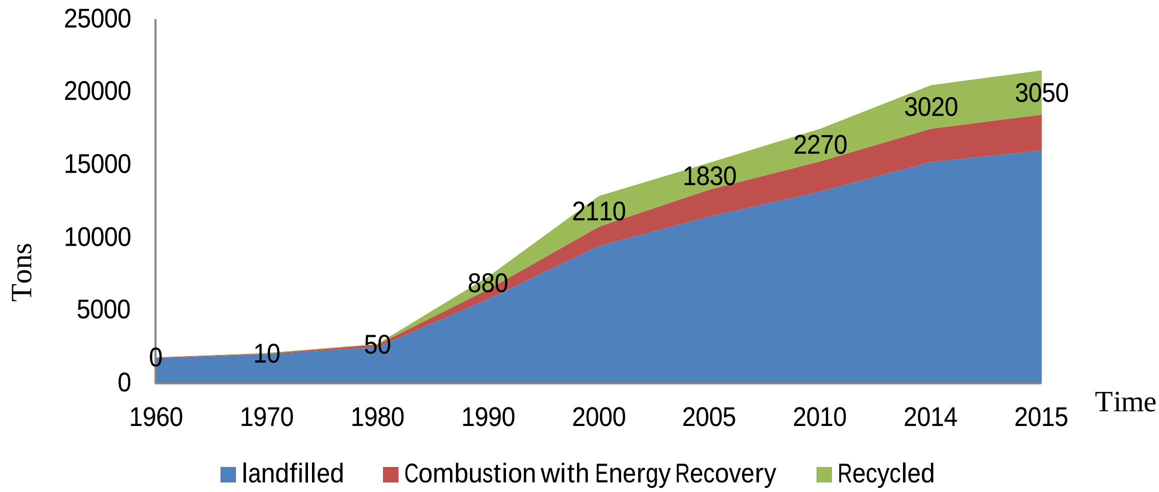


Figure 5. Textile waste management in the US from 1960 to 2015 [8]

The growth in landfilled and recycled textile from 1960 t 2015 is illustrated in Figure 5[8]. This trend is expected to increase in the future due to population growth and fast moving trends in the fashion industry [8]. In 2015, the recycled material weight was approximately 2,450 thousand tons (15% of textiles in MSW, which is 16,030 thousand tons) and more than 60% of generated textiles waste goes to landfills directly.

Cotton textiles can be recycled by using two methods: mechanical and chemical recycling. In chemical method, there is an obvious need for water and chemicals for dyeing and bleaching. The difference between two types of recycling (mechanical and chemical) is the wet processing that is eliminated or reduced in the mechanical recycling system. The focal center of the research presented here is on mechanical recycling which is a new concept in garment recycling that the color of final materials (recycled) is not taken into account and the color depends on the incoming products (mostly a shade of gray).

The general process of mechanical cotton recycling for apparel involves the respinning of waste fibers. Given that the mechanical process breaks the fiber, quality and strength of fibers are reduced and therefore, the recovered staple fiber must be blended with raw materials to impart increased strength. Thus, the outcome of this process has acceptable quality to be used as raw material in the same industry.

Other applications of recycled fibers as feedstock materials include a variety of nonwovens used for insulation, automotive industry, agriculture purposes, and oil sorbent sheeting, but the resale value of these kinds of material is lower than spun yarn. If input materials be over processed (shredded) most portion of the final products/ finished goods are just capable of being used in other industries despite the short length of fibers.

Chemical textile recycling has broad use in comparison with the mechanical method, but consumes chemicals and water for wet processing. Also, energy is required for heating and scouring processes. In comparison, mechanical recycling reduces the water consumption by up to 70% [2]. Mechanical method has some shortcomings such as: low-quality output due to the short length of fibers, longer processing time, and lower production rate. Therefore, the primary challenge cited as preventing widespread adoption of closed-loop respinning is how to effectively increase the volume of material collected and processed.

1.6.4 Reasons to do recycling

A textile recycling company did a sampling survey on a textile bank in England. The results from this survey show that from total 44,000 kg of cotton products 9,800 kg were recyclable (22.3%). Also, 31,400 kg and 2,800 kgs were wearable and waste respectively [35]. The survey also provided statistical data for post-consumer textile product waste. It is understood that most of the post-consumer material is used as second-hand clothes and only 7% of the total material is used as reprocessing fiber. Roznev et al [35] noted that waste from textile and other clothing had a dramatic rise from 1.4 million tons to 2.35 million tons, which 1.2 million tons of textile were disposed of as waste and

324,000 tons were collected by secondary textile industry for reuse or recycling. Moreover, more than half of the disposed clothes are donated to charities. Charities usually give the clothes away, sell them at lower prices in flea-markets/second-hand stores or the textiles are exported to foreign countries. Unsalable clothes in charity shops will be sold to textile recovery facilities or will be landfilled. Roznev et al. [35] also state that non-recycled textile waste constitutes about 4 percent of the landfill waste globally. So it is understood that the textile waste problem is a global concern.

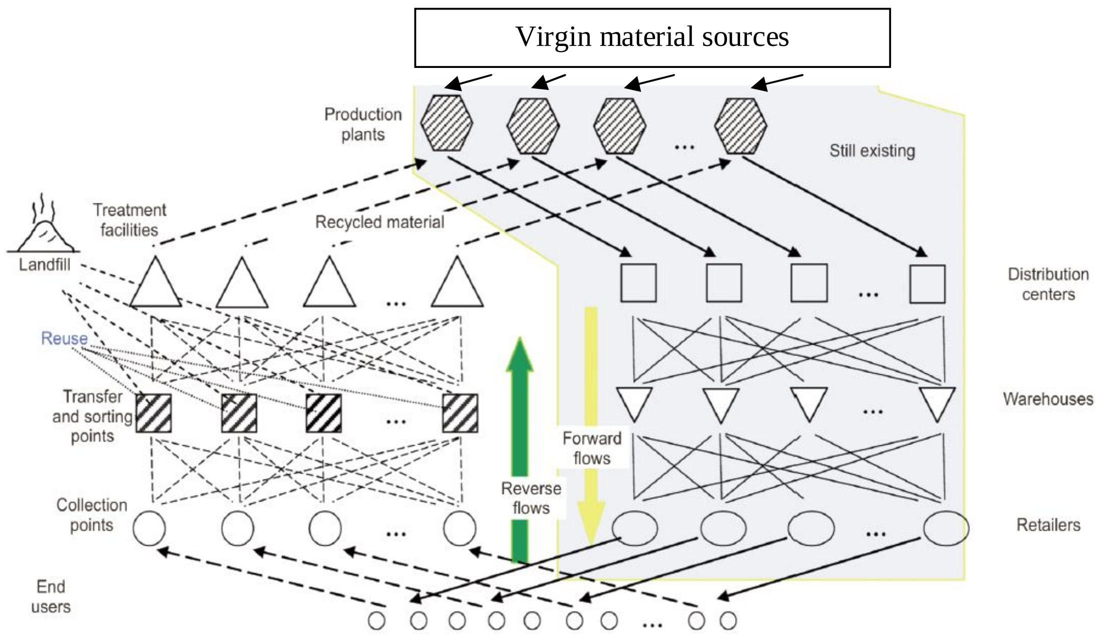


Figure 6. Textile closed-loop network [12]

The supply chain network in figure 6 illustrates the potential ecological and general benefits of textile recycling and the importance of recycling. The usage of raw material will be decreased, and there will be less landfilled waste than a linear production system.

1.6.5 Disposing

Consumers are more likely to donate expensive clothing because they feel guilty to dispose of an expensive and high-quality item which was worn only a few times while cheaper clothing would more likely be thrown away quickly[29]. Therefore, the new trend, offering closing at a more affordable price, will convince more people to dispose of their unwanted clothes instead of donating them.

The policies of some of the used textile collecting companies differ between each other, for instance, one of the garments collecting companies, based in Denmark, is trying to encourage people to recycle and donate more clothes to that company by offering them some promotions to use for their next shopping trip. Also, they distribute special bags for collecting clothes with a capacity of approximately 10kg. Based on the surveys people are willing to get to that specific amount of textile faster while they are using specific plastic bags [5]. All these practices mentioned in section 1.6 are used to reduce landfilling.

1.6.6 Landfill Disposal

The least desirable disposal method for solid waste is to send it into the landfill. The reduction of generated waste and to keep waste out of the landfills to protect the environment is the primary purpose of solid waste management. Physical and available space for landfilling is a big concern in the US and other developed countries.

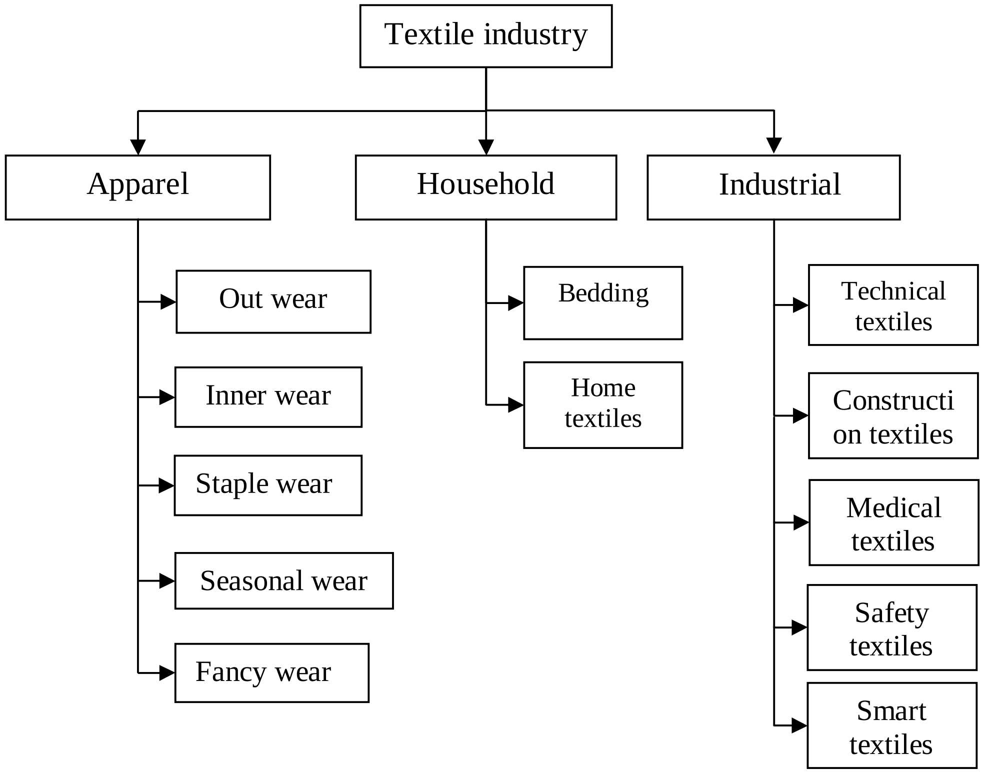


Figure 7. Businesses involved in the textile industry

Figure 7 illustrates the different businesses involved in the textile industry. In all the mentioned businesses there will be a noticeable amount of waste which needs to be eliminated to reach a green closed loop supply chain. However, the focus of this research is on basic clothing recycling. Different business strategies such as, for example, high fashion, fast fashion, and conventional fashion can be applied for apparel production with different types of materials. Figure 8, shows the classification of fibers. Among natural fibers cotton is the most used, while polyester stands in the first overall[36].

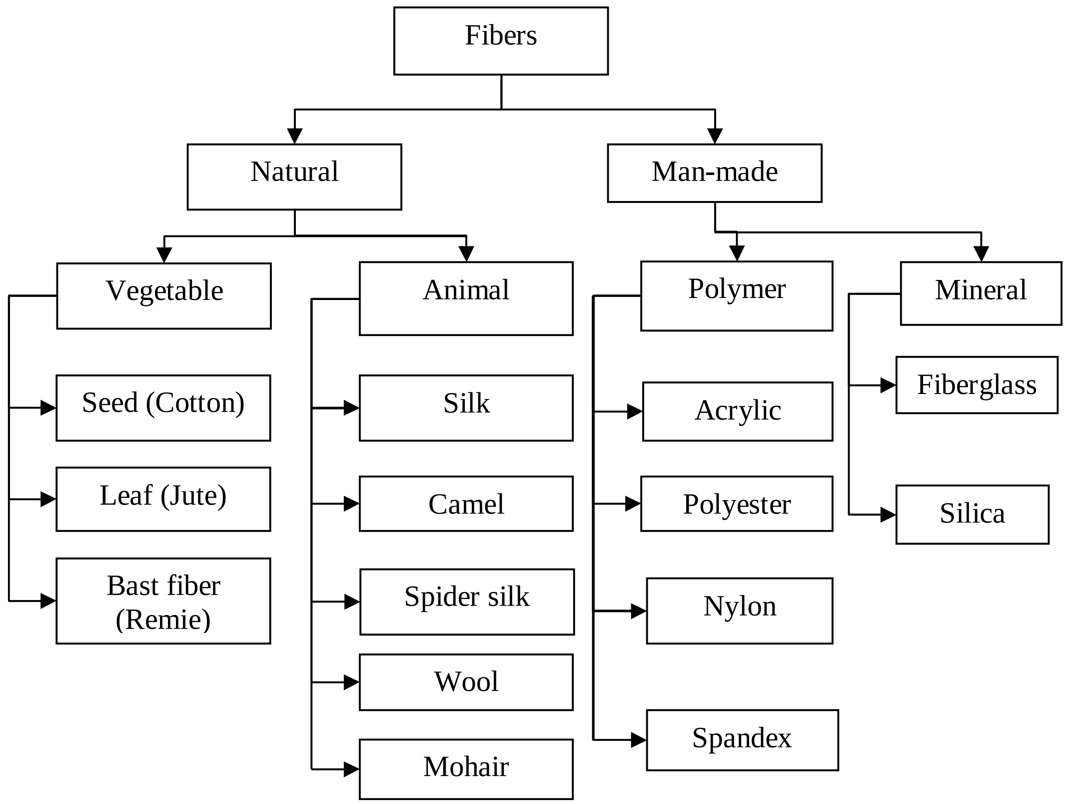


Figure 8. Classification of fibers

1. 7 Share of different material in clothing

Around 60% of clothes globally are made from synthetic fibers such as, for example, polyester and nylon [37], and the rest are made of cotton and other materials (Figure 9). Cotton has been used to produce clothing since 7,000 years ago, and it is the most common fiber among natural fibers due to its soft texture and breathability [36].

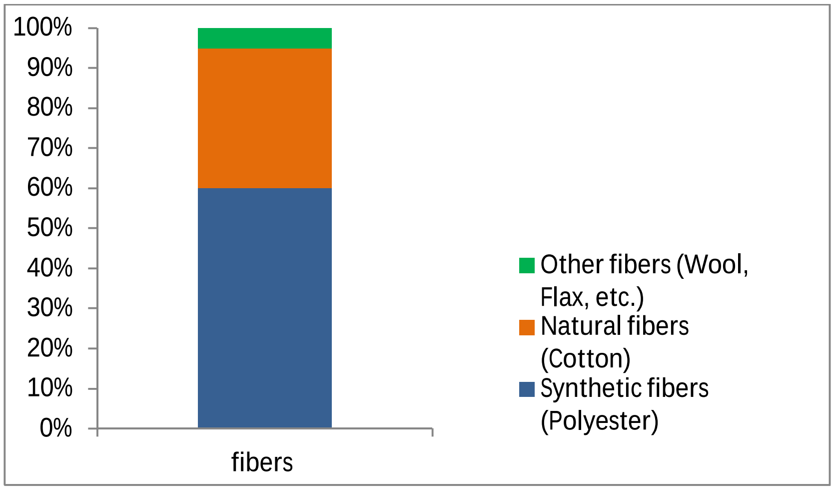


Figure 9. The share of different fibers in clothing in 2010

World fiber production is increasing significantly, for instance, it is expected cotton growing to increase up to 27 million metric tons in 2020 [38]. Carbon footprint, water consumption and land usage for fiber production depend on the type of used material in it. In figures 10 to 15, energy consumption and carbon footprint for the life cycle of a t-shirt made of cotton, polyester, and recycled cotton are shown. These diagrams are provided based on the database of CES EduPack by using Eco Audit tool [39]. The results are related to 10,000 T-shirt of 226 grams weight, which requires worldwide transportation (using ship, train, truck).

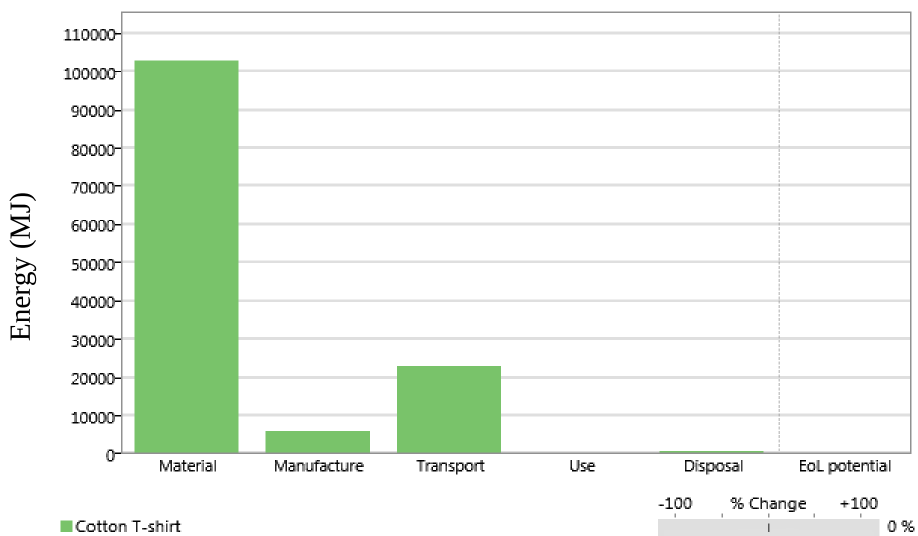


Figure 10. Energy consumption for production of 10000 cotton T-shirts

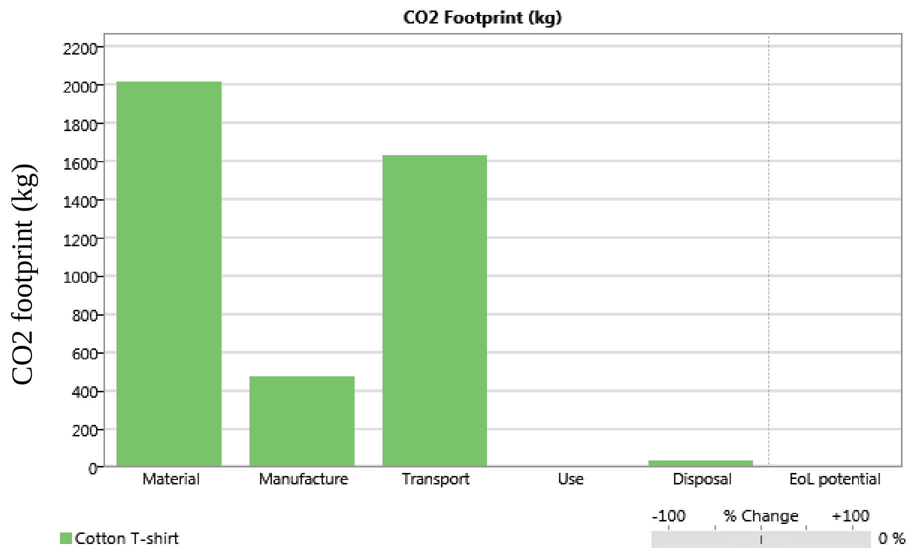


Figure 11. The carbon footprint for production of 10000 cotton T-shirts

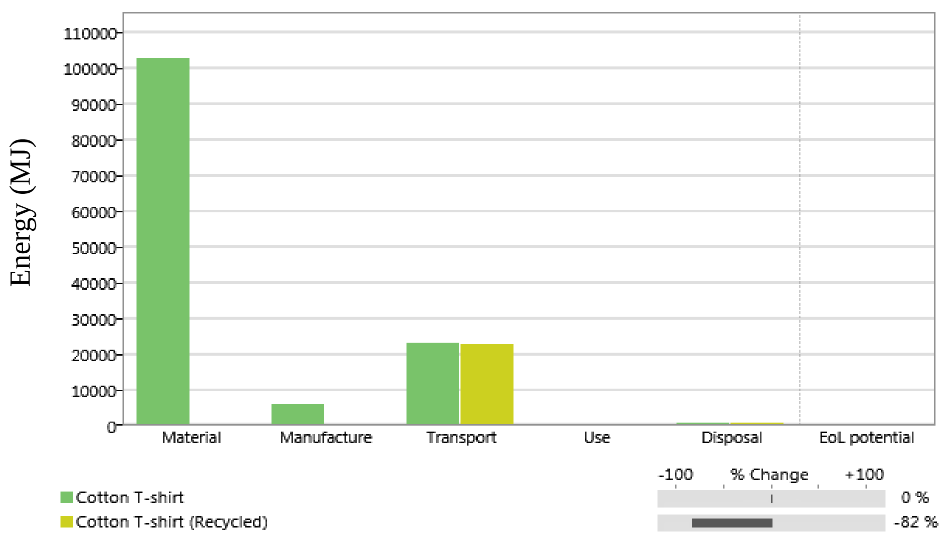


Figure 12. The comparison of energy consumption for cotton and recycled T-shirts

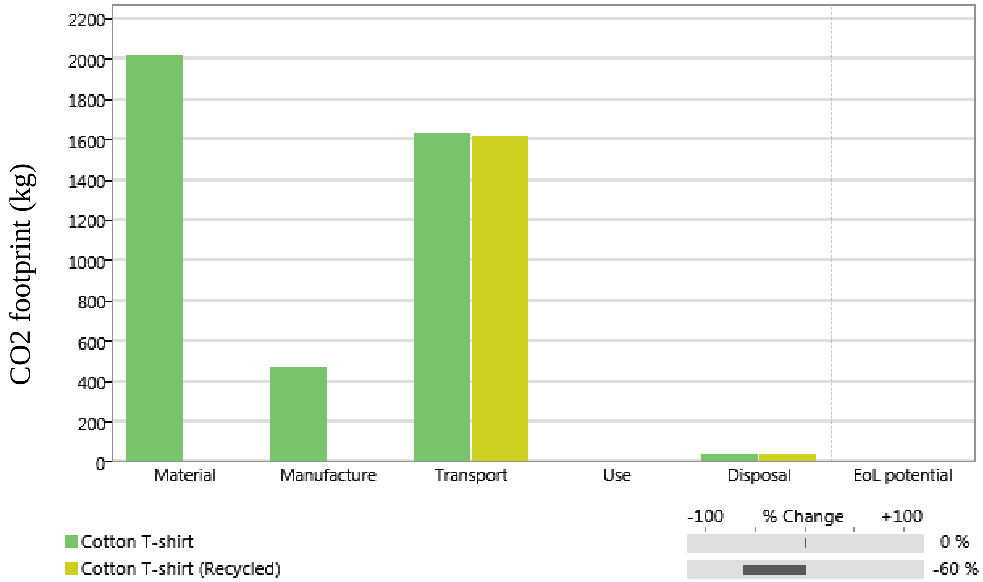


Figure 13. The comparison of the carbon footprint for cotton and recycled T-shirt

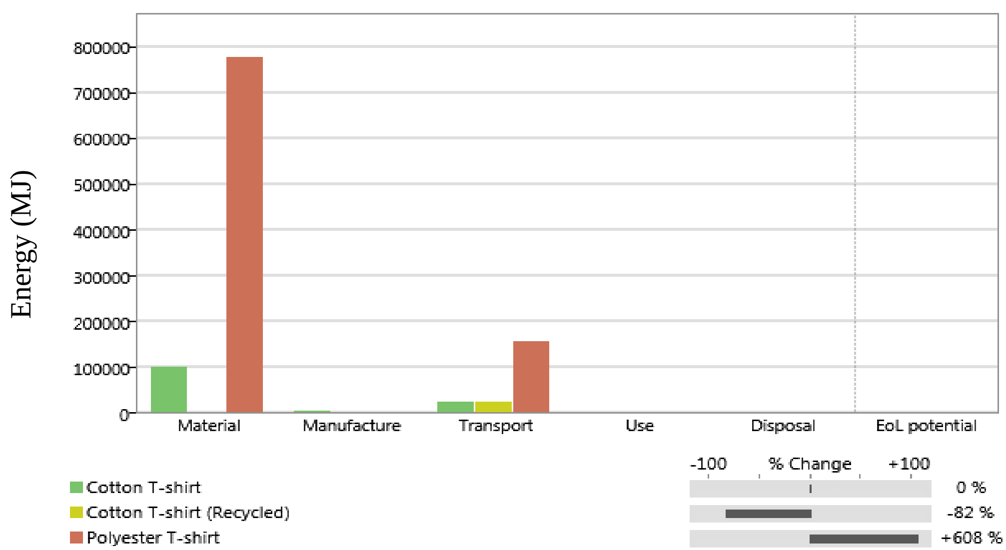


Figure 14. The comparison of consumption for cotton and recycled and polyester T-shirt

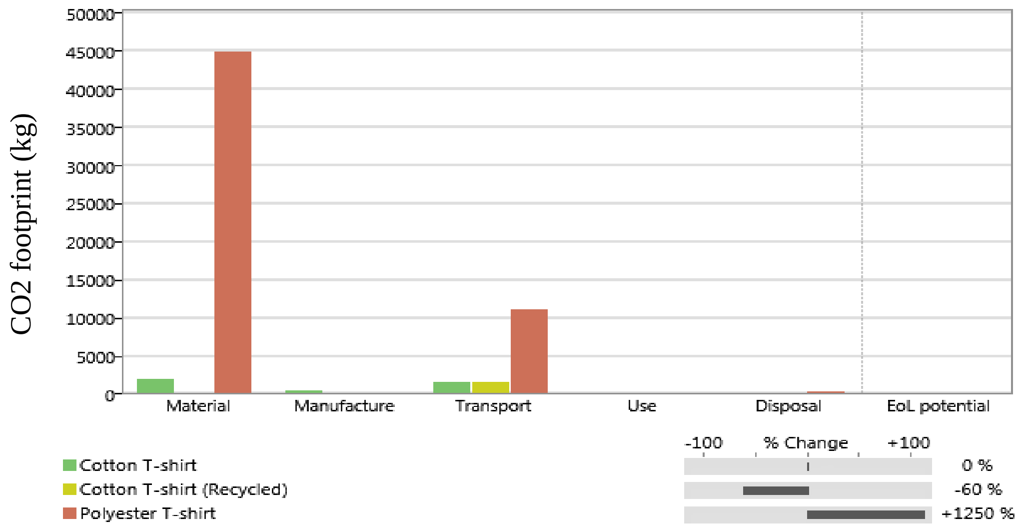


Figure 15. The comparison of the carbon footprint for virgin cotton, and recycled cotton, and polyester T-shirt

As it is illustrated in figure 12 and 13, energy consumption and CO_2 footprint for material and manufacture categories are eliminated for T-shirt production with recycled materials. It can be seen in figure 14 and 15 that polyester has the biggest carbon footprint and highest energy consumption among other materials, however, the amount of energy used for cotton production and T-shirt manufacturing is still noticeable.

1.8 Problem statement

Textiles are often associated with clothing which includes a large portion of this industry. Consumption of clothing has been increasing significantly. People shopping habits have changed in the past few years. Growing variety of clothes for different purposes are available, and that drives consumers to buy more non-essential apparels than before.

New production methods for clothing improve throughput and lower costs. There is a high demand for new fashions and people could have access to different products at a reasonable price. However, most of the fashionable items loose their appeal after a short period, as the obsolescent fashion with new ones. This growth in apparel consumption requires more space to dispose old clothes and more resources to make new products.

While many new and innovative methods are introduced for apparel production, limited researche is focused on disposed and use of post-consumer materials.

The chemical textile recycling process required use a considerable amount of water and chemicals which make this process eco-destructive. So, other innovative methods which do not use water during the process can be more efficient in saving fresh water.

1.9 Contribution of this research

Based on the conducted literature review, no existing comprehensive model was identified to analyze the traditional cotton recycling system in order to identify the potential improvements (throughput, human resources, and machines utilization) and introduce a new process which is capable of delivering such enhancement.

Therefore, a simulation modeling approach was applied to identified and evaluate various improvement opportunities and quantify their impact on the system. The objectives of the model presented in this study are to:

- Reduce the process lead-time
- Minimize the number of human resources needed
- Indicate the type of material for traceability purposes
- Monitor server's (machines) performance continuously
- Applying a job shop manufacturing system to introduce the new layout for recycling process

1.10 The objective of the study

The performance of flow shop manufacturing systems like textiles recycling which the input materials need to go through the same route to be processed highly depends on machines and human resources performance. Bottleneck stations can increase the production lead time. So by modeling the system and monitoring machines performance, it is possible to find the bottleneck stations in which a considerable volume of semi-finished products are in the buffer state and waiting to be processed. Therefore, the simulation model is used to find these stations and then take a proper action to find how and how much it is possible to decrease lead time which affects the system throughput.

1.11 Proposed approach

Previous research papers identified the environmental issues related to cotton recycling process which they all considered chemical recycling process in their studies. The majority of available research was done to find the impact of materials used on the environment and the quality of final products [40]. The quality of recycled yarns with a combination of percentage of raw materials is almost the same as 100% virgin cotton yarn [41]. So, the output materials are applicable to use as raw material to produce new fashion items. Moreover, the environmental concerns of mechanical recycling are significantly lower than disposing methods such as, for example, incineration or landfilling so in this study the recycling process is analyzed via simulation approach.

- Build a model of existing process
- Analyzing its performance using simulation scenarios
- Identify opportunities for improving by
  - Follow of goods
  - Technology updates (update model, repeat analysis, and compare the scenarios)

Therefore, to propose a novel recycling process with a new sorting and inspecting system a simulation model is provided to examine the changes and evaluate the results. Due to the complexity of the process and numerous random variables, methods such as mathematical modeling are not suitable for solving this type of problem.

A discrete event simulation model (the state variables change instantly at a separated point in time) is proposed to study the interactions of different components of the system. By varying the parameters and applying analysis methods like sensitive analysis allows finding the best production method in order to maximize the system outputs. By simulating the operation of the exits system, it will be possible to monitor the results of applied changes. For designing and analyzing manufacturing systems discrete event simulation can be used as a tool. For this purposes in this study, Enterprise Dynamics version 10.1 is used.

1.12 Research outline

The second section of this study presents a detailed literature review of the previous works. The third chapter includes the proposed model and steps involved in creating a simulation approach along with assumptions and notations. In the fourth chapter verification steps and validation and computational results from running different developed scenarios are presented. Finally, the last section of this study provides conclusion and possible direction of future studies.

CHAPTER 2: LITERATURE REVIEW

This study considers the recycling procedure of a simple product like a cotton T-shirt in the textile industry. The after use phase involves three different sections such as; recycling, reusing and remanufacturing. The focus of this research is on the recycling process.. The relevant literature is reviewed for all of the mentioned methods including the fast fashion industry and reverse supply chain modeling in the textile industry followed by a gap analysis.

2.1 Relevant literature review

Aggour et al. [14] examined the appearance of the fast fashion model based on ZARA business model as a pioneer in the fast fashion industry. They also analyzed a domestic retailer brand to find its strength from a supply chain management point of view and to propose a better fast fashion model. Their studies include different parts such as: design, sourcing, manufacturing, distribution, and retail to highlight the differences between a local and a big company (ZARA) model, but the share of the fast fashion in the textile industry is not mentioned (or investigated).

Caniato et al. [15] proposed case-based research in order to review the impact of the following factors: consumers who force companies to use green processes, various activities to develop sustainability, and finally the environmental KPIs for fashion companies. They have also compared international companies which are green brands with small businesses applying alternative supply chain networks. For analysis of performance, they focused on finding critical environmental criteria that companies are trying to improve by doing ‘‘green’’ practices.

Turker and Altuntas [16] tried to show the current situation of SSCM in the fashion industry by providing a conceptual map based on reports from nine different companies. According to the analysis the main focus of mentioned companies is on supplier agreement, studying different practices to prevent production issues for their business and having progress in supply chain performance.

Esteve-Turrillas and Guardia [40] discussed the impact of recovered cotton which is made of cotton fiber from both dyed and recycled materials. They also discussed that by use of organic cotton reduces the amount of harmful pesticides and chemicals can be significantly reduced. They observed and evidenced that use of recovered cotton to produce high-quality textile, adds value to the product from an environmental perspective. Moreover, the other environmental issues are dramatically decreased by of a recovery technology that eliminates cultivation, ginning and dyeing processes.

Bevilacqua et al. [42] focused on various environmental impacts of the cotton yarn production in major phases, e.g, cultivation, washing, and drying. It was a study the cotton supplied by four factories from different parts of the world. Their results showed that the dyeing process is most armful in cotton yarn production (1.24 CO_2 kg-equivalent), and followed by spinning process. Another key observation was updating the dyeing equipment may allow reducing CO_2 emission by 41.7% .

Zamani et al. [2] proposed three different methods for recycling processes for a specific waste that includes 50/50 mix of cotton and polyester to determine the environmental effects of each of them. They revealed that the material reuse process has the minimum carbon dioxide emission. They also collected data related to energy demand for each step involved in the textile recycling process.

Cue and Vidovic [12] examined the process of recycling disposed textiles to attain environmental sustainability. They proposed a mathematical model for a recycling process by considering both financial and environmental issues. The objective function is to minimize the cost of reverse logistics for textile recycling and its impact on raw material usage. The model was based on an existing network to establish reverse logistics. The results showed that the second-hand clothes exported to developing countries can cause some economic problems in the local garment industry. Therefore, the government is responsible for establishing the recycling process as a value-added concept.

Li et al. [43] attempted to find the impacts of social responsibility actions on the environmental effects of local companies in the fast fashion supply chain. They analyzed the corporate motives for applying sustainability governance in the fashion supply chain then discovered different sustainable features on the FF items. The case study on H&M tracked the benefits of governance mechanisms in fulfilling sustainability requirements.

Baydar et al. [44] studied the differences between the production of a conventional T-shirt and an Eco T-shirt. Admittedly, the T-shirt from organic cotton and dyed in the green dyeing process has remarkably reduced impact on the environment (greenhouse gas emission, and water consumption). They showed implementing such a green process can decrease aquatic eutrophication potential (97%) due to the removal of chemical fertilizers. For their research, they use four life cycle scenarios for regular, and Eco T-shirt and they assumed that incineration is the method to dispose of a T-shirt.

Muthu et al. [45] focused on textile materials to specify degree of recyclability in terms of environmental effects and economic profit. The price ratio between the raw material and recycled fiber was proposed as a metric of economic benefit from recycling methods. According to their proposed model, cotton is ranked sixth among ten materials assessed on recyclability.

Ganassi et al. [41] explored a new recycled and low-cost yarn made by presenting a new spinning process. The DOE approach was used to find the optimimize setting of recycling procedure. As the results it was deremind that the 50/50 blended yarn has almost equal quality and physical properties, similar to the whole cotton yarn. Spinning yarn with 50% of recycling fibers has also a noticeable impact on the price of yarn. The cost of raw materials in blended yarn was half of the total price. According to their study, the essential advantage of blended yarn in compare with pure cotton yarn was the decreased manufacturing cost by 33.5 %.

Moretto et al. [46] developed a sustainability roadmap for fashion firms. The five-step roadmap which can be used for the possible methods of improving the fashion productions. Fashion companies can design a roadmap considering sustainability and some exercises to be used in the supply chain network.

Dissanayake and Sinha [13] studied remanufacturing processes and the reverse supply chain requirements for fashion products. Study was based on five fashion companies in the UK. All obsereved remanufacturing processes required three major steps such as: collecting, sorting and cleaning. They considered five different sources the second-hand clothes were supplied from five key source: charity shops, consumers, SHC wholesalers, fabric merchants, and waste collection and sorting facilities. While usually remanufacturing businesses have low volume production, by implementing new collecting scenarios and making a connection with retailers there is a potential to increase the production volume and decrease the total production cost. The current sorting and disassembly process could be replaced by more efficient new technologies.

Sandin and Peters [20] reviewed the effects of recycling and reuse in the textile industry. Based on forty-one studies cotton and polyester were found to be the most studied materials. Most of the research originated in the Nordic countries due to their well organized waste collection and being the home of some fast fashion brands, (e.g. H&M). landfilling or incineration with programs like clothes reusing and recycling replacing has positive effect on environment.

Chen et al. [47] studied recycling of products with a short life cycle and its effects on the global supply chain. A mathematical model to minimize operating costs in the textile supply chain network was used. In the MIP model, product demand in different markets and the use of the recovered material was considered.

Birtwistle [29] found in his qualitative research that consumers are not aware of the needs for clothing recycling. Moreover, fast fashion consumers with throwaway attitude are willing to replace and dispose of fashion item before its defined life cycle. Meanwhile, the interviews conducted, indicate that media might be helpful in changing people’s shopping and disposal habits by increasing consumer awareness about the sustainability of fashion clothing.

Newell [24] studied the New York state recycling system in her study. This qualitative research covered reusing, upcycling and recycling systems. The main focus of the study was on efficiencies and inefficiencies in the textile waste recovery system. A survey on consumer behavior about disposability was taken to collect the primary data, analysis of which confirmed that consumer’s education and cooperation can be the key factor to keep textiles out of landfills.

Malilay-Pimentel [23] identified various practices to reduce textile waste flow to the landfill with policies. The author suggests additional bins for collecting all kinds of textiles (not of a specific type). The only condition to be met is that disposed items should be clean and dry in plastic bags. Also, an education campaign was proposed as a means of improving public awareness.

Carbone et al. [28] stated in their report that, to minimize the environmental impacts there is a need to increase reuse and improve collection process for recycling discarded materials. In order to reach this goal, methods such as: for example, evaluating the reuse and recycling systems or recognizing similarities and diversities in approaches to reuse and recycle apparels were proposed. The study also estimated textile flows in Denmark in 2010. Based on those estimations out of 89,000 tons of raw textiles only 12,000 tons go to the reusing process, 23,000 tons are exported to other countries, and 24,000 tons are directed to the landfill as waste. A considerable amount of raw materials which does not go to the separately collecting processes are part of municipal waste or go to an unknown destination, shows the importance of an appropriate collection method.

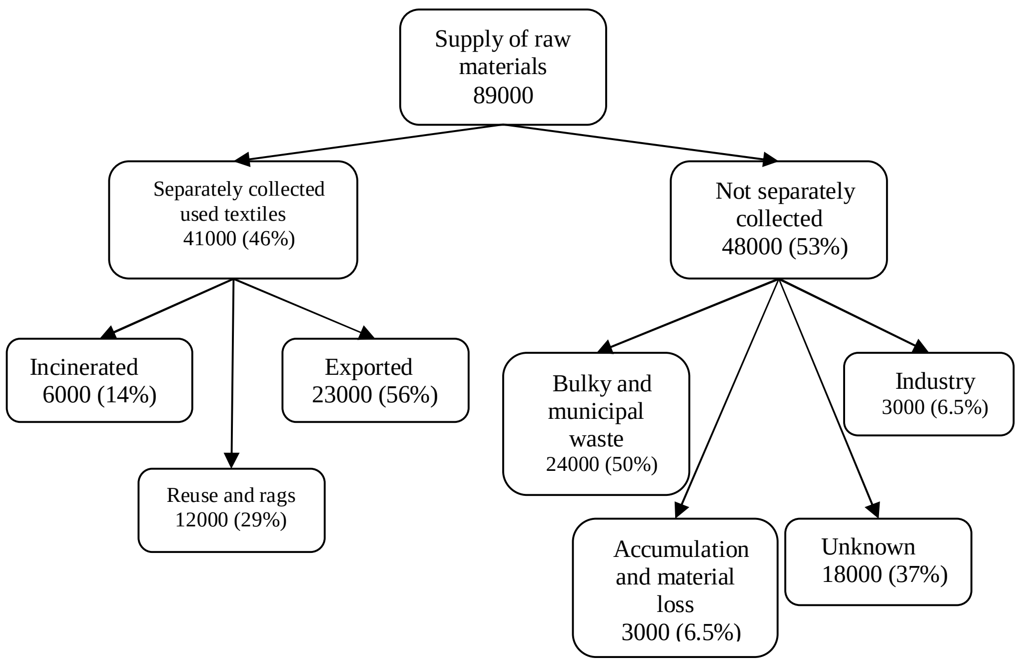


Figure 16.Textile Flow (in tons) in Denmark, 2010 [28]

Allwood et al. [48] studied material flows clothing and textile in the UK. Their work is one of the most referenced European studies in the textile waste industry due to its comprehensive nature.

The Cloudio's study [34] goes over the different environmental effects of textile industries. His paper discussed various steps in clothes production and some hidden aspects of this industry such as poor working conditions.

2.2 Gap in the literature and plan of work

Based on the conducted literature review, the majority of the research on reuse and recycling textiles or fashion products focused on environmental impacts by studying or comparing the type of materials, energy consumption or comparing the effects of incineration and landfilling on the environment. Cuc and Vidovic paper [12] seems to be the only research which provides a model for sustainability through clothes recycling. It proposed a mathematical model to minimize textile recycling costs and its effect on raw material consumption, reducing landfill usage. They also tried to simplify the assumption due to mathematical modeling limitation. Providing a model which considers a method to recycle a product and bring it back to its life cycle by applying a simulation approach which considers different improvement scenarios was not found in the literature.

In this research, a simulation-based experimental methodology is used to understand the impacts of different scenarios and production methods on the recycling system. The performance of servers is observed to apply improvement alternatives. By using the experimental methodology, the effects of each factor on the system can be understood. Moreover, by using simulation modeling method, it can be possible to consider machine downtime, average repair time, servers blocking time and several other parameters. All these parameters are valuable to monitor the performance of the whole system. This simulation-based model will be helpful to predict the system behavior, and it gives us the ability to analyze and redesign the actual system (real-world).

In order to summarize the relevant studies done in this area, a synthesis matrix is prepared for this purpose. Table 1 contains the reviewed papers in this chapter with a brief description of the solution approached and the objective of each research paper.

CHAPTER 3: SOLUTION APPROACHED AND WORKING ASSUMPTIONS

Analytical models are beneficial in presenting the problem concisely, providing a series of closed-form solutions, permitting assessment of the effects caused by changes in inputs on output measures, and providing the chance of reaching the solution. Their main shortcomings are related to the simplifying assumptions created to explain a system that might not be similar to real word problems or the mathematical model which can be complicated due to the problem size which could affect the optimum solution [49].

In simulation modeling, there is a possibility to model and describe complex systems, and it can be used for systems which do not yet exist or to study an existing model without making any changes and saving unnecessary costs. One of the weak points of these problem types is that they do not present a closed set of solutions. Each change made in the input variables requires a separate solution or a series of runs. In the following situation simulation can be used as an effective;

- The problem has no mathematical formulation
- There is a mathematical model, but it has no determined analytical solution
- There is a model or method, but the procedure to solve the problem is difficult
- When the aim is to experiment with a model before configuring the system
- It is impossible to do experiments on the real system
- It is possible to do experiments on the real system, but there are ethical reasons involved that don’t allow the experiment to take place [49]
- When studying the real system is costly and time-consuming
- When a prediction is needed for the system outputs

3.1 Simulation models

If the relationships between different parts of a system are simple, it might be possible to use mathematical modeling to study the system [1]. In real world majority of the systems in industries or services are too complex to be studied analytically so in these cases simulation model approaches are useful such as: Discrete Event Simulation, Continuous event simulation and Agent-Base Simulation (ABS). Actually few systems are completely discrete or continuous, but the most changes in a system will be considered to classify a system as discrete or continuous.

3.1.1 Discrete-event simulation

Discrete event simulation is a type of modeling of a system in which each event occurrence takes place in a specific time interval and leaves a unique trace in that time slot [1].

Applications of simulation methods vary broadly. Some of the problems that simulation can be a useful tool to solve them are as below:

- Analyzing and designing a manufacturing system, re-engineering of business.
- A group of people and servers that work together to reach a predefined goal. [1]

Based on this definition the system studied in this research is the flow of used products in the textile recycling process with a set of predefined procedures.

In order to run the simulation model, evaluate it numerically and save the replication results, simulation software along with a computer system is required. In this study, to create a simulation-based model and analyzing the outputs, the Enterprise Dynamics (ED) 10.1 (64-bit) software is used. ED is Object-Oriented simulation software, which is combined with the Event-Oriented method [50]. ED has the advantage of applying an advanced programming language (4D script) which provides flexibility in coding to the modeling procedure. Enterprise Dynamics has more than 120 atoms (entities) that can be used for visualizing by using the 3D feature along with 2D graphics to verify the simulated model. It gives the user the ability to consider inherent variables and predicts the interaction of model components on potential changes. Due to the variety of features, ED makes it possible to study server's utilization, buffer capacity, production rate, and the system inventory. The first step of each simulation project would be collecting data to be used as the inputs for the simulation model. Due to the complexity of this type of problems, and also confidentiality, commercial reasons or recycling company's trade secrets, finding relevant data could be very difficult or sometimes impossible [50]. When the available data are limited, the best analytical method would be a simulation method. Thus, in this study, the available sources such as research papers, companies' annual reports, and websites, taped recycling process videos and machines catalog have been used to collect related data.

3.2 Modeling for simulation

In this section, the 'after use phase' of a recycling disposed clothes will be reviewed. The following items are considered in the proposed simulation:

- Different categories for input material
- The ability to attach two different labels on each product (type and wait)
- Wait label calculates the total time that each product stays in the system
- Different processing times based on the label of each product
- Server's performance including; busy time, idle time and breakdown.
- The capacity of each queue and buffer
- Constraints related to precedence of each process
- Different cycle time for each server
- The number of machines used for processing each product

3.2.1 Model architecture

The first model (actual system) is presented in Figure 18. Any fiber (synthetic and natural) has specific recycling process. Cotton recycling process is highlighted with blue color. To model the existing system in simulation software two sub-systems are considered. First sub-system provides resources for the model. The products are generated in the first sub-system (sub-system 1) and then they are guided to the after use phase system (sub-system 2). In the second sub-system (sub-system 2), products are assigned to different output channels by following a Bernoulli distribution [12]. Finally, the processed products will be considered as the system output.

3.2.2 Sub-system 1: Product generation

As it was mentioned in section 3.1.1 to model the system, it is required to use 4Dscript programming language for coding which most of its commands are defined specifically for simulation modeling. These codes need to define in *Atoms.* Atom is Standard simulation objects (the so-called 'Atoms'), in which the behavior of the real life equivalents is captured that play the role of an entity in the simulation model.

Input materials which come from a source atom in a simulation model could have different labels to identify different type of product. Although this thesis intends to study a simple product like cotton T-shirts, in the proposed model, different labels are considered to determine the color and type of each product. Therefore, at the time of generating products, they are programmed with a specific label so that they could be tracked down in the system.

3.2.3 Sub-system 2: After use phase

The second sub-system, which starts with collecting used clothes, can be divided into five separate channels; recycling (output is woven), remanufacturing, waste, and reuse. In this research, the focus is on mechanical recycling. Therefore, it is assumed that two output channel is required that 20 percent of the total generated products go to channel 1, which is disposal (directly into the landfill) and the rest goes to the recycling process [13].

To consider a safe inventory level for the first warehouse (as soon as the material arrives in the system it is kept in the warehouse), a Kanban Bin inventory system is used. So, when the average content of the first warehouse reaches a certain level, an order will be placed. By taking this preventative action, there will be enough material for the sorting process. In the Kanban Bin atom, the initial inventory is considered 1 ton and the reorder level is 500 kg of material. Hence, if the available products in the first warehouse are 500 kg, an order of 1000 kg of material will be placed.

3.3 The main framework of the model

In the main framework of the model (Figure 21), methods of recovering and reusing fibers, required equipment, material flow, material sorting and the differences between the current recycling system and proposed alternatives are discussed. Diagrams which are shown in Figure 17 and 18 are used for programming purposes in order to generate material and sort them based on their defined labels.

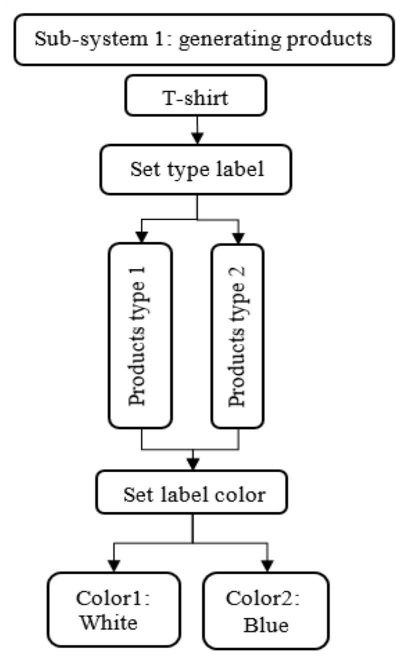


Figure 17. Subsystem 1: the introduction of material to the system

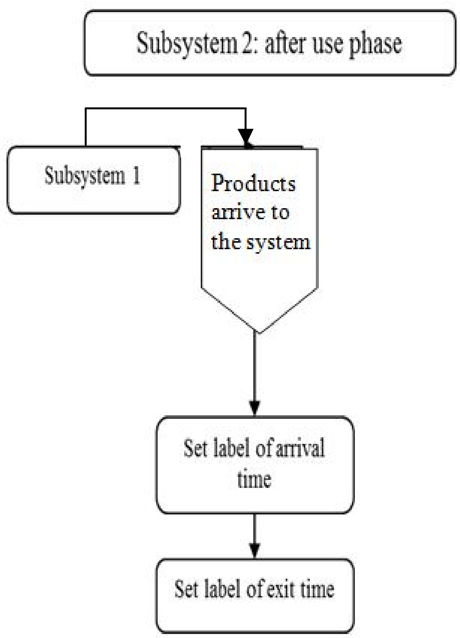


Figure 18. Subsystem 2: products arrival to the system

Clothing items can have two-phases (use and after use phase). A product can go through different processes after its use phase to be used again. With considering the quality, color, shape, and size of the material, different methods can be used to reuse the disposed items. Generally, most of the SHC is suitable to be recycled with no conditions while for other reusing methods, a minimum level of quality is required.

The output of the recycling process would be a woven fiber which can be used in the same industry. Moreover, the output materials which do not have the required quality to be used in the fashion industry (due to the short fiber length) could be used in different industries [51]. Some of the industrial applications of low-quality recycled fibers are listed in table 2. Moreover, Figure 19 illustrates all the involved processes that can be used in a textile reuse system.

Table 1. Different applications of low quality recycled cotton

Application of recycled cotton
Automotive headliner
Thermal insulation
Acoustic insulation
Horticulture
Artificial growing media
Extreme conditions clothing
Odor control
Electrical insulation
Spill absorption
Metal polishing
Oil filtration media
Stain application

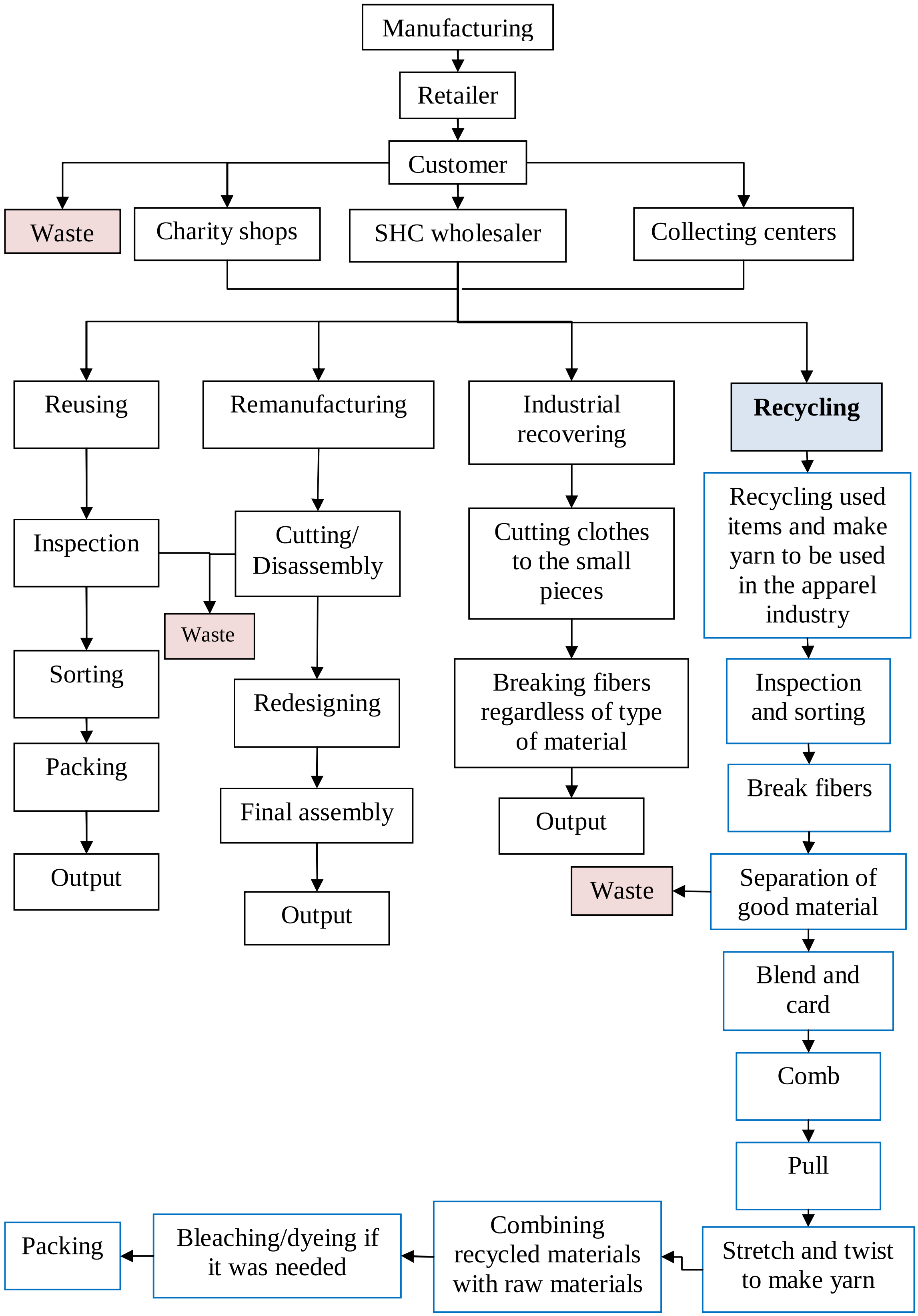


Figure 19. The processes involved in the textile reusing system

In the proposed system, a simple product such as a T-shirt is considered for recycling process. To produce a simple item like a T-shirt, 2,700 liters of water and 1.85 to 10.5 dose of chemicals (depend on the quality of the product and manufacturer structure) is used, while for growing and harvesting of just 1 kg of virgin cotton 10,000 liters of water is needed [40]. Most of the cotton suppliers and clothing companies are located in countries such as Pakistan, India, Bangladesh, and China, where the labor and other related costs are much cheaper than European countries which are pioneers in textile recycling and remanufacturing. Therefore, the total production cost of new clothes compared with recycled and upcycled items is often lower. Moreover, clothing companies (especially fast fashion businesses), use the mass production approach to manufacturing fashion items, which is an inexpensive way of producing clothes and will result in cheaper products [52]. Thus, all of the mentioned points could impact the sale price of the product.

The cotton price in the world markets is provided in table 2. Since 60 percent of the final price of each product is the raw material, by using an efficient textile recycling system more resources (raw material) can be saved [45].

Table 2. Price of virgin and recycled fibers adapted from [45]

Fiber	**Virgin fiber price in CAD/ton**	**Recycled fiber price in CAD/ton**	**Description and source**
Cotton	3202	759	Length of fiber: 1.5-2.5 cm (Daytrade.com)

As it is shown in figure 21, different processes are involved in the textile reusing system. Post use phase starts when the consumer disposes a piece of used clothes. Remanufacturing, reusing and recycling are the most common methods to reuse obsolescent and disposed clothes.

3.4 Simulation process

Simulation is a procedure to imitate a process, unit, trend, etc. without applying an actual change in the real world to save the cost and time of doing the real experiment. With recent developments in information technology and computer software packages, the simulation process can be done with high accuracy in the minimum amount of time. In this study, a simulation-based model with improvement scenarios is provided to improve the recycling process. In the proposed model the focus is on mechanical recycling; therefore, bleaching and dyeing processes which are recognized as part of chemical recycling are not the concern of this research. Thus, at the end of the recycling process, the color of the final product is not considered to be a key factor. The application of this type of recycled raw material could be socks knitting, tote bags, and wallets in which the color of the final product is not as important as it is for outfits and formal clothes for consumers. Currently, a company in California uses this innovative method (mechanical recycling) of recycling to produce environmentally friendly, recycled products without using any chemical or water [53].

3.5 Description of the recycling process

The first step in the textile recycling process is to collect used items which are assumed to be taken from charity shops and whole sellers. The next step which is time and labor consuming is inspection and sorting, where operators should check the quality of each of the clothing items and based on the sorting instructions they should decide whether those clothes are suitable for recycling or not. Another factor which needs to be checked before operators transfer fibers into the bins is the color and texture of the fiber. Therefore, the quality and color of the final products depend on the input material (If the color of the final product is irrelevant the color sorting can be eliminated so, the color of the final product will be in gray shade).

The third step is shredding, cutting fibers to small pieces and blending them. This process is fully automated so, the performance of the machine plays a vital role in the system. The fourth step is mixing the already shredded fibers with a percentage of virgin material (cotton). This percentage may change according to customer’s order. Carding, combing, pulling, stretching, twisting and knitting are the next main steps in recovering cotton fiber.

Figure 20 shows the differences between the recovered and the conventional production method of cotton. As can be seen, for recovered/ recycled products, cotton cultivation process is eliminated and instead, collecting process is introduced. The other highlight would be the amount of transportation: virgin cotton cultivation needs by far more movement due to the diversity of involved processes. Even though disposed clothing item may require many activities in fiber recovery, they can be done in the same plant.

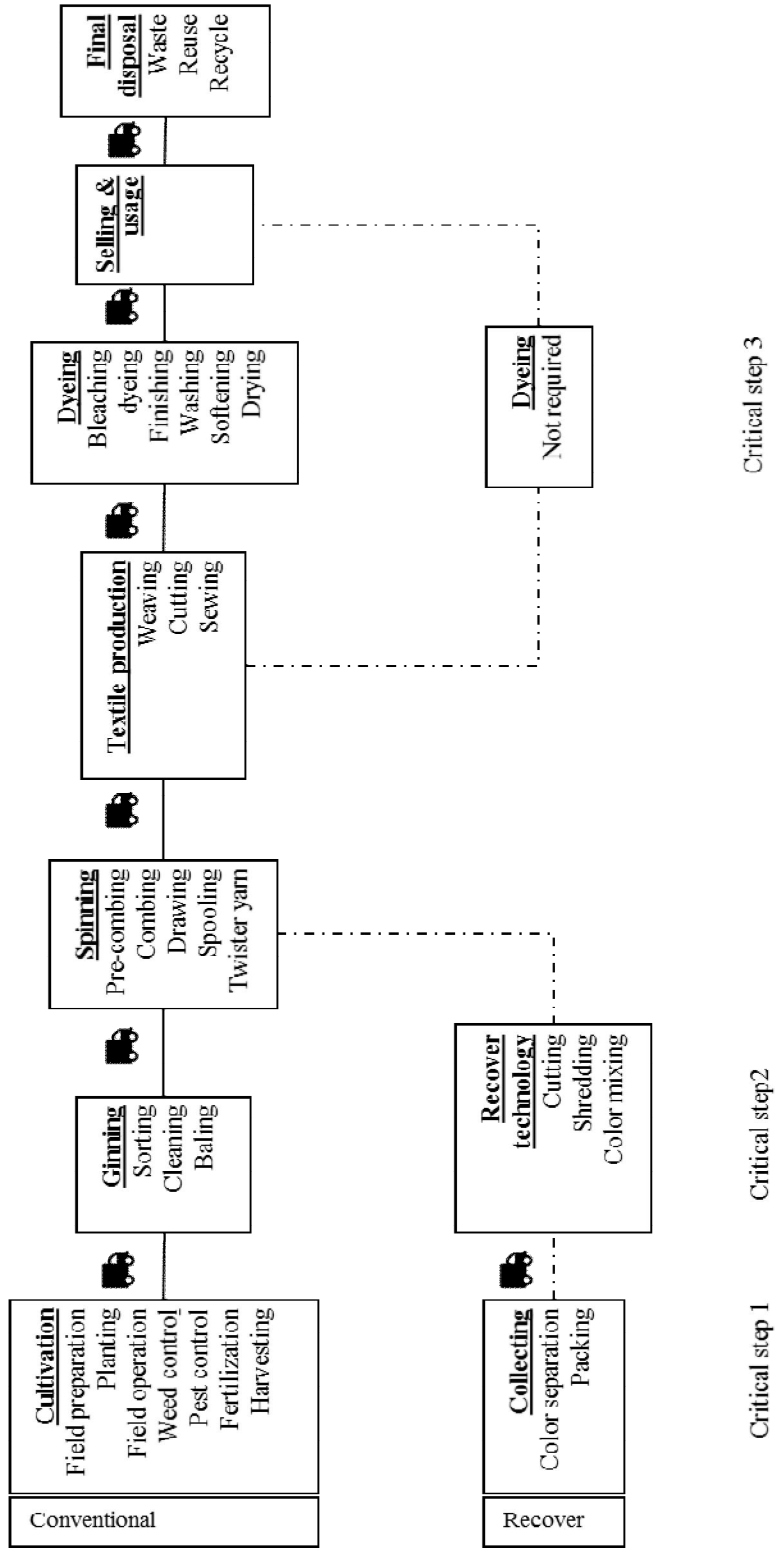


Figure 20. Differences between recovered and conventional production method of cotton adapted from [40].

By using recycled raw material and a smart selection of colored fibers, one can eliminate the process of dyeing cotton and the environmental impacts related to cotton cultivation. Even though, cutting and shredding steps have some side effects, they are not as harmful as chemicals.

The existing system operations are illustrated in Figure 21, in which the recycling process starts from inspecting of pieces. After inspection and sorting the pieces need to go through a series of work stations to be processed.

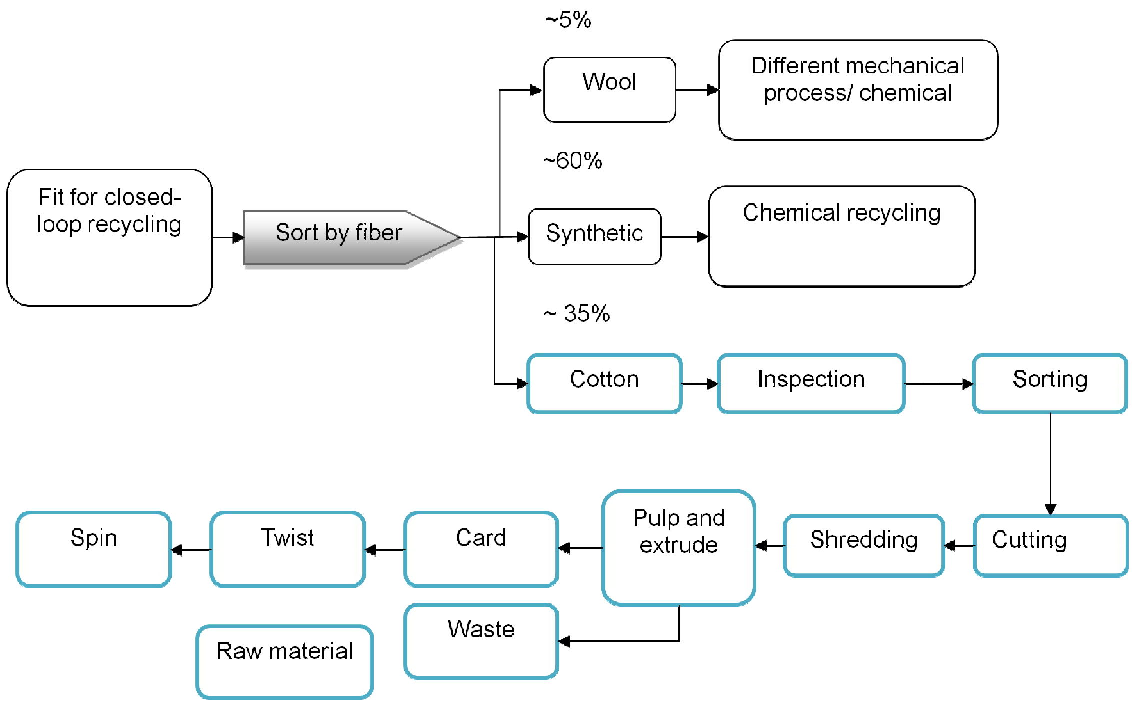


Figure 21. The existing system operations

3.6 Notations and assumptions

In this section, the assumption taken to create the simulation model and notations are explained in detail.

3.6.1 Notations

The servers which are used to show the machine performance or operator activities in a serial production line are presented by S_i. Also, queue atoms (Q_j) are used to represent the temporary buffers and are located before each server. The rest of the parameters are as below;

P_i = Cycle time of server S_i

SS_i = Setup time of server S_i

MTTR = Mean time to repair

MTTF = Mean time to failure

MTTR and MTTF are considered when the server is busy (busy time)

B = Batch rule number (B in, 1 out / B in, B out / 1 in, B out)

In this model, it is assumed that all the queues have enough capacity to take a new product. Due to the nature of products, the capacity of the queue is considered to be a big number. For instance, the first and the last buffer capacity should be considered big enough to accommodate inputs. However, for different replications, a limited capacity of the queue can be considered to observe the performance of the machine.

Cp = capacity of queue Q_i

T = simulation clock time

Measurement = hours

3.6.2 Assumptions

The assumptions which are taken to simulate the model for the recycling procedure with six machines and 13 queues are as below;

1. The flow of the incoming material to the first queue is continuous. The first server will never be idle.
2. The first process starts with a startup inventory.
3. The buffer before the last server (packing server) in the production line has unlimited capacity; therefore, there will be sufficient space for all finished goods which are ready to leave the system. Thus, the last server will never get blocked.
4. Depending on the machine type, the amount of material which is processed by each machine will vary (based on a predefined Batch rule).
5. Buffers between two machines have a limited capacity. The maximum capacity of queue is Cp_i.
6. The machines breakdowns occur randomly and follow a random distribution function. While the server is idle, no breakdown is considered.
7. There is no preventive maintenance planned for each machine; thus, machines are not stopped for maintenance.
8. Transferring, loading and unloading time are considered as part of cycle time.
9. No failure occurs for in the queues. Therefore queues will keep serving continuously.
10. Repairs are done immediately after breakdown with no delay.
11. The number of products which are produced in the source atom is not limited.
12. Set up time is considered for machines which need to load and unload materials repetitively.

13. The maximum loading capacity of each machine is considered 200 kilograms.
14. Cutting and shredding machines start working after receiving 100 kg of materials.
15. The unit of product measurement is kilogram (kg).
16. Each box at the end of the recycling process is defined as 100 kilograms.

3.6.3 System performance

To observe the system performance, different parameters are used in the simulation model, which are as follows:

T_o = Total output of the recycling system (finished products)

C_t = Cycle time to process each product on each machine

QB_i = Average content of the queue

Sb_i = Time in which machine is blocked

SIT_i = Server idle time

QF = Capacity of the queue

QF_i = Time when the queue capacity is full

These parameters can be utilized to improve the performance of the system. For instance, by using QF which is used to observe the capacity of the queue, it is possible to estimate for how long a queue is full. One can also review the impact of queue capacity on the next server.

3.6.4 Labeling

The features of a product which are unique and specific for that product can be attached to it by labels. In the proposed model, two labels are considered to be attached to each product at the moment of arrival to determine the type and arrival time. At the end of the process, the label which was attached to the product to record the total time spent in the system will be called. Also, based on the attached labels, the cycle time might be different. Depending on the label the product may follow a unique sequence to be processed.

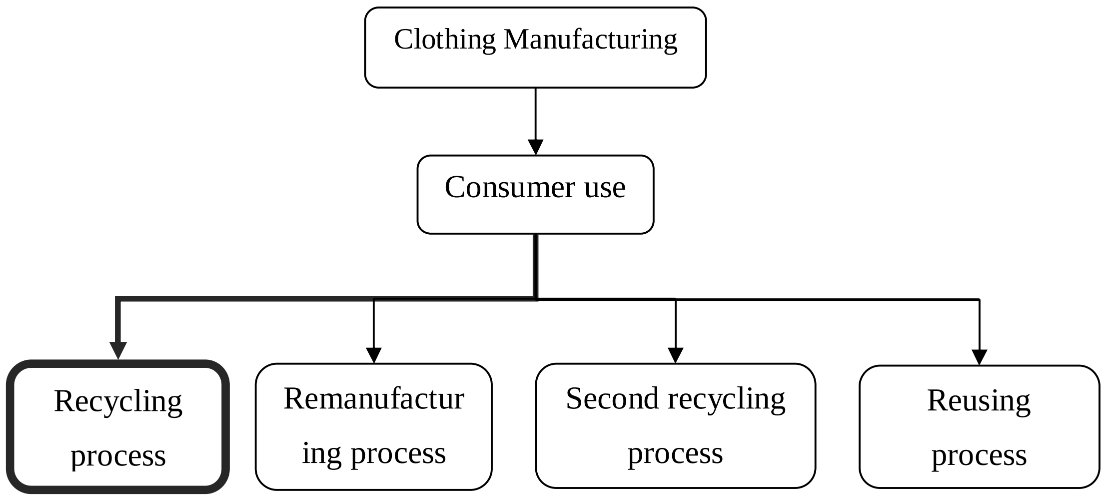


Figure 22. Textile after use phase diagram

CHAPTER 4: METHODOLOGY

In this chapter, the proposed simulation-based modeling is explained in detail to evaluate the textile recycling production line and to determine the required parameters of the model to maximize the system output.

4.1 Model description

To model a system in the simulation software environment, different components such as, for example, product, source, queue and, server are required. In ED software *atoms* should be used to show the role of each object or entity. Atom can be applied for machines, parts, products, operators or even tables or graphs. To use any of these atoms they need to follow a sequence, for instance, queue atom must be used before the server even if there will be no line or buffer for a specific server (machine, operator, and station) in the actual model.

The flow of used material in a recycling system is illustrated in Figure 19. The focus of this study is on a recycling system. Thus after products are entered into the system (first warehouse, which has an infinite capacity), they will be guided to the inspection and sorting station. When the simulation model is run, product P_j will be directed to the first work station. Then the product will be processed by the first machine if that machine is not already busy or not idle due to break down. In case the machine is busy, the product will wait in the queue until the servers become available. When the first step is done, the product will be directed to the next server (Mi) in the same manner. The process goes on until the product has gone through all of the machines.

Server's availability depends on its cycle time (processing time) and downtime. If the machine is in its failure mode it goes off-line and quick action for repair is needed and when the repair is completed, the server goes back online and will start processing the products again. Downtime includes failure and repair time. During downtime, products are waiting in the queue, and the program will add this time to the total time that an item spends in the system. Product(s) are directed to the servers as soon as servers become available.

Queue discipline for all of the buffers is based on first in first out (FIFO) rule. Hence, a product will leave the queue based on the mentioned inventory management system. The input strategy for each buffer depends on the previous server that the product has visited. When products pass all of the servers, they will leave the system and will be stored in a warehouse. In the first warehouse (*ground storage atom*), several columns and rows are defined to accommodate new products; thus a table is created for this purpose and if any row/column is occupied, '*rows ascending command*' will search for the next available row.

The same procedure will be repeated until the simulation time is reached. When a new simulation run (number of separate runs depends on the number of observation in Experiment Wizard) starts, it repeats the described process without considering the results of the previous run/runs. Finally, the results of each run will be recorded for further analysis.

To count the system outputs, virtual storage (*sink atom)* is located to hold the final products with unlimited capacity to make sure that there is enough space for finished products.

4.2 Different components of the simulation model

In this study, different '*atoms*' are used to model the system. Product atom is used to show the movement of the input material from the beginning of the process to the final step. The other duty of the product atom is to keep the predefined labels. Furthermore, a source atom is required to set the entry rate of the product. Source and product atoms are two connected components. Hence, whenever components like a pallet, box, and raw material are needed to be used in the model, an individual source atom is required to generate them.

Additionally, to prevent unnecessary stop time and delays in the production line, buffers are located between machines. The queue atom is one of the most essential and critical components of the simulated model which facilitates the study of the server's performance.

4.3 Key factors in the simulation of the recycling process

4.3.1 Inter-arrival time in source atom (for disposed materials)

As it is discussed in section 3.1, in order to recycle a clothing item, various activities need to be carried out in a predefined order. Most of these activities can be automated except inspection and sorting which require human operator's presence. Outcomes of sorting and inspection are highly dependent on the operator's skill and performance, therefore, can be time-consuming. Any machine used in the textile recycling process has its own specific cycle time, repair time and breakdown time and, any timing variation can affect the overall system's performance and behavior.

Based on the previous discussion in section 3.1, inter-arrival time is considered to be very small and is causing no shortages in the system. Thus, the sorting process starts without waiting for new input. In this study, due to random data and the difficulty of having an accurate approximation, it is assumed that every ten seconds a product enters the first queue to be processed (so there will always be some products in stock).

4.3.2 Distributor atom

The first queue acts as a transitional warehouse to store incoming products. To accommodate the high volume of products, the capacity of this *queue atom* is considered to be 10^4 items. The ability to consider an infinite capacity for a buffer is one of the differences between simulation models and linear programming models (LP). This virtual queue is intended to allocate products to different channels in which servers are connected. In order to assign products the Bernoulli distribution is used to define share of each output channel in ED 4DScript environment.

4.3.3 Connecting channels

In this simulation model channels are used to show the precedence constraints. Each atom can have several inputs and outputs depending on the programming commands; therefore, the number of channels for each atom may vary.

4.4 Breakdown time

Breakdown time is part of the lead time. This specific time cannot be considered in the approaches like mathematical modeling due to the complexity of programming LP models. Thus, in the proposed simulation model mean time to failure (MTTF) and mean time to repair (MTTR) are considered for servers to represent the real world situations.

4.5 System timing

To track different products throughout their travel in the system from the beginning to the final step, the labeling commands record the total time that each product spends in the system. For this purpose, after the time label is attached to each product, it is required to initiate, and update '*time function*' at the end of the process. To calculate the total time that a product spends in the system, the time label should be called before that product leaves the system (trigger on exit).

4.6 Sorting and inspection station

In the sorting process, which is costly and time-consuming, human resource is needed. After operators open each donated bag of clothing, they may find on average five to ten different items, [5] and each clothing item has to be handled separately. For modeling purposes it is assumed that each received bag contains seven items (seven or less). In other words, when each bag enters the inspection center, there will be seven or fewer products (considering 15% of waste) that go to the next station. For this reason, a batch size of seven is defined in the sorting step [40].

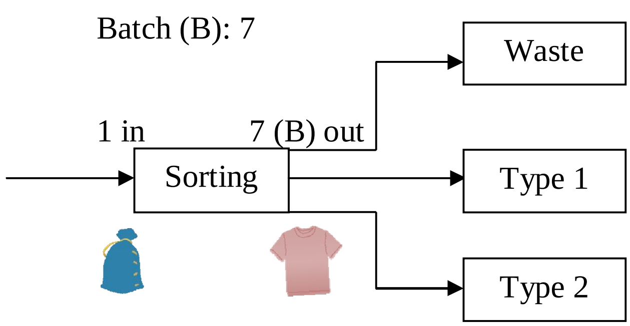


Figure 23. Batch rule

Figure 24 specific type of sorting bins chosen for each product category (in this study two type are products are considered). Sometimes the variety of clothing items could lead to the incorrect item bin placement and therefore affecting the speed of the production line and quality of the final product. In the presented model, it is assumed that the product has only two different types to simplify the modeling of sorting; type one and type two. In the simulation model, while the products follow is generated (in the *trigger on creation* of source atom), two types of products are defined as follow: type one is gray, and type two is blue. The assumed distribution of products and waste is shown in Figure 24.

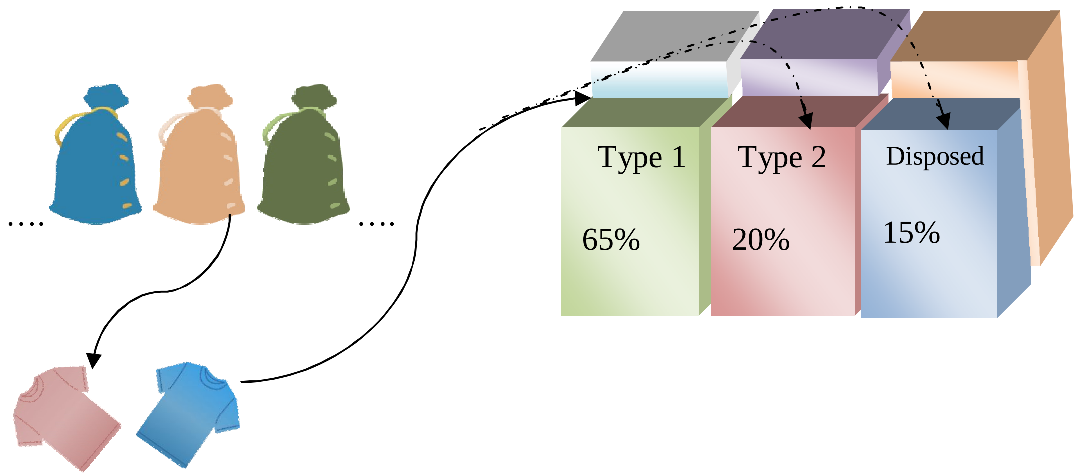


Figure 24. Inspecting different products in the sorting station

4.7 Spinning

All of the positively identified material in inspection (85 %) [40] cannot be entirely utilized due to either low quality or short fiber length; therefore, recycled material has to be combined with raw material (in this case virgin cotton). The amount of virgin cotton used in this step effects the pricing and the quality of the final product.

4.8 Queue capacity

The capacity of the buffers in a production plant has is limited; thus, a capacity limit is considered for each buffer (queue). When a queue is using all of its capacity or it is over capacity, it means that the server ahead that buffer is busy all the time or there is the machine or operator are at max capacity and cannot process more. Detecting variables such as: busy operator and machine that address delay can be helpful to find out bottleneck stations.

4.9 Warm up time period

The system that is used in this study is a non-terminating system; therefore, the model needs some time to reach a steady-state. In non-terminating systems, basic conditions (e.g., initial inputs) have a considerable effect on the process outcomes. In this type of production system, semi-finished items are transferred from one to another period. Thus, to get repeatable results from the model, a warm-up period is considered. In this study, fifteen minutes is considered as the warm-up time, and a '*separated run*' method is used for *experimental wizard* based on the nature of the model.

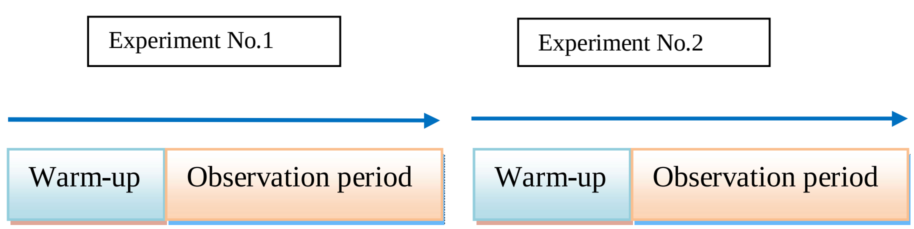


Figure 25. Experimentation with separate runs

There is not a specific formula in statistical and simulation references to be used to calculate the warm-up period which is determined empirically. According to modeling handbook [54] warm-up period can be identified from a data based on the observation from experiment runs (warm-up chart is plotted). The horizontal axis represents time and the vertical axis - throughput/hour. The amount of processed material in the first two stations is used as an index. For each eight hours period, three different replications were done in the simulation model. Based on the results of each run the below diagram is completed. As shown in the Figure 26 after 30 minutes, the system reaches a relatively stable condition. So, the model will run for 30 minutes without using the information from this running time. By considering the warm-up time, simulation model will run for a specific number of separate runs and the output of each run will be recorded for the next level of this study.

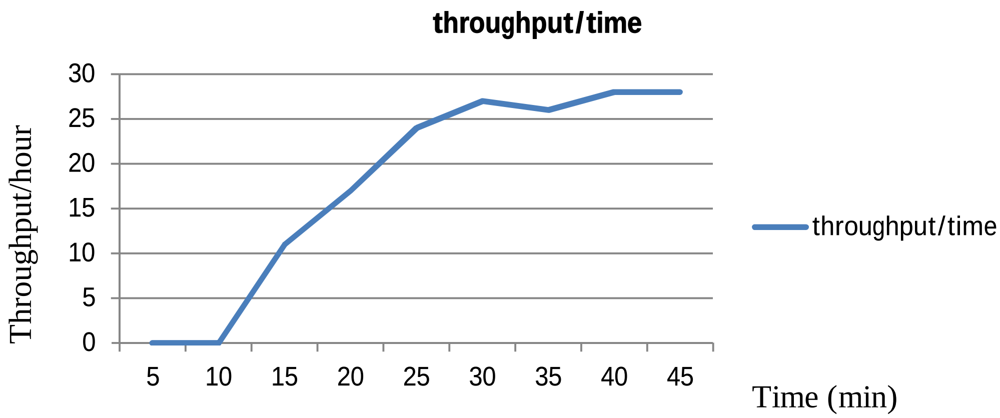


Figure 26. Warm up diagram for the simulation model

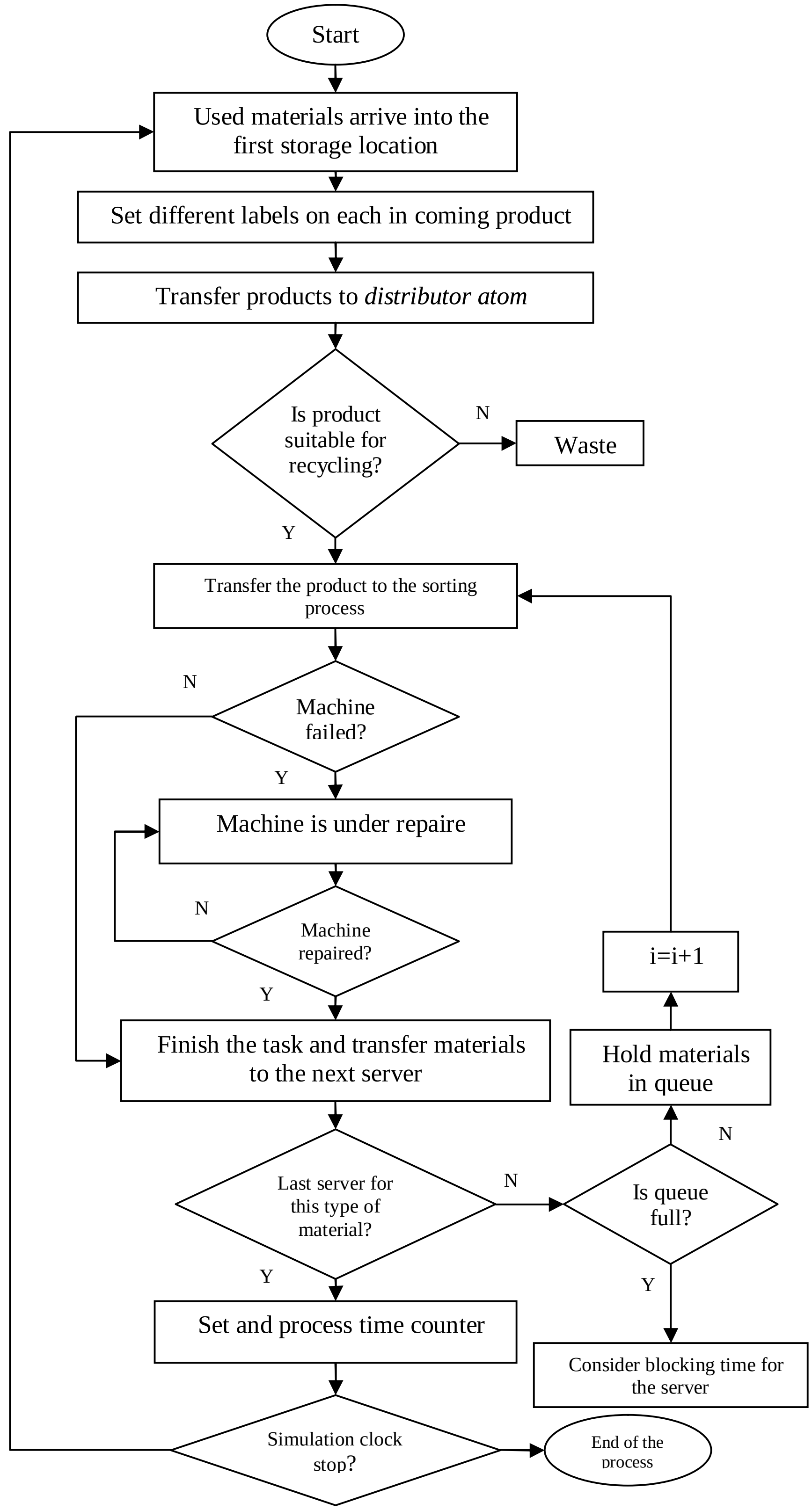


Figure 27. Simulation process flow chart

4.10 Data collection for the simulation model

As it was mentioned in section 3.1.1, limited amount of data is available for this type of study; therefore, different sources such as available data in the reviewed literature, company's annual reports, video recording, podcasts, and textile recycling equipment catalogs have been used. The various working processes are taken from recycling companies located in the USA and Europe. Most of these companies follow similar procedures.

The Minitab statistical software (Version 17) and *Autofit* tool in Enterprise Dynamics package are used for statistical analysis and to estimate the most appropriate distribution functions as input parameters. The machine cycle time and the breakdown were extracted from the equipment catalog, and random numbers were generated to find the appropriate distribution function.

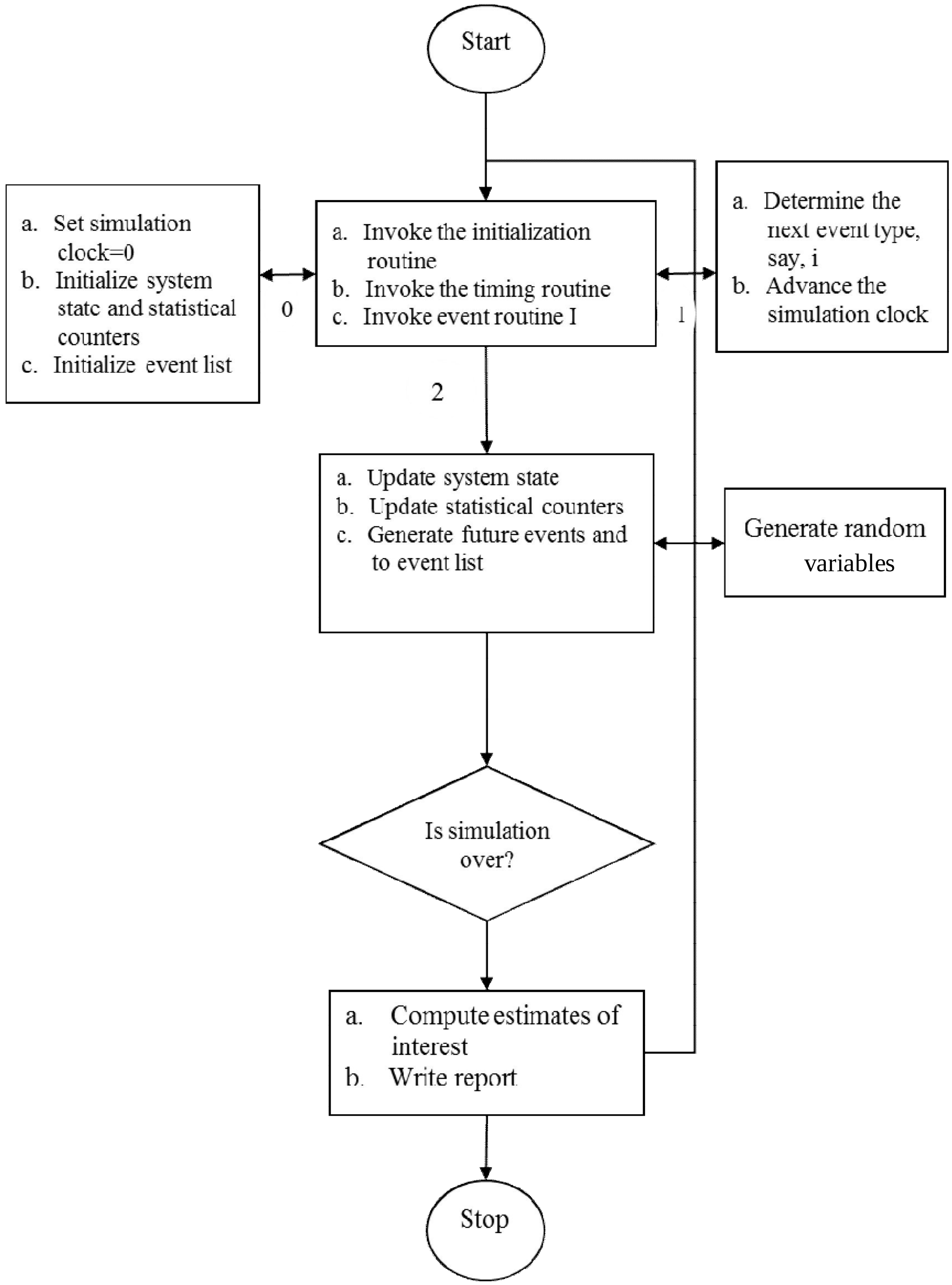


Figure 28. Flowchart for basic simulation programming [1]

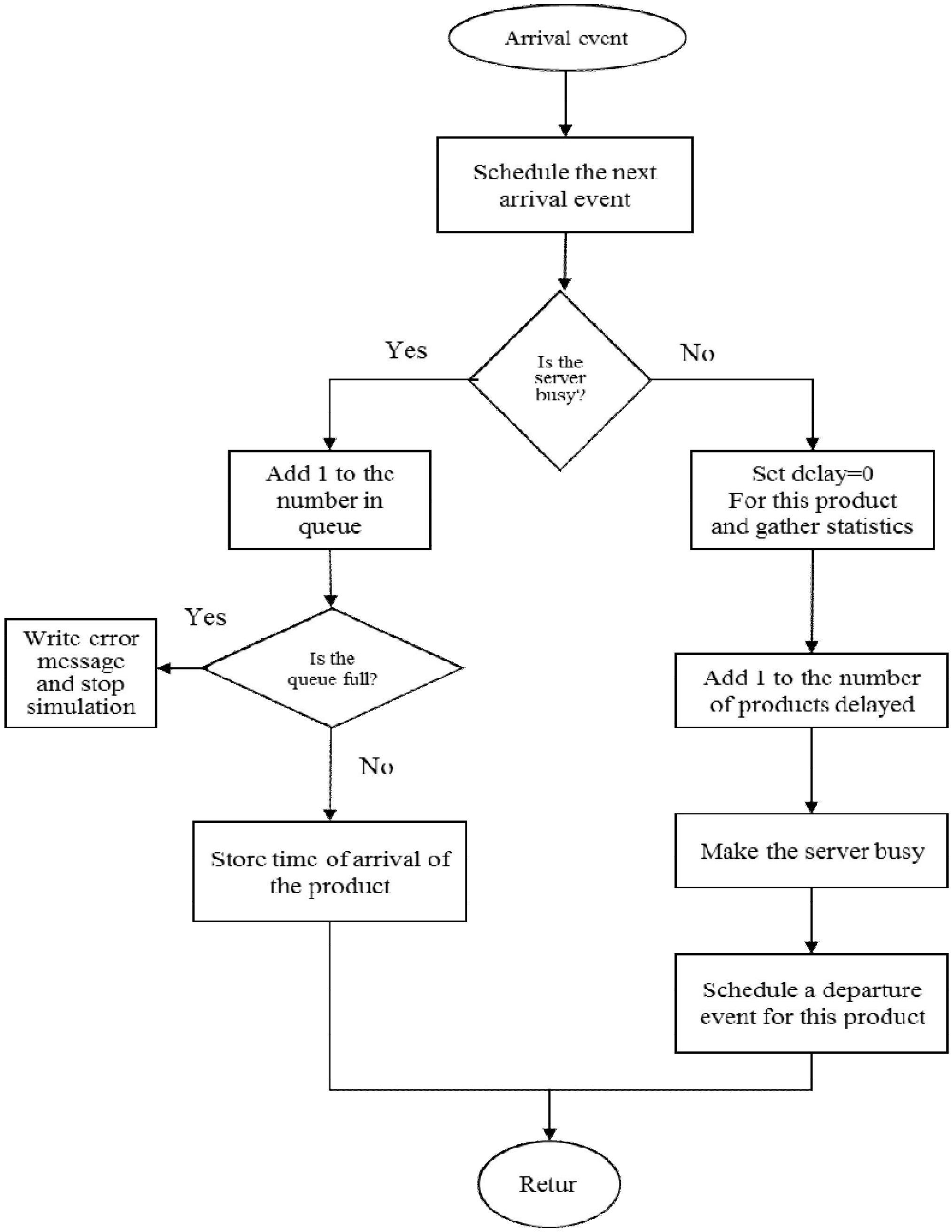


Figure 29. Flowchart for arrival routine, queuing model adapted and modified from [1]

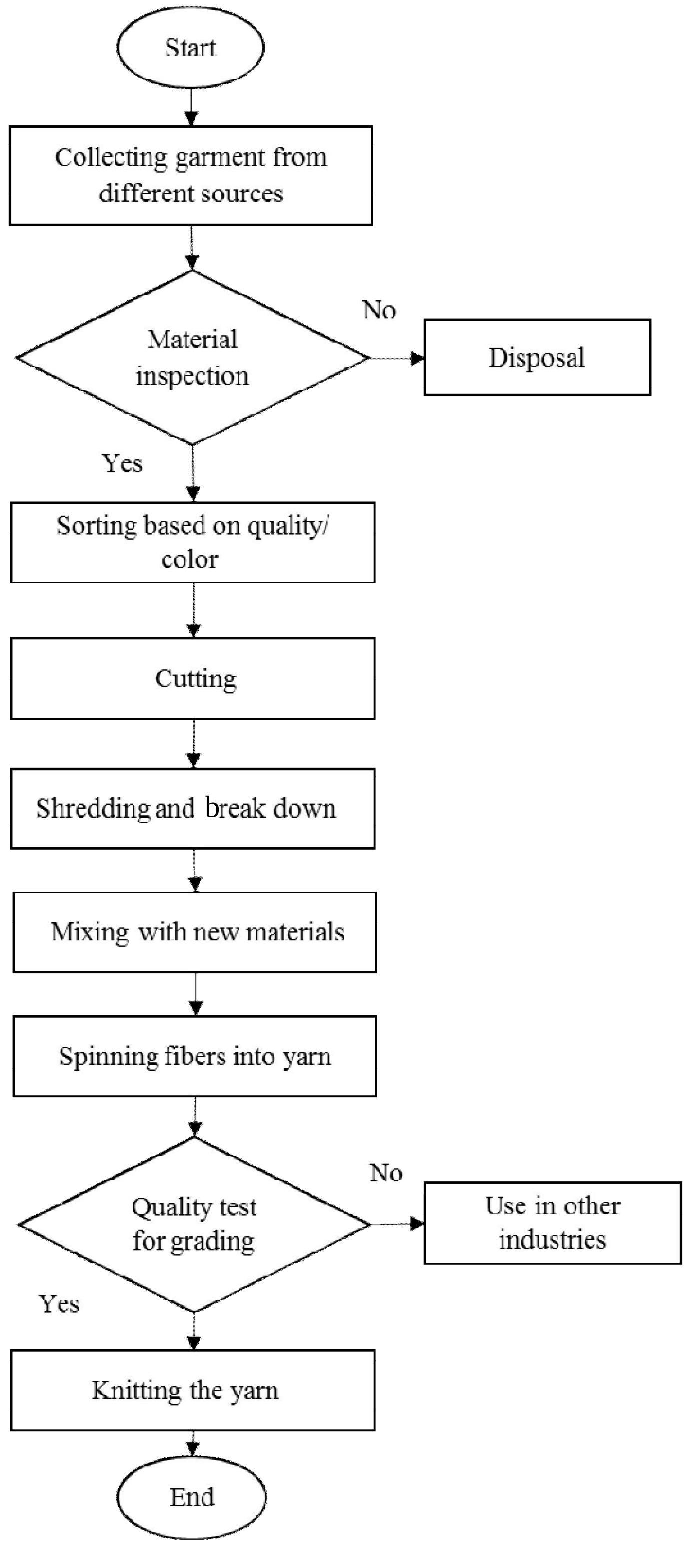


Figure 30. Textile recycling processes

4.11 Determining the minimum numbers of replications

With due attention to the random parameters of the model, it is not possible to get reliable and accurate results by only a single run. Thus simulation runs have to be repeated (replicated) to provide enough data for corresponding statistical distributions describing the process being simulated. The minimum required number of replications can be calculated by using equation 1. The results of 10 replications were collected to find the value of variance and average content of final ground storage. The results are recorded within 95 percent of the confidence interval.

$$n \geq \left(\frac{t_{\frac{\alpha}{2}, n-1} * s}{\Delta} \right)^2 \quad (1)$$

N = number of replications

S = standard deviation of replications

In equation 1, α is type one error and $t_{\frac{\alpha}{2}, n-1}$ is the distribution function of *t* with n-1 degree of freedom and Δ is acceptable error (acceptable error to assess the value of the objective function).

$N \geq (2.165*0.41/0.05)^2$

$N \geq 315.16$

N = 316

By knowing the minimum number of replications, based on assumptions the model is run for two working shifts (16 hours). *Experimental Wizard* which is a tool in the ED package is used to run the model for 316 replications. Table 3, shows the average number of system output, standard deviation and maximum/minimum time that a product spent in the system. In average ≈ 12 boxes (1200 kg) of recycled cotton will be in the last warehouse after the runs are completed. The mean time that a product needs to pass through all processes is 1028.73 second.

Table 3. The results of 316 replications

	Average	**SD**	**Lower bound (95%)**	**Upper bound (95%)**
The content of final storage [Box/Bale of 100 kg]	12.78	1.62	12.60	12.95
Time spent by a Product in the system [second]	1028.73	76.16	1020.31	1037.16

4.12 Results of the base model and improved scenarios

4.12.1 Base model (current setup)

In this section, the results of running textile recycling simulation model are presented and then new solutions and methods, used to improve the system, are explained. For this purpose, outputs of a single run and 316 replications of the simulation model are analyzed.

The summary report of the simulation model is presented in Figure 50. The average content of the queue before sorting station which is highlighted in Figure 33, consists of 28 units. Also, at the time when the simulation is over, 56 products are observed as the current content of this buffer (queue 13). Although the average content of queue 53 and 65 is very high in comparison with other queues (figure 33), it will not affect the average output of the system. The reason behind this is that these queues are located after the two source atoms, which produce raw material for spinning process and containers to store the products. It means that queue 53 and 65 are considered as temporary storage. Additionally, sorting station and cutting machines are busy 95% of the simulation time. The shredding station is idle in 57% of the total time (figure 31 and 32).

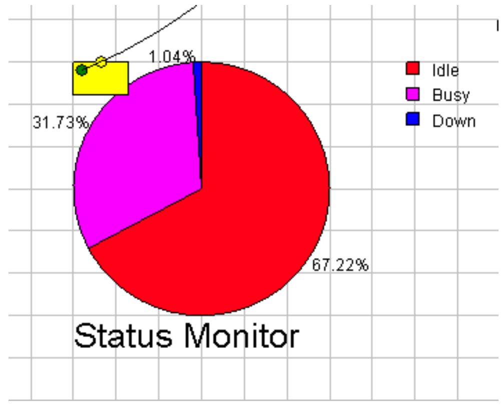


Figure 31. The performance of the twisting machine after 8 hours simulation run

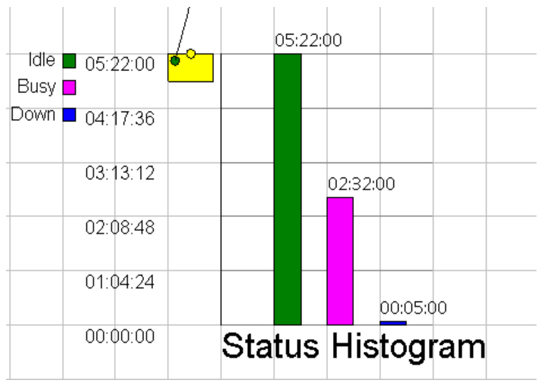


Figure 32. The performance of the spinning machine after 8 hours simulation run

Graphs and '*status monitors*' are used to study the performance of servers (inspection, cutting, shredding, and twisting). In each diagram, the server's busy time, idle time and downtime are taken into account. By analyzing the results, it is understood that the inspection station is busy 93% of the simulation time and it is down about 3% of the total time. Due to the high volume of activities in serving, the utility of the inspection server is above the optimal (optimal utility is usually considered between 70-80 % [50]). The *status monitor*, which is used to monitor the status of the atoms, obtains this information by reaching a section which contains all the data related to each atom (atom brain). Moreover, *status histogram*, which has the same function as the *status monitor* is used for cutting machine. The *status histogram* illustrates that cutting machine is approximately idle for 8 hours (half of the total simulation time). The cutting machine itself is down about 30 minutes of the simulation time. By observing the utility of twisting station, it is understood that this server has the best performance in the system with being busy in 65.07% of the total running time.

The spinning server in which recycled material is combined with raw material is idle 56.91% of the total run time (about 8 hours). Thus, based on the recorded results, inspection and cutting centers are considered as the bottleneck stations.

In the presented summary report fig 50, the total number of the system output is 14; however, 26 boxes are entering the system as inputs. Therefore, the useful output of this recycling system is almost half of its inputs (53.84%), which includes both waste and work in process due to the low speed production process. With due attention to the current status of the base model, solutions to maximize the number of recycled items are proposed in the next two sections.

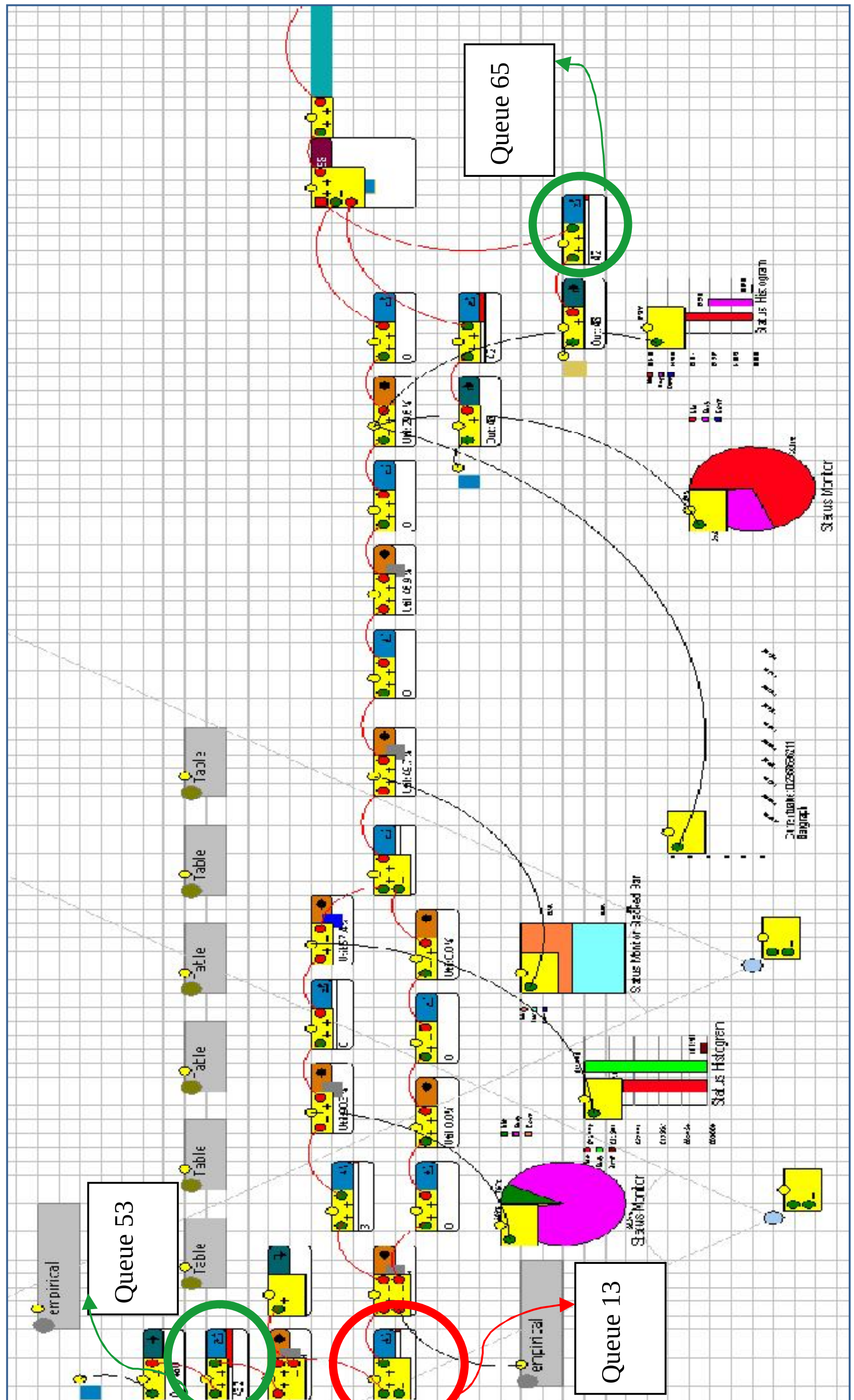


Figure 33. 2D view of the base model after 8 hours of run

4.13 The first improvement model

As it was discussed in section 4.12, some stations such as, for example, inspection need human supervision of a skilled operator. Operators need more time and space to implement the inspection procedures in sorting station in contrast to twisting or spinning stations which are fully automatic. Therefore, one improvement scenario to increase output to be considered is addition of a parallel station with the same performance for inspection and cutting stations. By doing so, the total process time will go down.

To further improve the first scenario, by considering the same principle, an intelligent sorting system can be introduced for the sorting station. The inspection procedure remains the same as before (manual), while the sorting process is to be carried out by a machine which has an electric vision sensor.

Indeed, of sorting clothes manually, operators check the quality of the item and then put the clothes on a fast speed conveyor for an intelligent suction system to pull the products based on their color. By using this sorting method not only the process time will be reduced but also the operators' errors will be eliminated. The proposed sorting system is illustrated in Figure 34. This system contains buffers, bins, suction servers, and a conveyor.

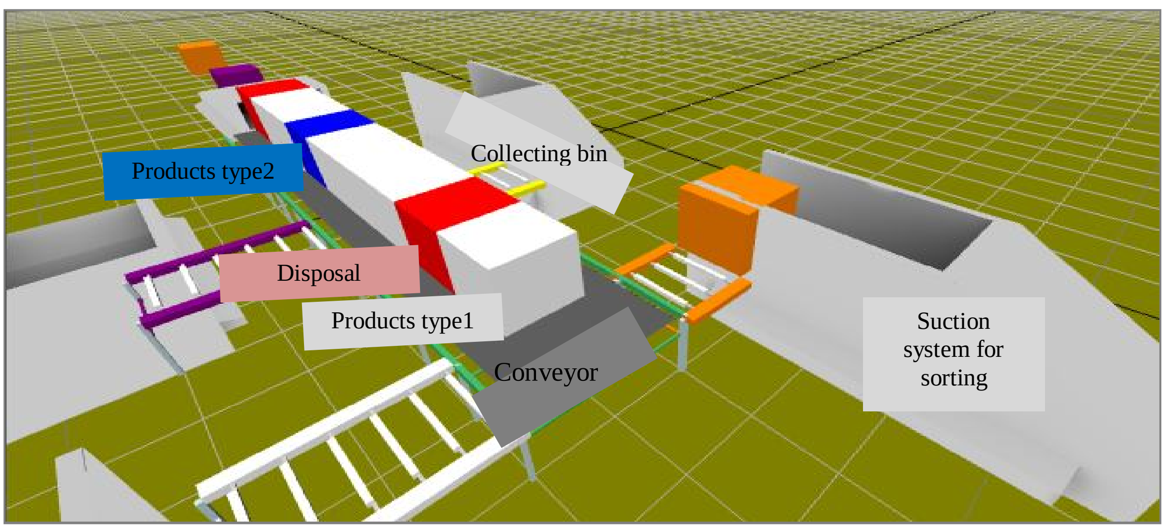


Figure 34. 3D view of the proposed system in the first improvement scenario

Considering the goal which is maximizing the production rate, the number of output pallets has been increased to 19. The result of the first improvement scenario is shown in table 4. As can be seen, due to the accuracy and high speed of this system, the output should increase by 18%.

Table 4. Results of running the first improvement scenario

	System inputs	**The average number of outputs**
Base model	26	16
First improvement scenario	25	19

4.14 The second improvement scenario

4.14.1 Introducing a novel separation method and a different process flow

Cutting clothes to the small pieces is another activity that slows down the production speed (figure 35). In the cutting station, clothes are cut into small pieces by being run through a fixed cutting blade. Currently this is the most popular method in industries for cutting fibers and requires a skilled operator. Due to the variety of types and shapes of clothes, there is not a fixed pattern to cut them and use most of the material. Therefore, the amount of waste produced after this process is noticeable.

Based on the recent research, some innovative methods are proposed to avoid manual cutting. In the new technology, in order to cut the clothes, a heating process is used. In this method, items are heated in a heating machine for a specific amount of time so that the clothes would lose its stitches. To use this new cutting method, the container capacity of the machine, the fixed and variable costs related to the machine and texture of the input materials should be considered as key factors.

The most important advantage of using the new process flow would be saving more time and material. So, it is expected to minimize the cycle time which has a major impact on the production rate.

Considering process flow (general process) showed in figure 21, the first step would be the inspection which includes disassembly of product attachments. Depends on company priorities, type of material or material quality the second step (sorting) would be done. In mechanical recycling plants, however, the incoming materials include a variety of texture or quality all the cotton products will pass the same set of machines. This action can have an impact on the final product's quality [40] and total production time. Due to the short length of shredded fibers, at the final stage (spinning) there is an inevitable need for a combination of raw cotton with recycled one. Therefore, one of the existing issues in textiles recycling production is the short length of recycled fibers while they are processing for spinning and pulling. The short length fibers are considered as waste or are downcycled for use in other industries.

Another issue related to this industry is the production rate of waterless mechanical recycling is lower than traditional textiles recycling (chemical), so the proposed model aims to increase the production rate. The advantages of applying the proposed system are as follow:

- Lead time reduction
- Output with higher quality
- Less waste during the process
- Cutting down the use of raw material
- Reducing the number of human resources
- Doing the sorting and inspection process at the same time/location

The proposed model is shown in the below diagram:

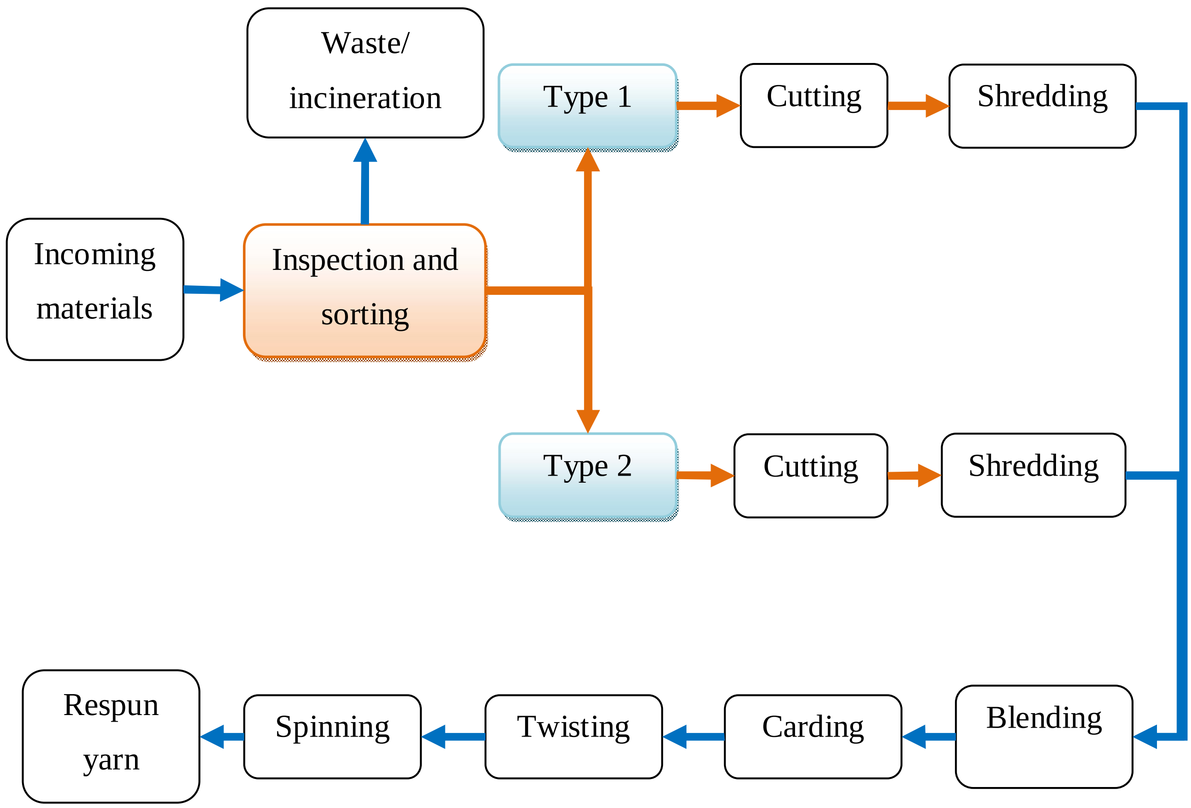


Figure 35. The proposed process for mechanical recycling of cotton fibers

When the input products classify at the second stage, each group of materials goes through a specific route to be cut and shredded. These two processes play essential roles in the length of recycled fibers and also system processing time. After the second step when the fibers are shredded, both groups of materials need to blend to be processed in pulling, carding and twisting stations.

Preceding each station, are the buffers to hold products for the next process step. The capacity of buffers is considered to be limited in modeling to analyze which working station has more products waiting to be loaded on machines (station blocking or starvation).

Considering the assumptions of the model, two types of material with different quality and density are entered into the system. In the base model, different types of traceable material are used, and all of them follow the same route. This can increase the process time. The increased time that each product spends in the system could affect the quality of the final product due to the over processing (short length of fiber). Thus, a different sequence for items to be processed is proposed.

Types of Material	Type 1	Sorting	Inspection	Cutting A	Shredding A
	Type 2	Sorting	Inspection	Cutting B	Shredding B

Table 5. The production plan for different types of material

Therefore, the material type two will spend less time on the cutting and shredding machine. The first two steps are the same in both categories. With these changes made to the system, some unnecessary processing time will be eliminated for type two materials. Indeed, those products which need more time to be turned into short fibers follow a different process sequence. This proposed alternative is based on the job-shop manufacturing system strategy in which a job needs a unique setup and sequence to be processed [52].

Finally, by reducing the machine cycle time and introducing a new process sequence, after running the model several times, it is observed that the number of output has increased to 43%. The system throughput for the second improvement scenario is shown table 6. The reason that system input increase to 29 is the logic of source in the simulation model, which generates input material every one to two minutes.

Table 6. Results of running the first and second improvement scenarios

	System inputs (bale of 100 kg.)	The average number of outputs (bales of 100 kg.)
Base model	26	16
second improvement scenario	29	23
First improvement scenario	25	19

4.15 Analyzing the scenarios

In order to choose one improvement scenario, both scenarios should be tested before making any decision. For this purpose, the already discussed changes are applied in the system, and the results of 15 replications are presented in table 7. Duration for running the simulation model for both of the alternatives is the same (each replication is 8 hours). Due to the random parameters in model the results of each replication is different.

Table 7. The average content of each improvement scenarios output

Number of replication	Alternative 1	Alternative 2
1	19.5614	22.6457
2	19.4341	24.7544
3	20.5411	22.3241
4	20.0446	23.2411
5	19.7447	22.9451
6	19.0132	22.2454
7	21.0670	24.5711
8	20.0124	24.2457
9	20.3712	24.6555
10	19.6466	23.2574
11	21.7178	22.6540
12	20.6254	22.6547
13	19.6777	24.2547
14	21.0224	24.3641
15	19.9414	23.2447

4.16 Selecting one of the alternatives as an improvement scenario

In this section, the results of separate runs are analyzed to choose one of the scenarios. For this purpose, the Welch confidence interval approach is used [1]**.** This method is based on Smith-Satterthwaite *t*-test. In order to use this approach, the mean and standard deviation of each data set is calculated and presented in table 9. The results of running the first scenario are shown with X_1, and X_2 represents the second scenario's output in table 9.

With the Smith-Satterthwaite test, the number of degrees of freedom is calculated by using equation 2.

$$\text{d.f.} = \frac{\left(\frac{s_1{}^2}{n_1}+\frac{s_2{}^2}{n_2}\right)^2}{\frac{\left(\frac{s_1{}^2}{n_1}\right)^2}{n_1-1}+\frac{\left(\frac{s_2{}^2}{n_2}\right)^2}{n_2-1}} \tag{2}$$

In this formula:

d.f. = degrees of freedom

S_1^2 = sample variance of the first scenario

S_2^2 = sample variance of the second scenario

n_1= sample size of the first scenario

n_2= sample size of the second scenario

The Welch confidence interval can be estimated with the equation;

$$(\bar{x}_1 - \bar{x}_2) \pm\ t\alpha_{/2,df} \times \sqrt{\frac{s_1^2}{n_1}+\frac{s_2^2}{n_2}} \tag{3}$$

$\bar{x}_1$ = the mean of the first scenario replications

$\bar{x}_2$= the mean of the first scenario replications

t= the t value for the d.f. degrees of freedom and

If zero is included in the Welch confidence interval, it means that there is no statistical difference, and there is no considerable difference between the simulated models otherwise, alternatives' performance are different and based on the Welch confidence interval one scenario is chosen. The mean and standard deviation of 15 replications of scenarios is summarized in table 8. Based on equation two the degrees of freedom is:

d.f. = 27.33 ≈ 27

Table 8. Average and standard deviation of alternatives

	Alternative 1	**Alternative 2**
Average	20.1614	23.47051
Standard deviation	0.724642	0.907549

According to the Welch confidence interval, and the degree of freedom for *t* distribution, the confidence interval will be [-3.80914, -2.80907]. Zero is not included in this confidence interval with the α level of 0.05. Thus, the proposed alternatives are statistically different. Since, the goal is maximizing the number of outputs and the mentioned confidence interval is negative, the second alternative is preferred.

4.17 Results

The summary of simulating the base model and the two alternative scenarios is provided in Table 9;

Table 9. Summary results

	Basic model	**First scenario**	**Second scenario**
The average output (Avg. content) (Bale of 100 kg)	14	20	23
Number of added/changed station	-	2	3
Simulation time	16 hours	16 hours	16 hours
Replication length			

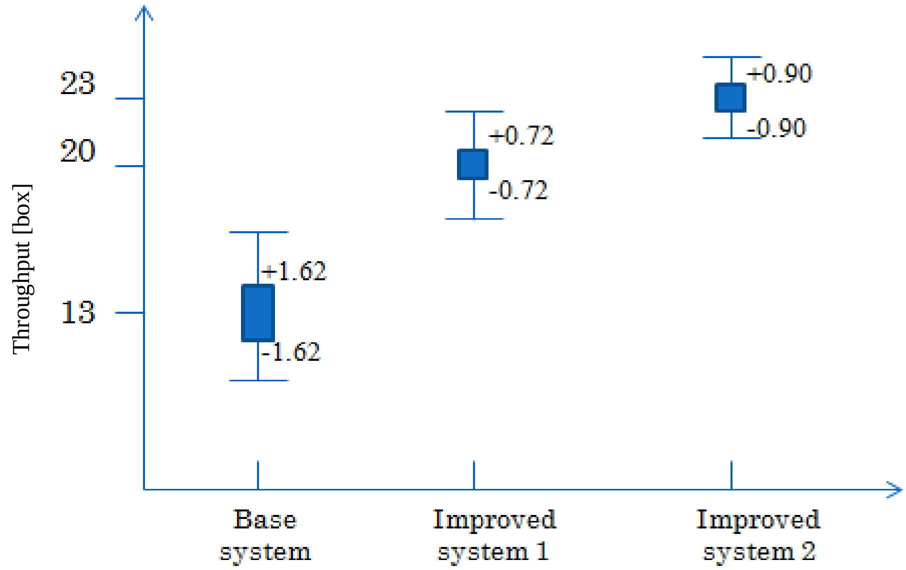


Figure 36. Comparison of the base and proposed systems

Figure 36 illustrates the average numbers of outputs for the base and proposed models. The results of the second proposed model show that the variation of outputs also has increased.

4.18 Verification and validation of the model

The ED simulation software has many tools for creating animation and 3D features. The simulation model discaussed in this research has also been presented in a graphical environment; therefore, the model can be verified with the application of available tools and features in the software. Moreover, by applying different shocks (very big or small parameters) to the model, the results can be tested. For instance, by considerably reducing the inter-arrival time it is expected to see fewer product atoms in queues. In other words, running the simulation model with a different set of input parameters results in reasonable outputs. ED also provides other verification tools such as *StatusMonitors*, *MonitorStacker*, and *Histogram* that illustrate busy time, downtime, blocking time and idle time for each specific server. Considering the taken assumptions, these features are used to verify the presented simulation model.

Furthermore, traceability is another powerful technique which is used for the verification purposes in this discrete event simulation model. By programming the products at the first step to be traceable (attaching label on them), they were tracked to observe if they are on the right route. Running the model with simplified assumptions and the minimum problem size is the fifth technique which is used to verify the model [1]. After the assumptions are simplified, the outcomes tend to be sensible.

Validation is required to achieve the accuracy and certainty of the model performance. In studies where the actual data of a system are available, the model data set and actual system data set should be compared with each other in order to assess the process. For this purpose, methods such as statistical tests (null hypothesis), non-parametric test or F-test for equality of variances can be used to make sure the throughputs are almost the same. The mentioned methods and carrying out the statistical calculations are not applicable to this study since there is not enough available historical data, feedbacks or evidence for such a new structure in the textile recycling system.

CHAPTER 5: CONCLUDING REMARKS

5.1 Conclusion

As society is paying more attention to the problems associated with landfilling old textile and fashion obsolescence, improvements in the textile recycling industry are expected to continue. It is expected that the textile recycling industry continues to grow in the near future. Therefore, the proposed system modelscan be used for further studies, and they can be expanded to find the other improvement alternatives.

In this study, a simulation-based model was presented for a textile recycling process with integration of sub-models. By analyzing the results of the model, it was observed that in comparison with the base model provided based on the available information and taken assumptions, there would be a noticeable difference in the number of final products (recycled items) by using the proposed scenarios. The experiment results express that by applying the proposed alternative (2), it is possible to increase the finished goods volume by 43%.

5.2 Future work

In order to follow the main purpose of this study to improve the garment manufacturing facilities and increase the production rate it is recommended to focus on the other area of textiles recycling system. Suggested future research includes the process of collecting garment and also locating the garment collecting containers to accelerate the collecting process. Considering demand fluctuation and providing a model to predict the demand can also be studied in the future.

The methodology discussed in this study can be applied to any real textile recycling production line to achieve the maximum output by using a new method in the production process. Therefore, based on the machine type and system capacity, input parameters may vary in different production plants. Moreover, the quality of outputs of the proposed model with the conventional method can be investigated.

REFERENCES/BIBLIOGRAPHY

1. Law, A.M., W.D. Kelton, and W.D. Kelton, *Simulation modeling and analysis*. Vol. 2. 1991: McGraw-Hill New York.
2. Zamani, B., et al., *A carbon footprint of textile recycling: A case study in Sweden.* Journal of industrial ecology, 2015. **19**(4): p. 676-687.
3. De Silva, R. and N. Byrne, *Utilization of cotton waste for regenerated cellulose fibres: Influence of degree of polymerization on mechanical properties.* Carbohydrate polymers, 2017. **174**: p. 89-94.
4. CBC. *Textiles are the next frontier in recycling for cities looking to cut waste*. 2016, May 19; Available from: https://www.cbc.ca/news/technology/textile-recycling-1.3569138.
5. SMART. *Secondary Materials and Recycled Textiles Association Media kit*. 2017; Available from: https://www.smartasn.org/SMARTASN/assets/File/resources/SMART_PressKitOnline.pdf.
6. Bureau, U.S.C. *US and World Population Clock* 2018; Available from: https://www.census.gov/popclock/.
7. BIR. *Annual report* 2017
8. EPA. *Facts and Figures about Materials, Waste and Recycling*. 2018 July 2018; Available from: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/textiles-material-specific-data.
9. EPA, *Science and Research at the U.S. Environmental Protection Agency*, in

2010: Washington

10. Company, H. *How many cars are in the US? Need car ownership statistics? Vehicle ownership data, automobile statistics and trends.* 2018; Available from: https://hedgescompany.com/automotive-market-research-statistics/auto-mailing-lists-and-marketing/.
11. Hawley, J.M., *Textile recycling: A systems perspective*, in *Recycling in textiles*. 2006, Woodhead Publishing Limited, UK.
12. Cuc, S. and M. Vidovic, *Environmental sustainability through clothing recycling.* Operations and Supply Chain Management, 2011. **4**(2/3): p. 108-115.
13. Dissanayake, G. and P. Sinha, *An examination of the product development process for fashion remanufacturing.* Resources, Conservation and Recycling, 2015. **104**: p. 94-102.
14. Aggour, A., A. Moussaid, and A. Abou El Hassan, *Fast Fashion in the Moroccan Apparel Supply Chain: A Case Study*. Vol. 7. 2016. 17-24.
15. Caro, F. and V. Martínez-de-Albéniz, *Fast fashion: business model overview and research opportunities*, in *Retail supply chain management*. 2015, Springer. p. 237-264.
16. Turker, D. and C. Altuntas, *Sustainable supply chain management in the fast fashion industry: An analysis of corporate reports.* European Management Journal, 2014. **32**(5): p. 837-849.
17. H&M. *Recycle your clothes*. 2018; Available from: https://about.hm.com/en/sustainability/get-involved/recycle-your-clothes.html.

18. Caniato, F., et al., *Environmental sustainability in fashion supply chains: An exploratory case based research.* International journal of production economics, 2012. **135**(2): p. 659-670.
19. OTR. *What are Organic Fiber Products and How Can You Label Them?* 2012; Available from: https://ota.com/sites/default/files/indexed_files/What_are_Organic_Fiber_Products.pdf.
20. Sandin, G. and G.M. Peters, *Environmental impact of textile reuse and recycling–A review.* Journal of Cleaner Production, 2018.
21. Kerr, J. and J. Landry, *Pulse of the fashion industry* 2017: Copenhagen
22. Weber, S., *How Consumers Manage Textile Waste*. 2015, University of Waterloo: Canada p. 162.
23. Malilay-Pimentel, C.E., *Reducing textile waste in Metro Vancouver landfills*, in *School of Public Policy Faculty of Arts and Social Sciences*. 2017, University of British Columbia: Canada.
24. Newell, A., *Textile waste resource recovery: A case study of New York State's textile recycling system.* 2015.
25. Caroline Chalmer, et al., *Seven sustainability priorities for fashion industry leaders*. 2018.
26. *I:co closes Loops*. Available from: https://www.ico-spirit.com/.
27. Allwood, J.M., et al., *Well dressed.* The present and future sustainability of clothing and textiles in the United Kingdom, 2006. **1**.
28. Carbone, C., C. Hill, and C. Meyer, *Textiles: From Waste To Resources in Denmark*. 2016, Worcester Polytechnic Institute.
29. Birtwistle, G. and C.M. Moore, *Fashion clothing–where does it all end up?* International Journal of Retail & Distribution Management, 2007. **35**(3): p. 210-216.
30. Han, S. and T. Cassidy, *Upcycling fashion for mass production.* 2013.
31. Woolridge, A.C., et al., *Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: An UK energy saving perspective.* Resources, conservation and recycling, 2006. **46**(1): p. 94-103.
32. Ravenhall, L. *Fast fashion & the destruction of developing countries*. 2016.
33. Rivoli, P., *The travels of a t-shirt in the global economy: An economist examines the markets, power, and politics of world trade. New preface and epilogue with updates on economic issues and main characters*. 2014: John Wiley & Sons.
34. Claudio, L., *Waste couture: Environmental impact of the clothing industry.* Environmental health perspectives, 2007. **115**(9): p. A449.
35. Roznev, A., et al., *Recycling in textiles.* Supply chain Management, 2011: p. 1-20.
36. Howell, S. *How Much of the World's Clothing Is Made From Cotton?* 2017; Available from: https://www.livestrong.com/article/1001371-much-worlds-clothing-made-cotton/.
37. Resnick, B. *More than ever, our clothes are made of plastic. Just washing them can pollute the oceans.* 2018.
38. Bain, M. *If your clothes aren't already made out of plastic, they will be*. 2015.
39. EduPack, C. *CES EduPack tools and resources for students*. 2018; Available from: https://grantadesign.com/education/ces-edupack/.

40. Esteve-Turrillas, F. and M. de la Guardia, *Environmental impact of Recover cotton in textile industry.* Resources, Conservation and Recycling, 2017. **116**: p. 107-115.
41. Wanassi, B., B. Azzouz, and M.B. Hassen, *Value-added waste cotton yarn: Optimization of recycling process and spinning of reclaimed fibers.* Industrial Crops and Products, 2016. **87**: p. 27-32.
42. Bevilacqua, M., et al., *Environmental analysis of a cotton yarn supply chain.* Journal of cleaner production, 2014. **82**: p. 154-165.
43. Li, Y., et al., *Governance of sustainable supply chains in the fast fashion industry.* European Management Journal, 2014. **32**(5): p. 823-836.
44. Baydar, G., N. Ciliz, and A. Mammadov, *Life cycle assessment of cotton textile products in Turkey.* Resources, Conservation and Recycling, 2015. **104**: p. 213-223.
45. Muthu, S.S., et al., *Recyclability Potential Index (RPI): The concept and quantification of RPI for textile fibres.* Ecological indicators, 2012. **18**: p. 58-62.
46. Moretto, A., et al., *Designing a roadmap towards a sustainable supply chain: A focus on the fashion industry.* Journal of Cleaner Production, 2018. **193**: p. 169-184.
47. Chen, X., Y. Huang, and T. Murata. *Optimization method of short life cycle product supply chain network with recycle flow and dispersed markets*. in *Industrial Electronics and Applications, 2008. ICIEA 2008. 3rd IEEE Conference on*. 2008. IEEE.
48. Allwood, J.M., et al., *Well dressed?: The present and future sustainability of clothing and textiles in the United Kingdom.* Journal of the Home Economics Institute of Australia, 2015. **22**(1): p. 42.
49. Mehrjoo, M., *Supply Chain Risk Assessment for Perishable Products Applying System Dynamics Methodology-A Case of Fast Fashion Apparel Industry*, in *Department of Industrial and Manufacturing Systems Engineering*. 2014, University of Windsor: Canada.
50. Azimi, P., et al., *Optimization Via Simulation and Enterprise Dynamica Tutorial*. Vol. 2. 2013: QIAU.
51. INC, M.W.M. 2018; Available from: www.millerwastemills.com.
52. Tompkins, J.A., et al., *Facilities planning*. 2010: John Wiley & Sons.
53. Osombrand. *Promoting a circular economy in the textile industry*. 2018; Available from: http://www.osombrand.com/osomtex/.
54. Chung, C.A., *Simulation modeling handbook: a practical approach*. 2003: CRC press.
55. Hogan, R., et al. *Reducing the cost of cotton production*
56. Incorporated, C. *Harvest Loss Calculations*. 2018; Available from: https://www.cottoninc.com/cotton-production/.
57. Thompson, L. and D. Hitchen, *Recycling grade textiles collection demonstration projects*. 2014: The UK.
58. Palm, D., *Improved waste management of textiles* 2011, IVL Swedish Environmental Research Institute Ltd. : Sweden

APPENDICES

Appendices 1. Analysis

The final target of every clothing producer is to increase the business profitability. Political, economic and environmental issues make it difficult to achieve this goal [55]. Furthermore, the cotton production procedure has its obstacles like agriculture policy, high-cost fields, machinery management and issues related to growing which are listed below:

- Excessive rain at the time of sowing
- The high temperature at flowering step and drought
- Soil quality
- Virus incidence on leaf
- Pest attack and early die out
- Irrigation system
- Whether fluctuation

After the cotton harvesting stage, cotton balls which are on calyx need to go through processes such as, cleaning and grading. In this stage, the amount of waste fluctuates between 7 to 10 percent depending on the area where the cotton is cultivated, and this number can rais to 20 percent [56]. Mentioned factors have a noticeable impact on cotton pricing. Table 11 shows costs related to the cotton cultivation in Australia which is one of the biggest cotton producers. Gross and net income for 800 pounds of raw cotton per acre is approximately 1900 USD. Production costs may vary year to year or season to season based on the location of the field [55].

Production costs (2011)	**Price (AUD/HA)**
Insecticide and Bollgard[1]	400
Fuel	350
Seed	110
Fertilizer	390
Total production cost	2500
Total income	5100
Net profit	2600

Table 10. Table Costs of production of raw cotton in Australia (2011)

The cotton production costs are increasing considerably (figure 35), which is an issue facing the cotton growers. On the other hand, rising costs of production have a direct impact on the clothing price and clothing manufacturing profitability. So there is a need to be looking for ways to make clothing production more profitable and from an environmental point of view more sustainable. By saving more in production stage not only it can reduce the total cost but also it will be environmentally friendly.

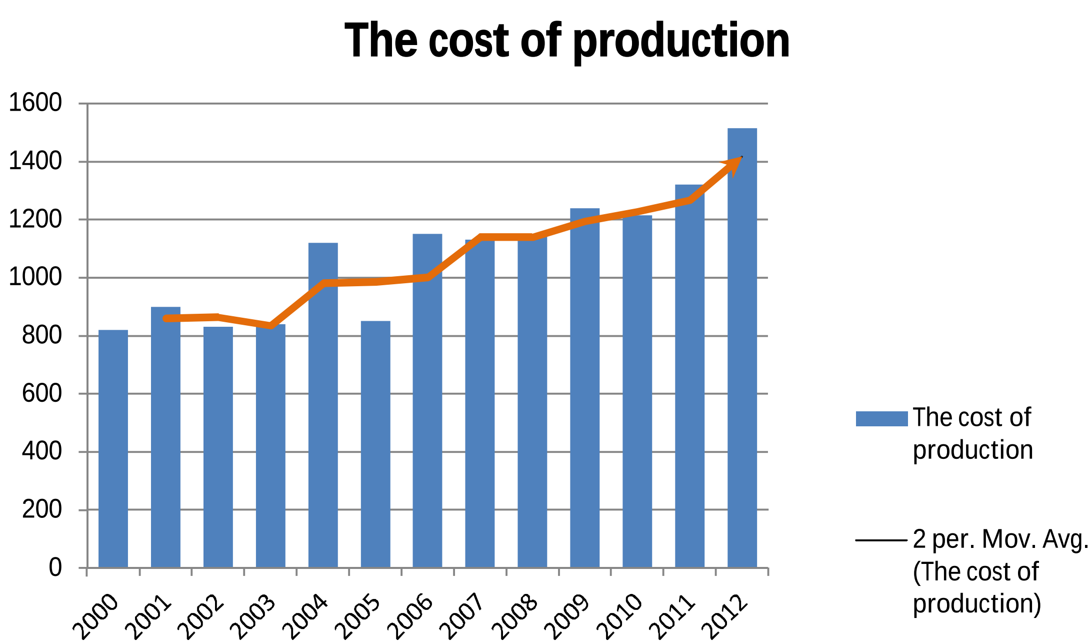


Figure 37. Cost of cotton production in Australia from 2000 to 2012.

[1] Bollgard is the technology that provides protection for cotton seeds

Recycling the used clothing item can be a profitable substitution for virgin materials. Although some of the cotton recycling manufacturers use some percentage of virgin material in the production process, the total manufacturing price can be lower in comparison with 100% virgin materials. Approximately 60% of the total price of a clothing item is related to its used material. By increasing the recycled material production rate, the related cost will be reduced. So, if by 10% increase in production rate the price of recycled material decrease by 2%, it is possible to have a 12% reduction in total price.

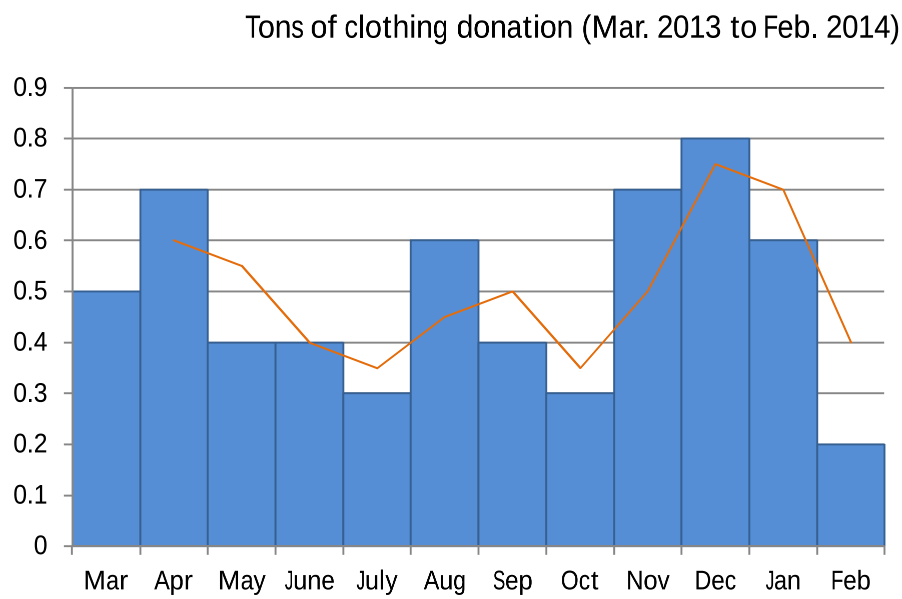


Figure 38. The amount of donated clothes collected from the weekly collection for a recycling plant in the UK

Producing recycled cotton and production of virgin cotton has some difficulties, for instance, demand unpredictability. As it is shown in figure 36 in some seasons, the donation rate is lower than the average which it shows the donating rate fluctuation [57], but by studying related historical data, it can be possible to have a rough estimation for the rate of incoming products. In this case, based on the results from Minitab software, Gamma is the best distribution that fits these datasets due to its P-value which is bigger than 0.05 and the data points roughly follow a straight line (figure 37).

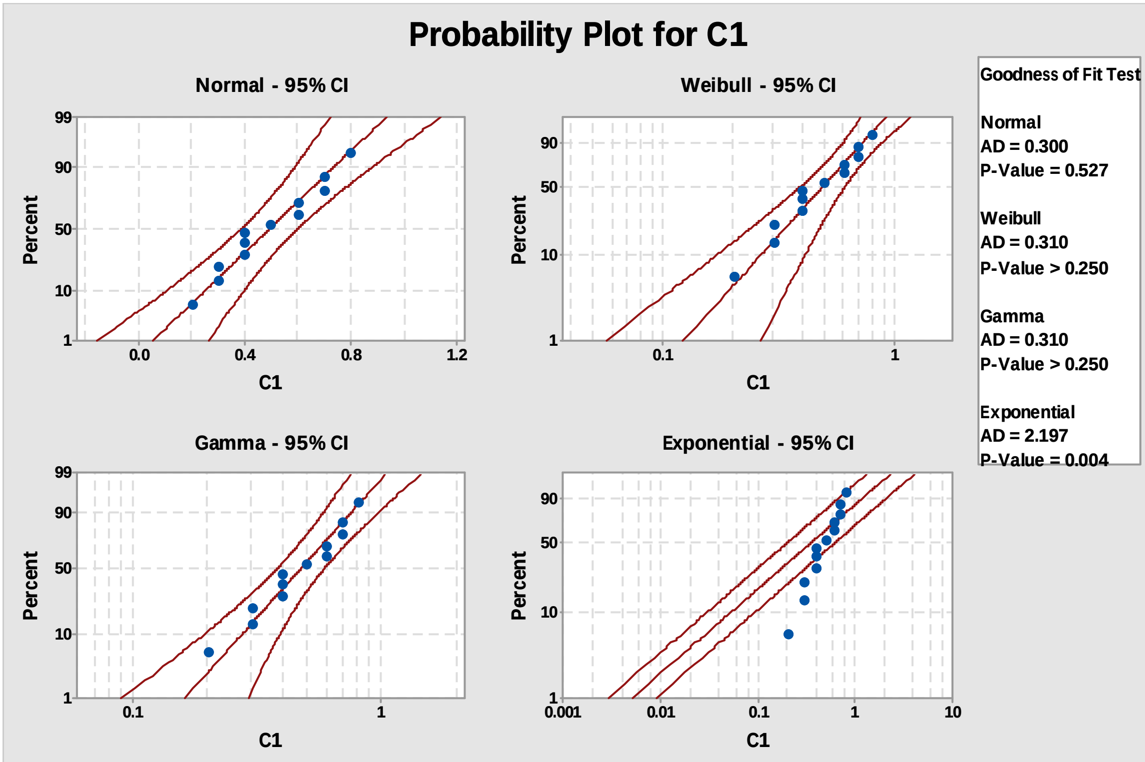


Figure 39. Determining the distribution of clothing donation (figure 36)

The cotton loss is one of the most critical issues related to cotton production and cultivation. As it is illustrated in figure 38, for a yield of 800 pounds per acre, different processes such as, for example, growing, harvesting, and cleaning are involved in the cotton production stage. In each of these steps, there is some amount of loss and waste. Based on the historical data, there is 3% to 7% waste for each process [56] depending on the quality of harvested cotton.

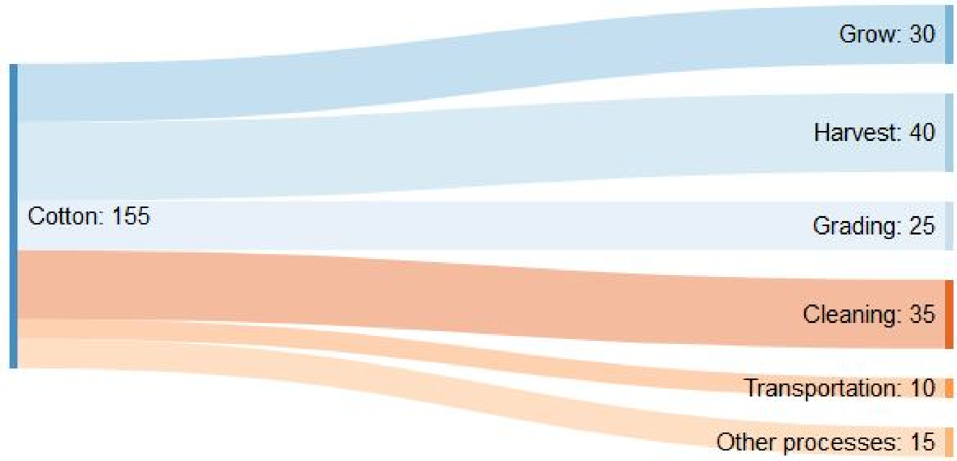


Figure 40. The cotton loss in different stages of production

Appendices 2. Discussion

There will be so many factors that can have a considerable impact on textile recycling. Palm [58] studied an environmentally improved textile recycling system. In his report, he provided connections between sustainable waste management factors which are shown in Fig 31. There are various contributors which affect the relationship between textile recycling and waste management, in this research, the purpose is to explore a simulation of hypothetical recycling process which is created by taking the discussed assumptions and proposed scenarios. Additionally, studying the interaction between different components of the model is taken into account to realize how the change in input parameters affects the outcome of the model.

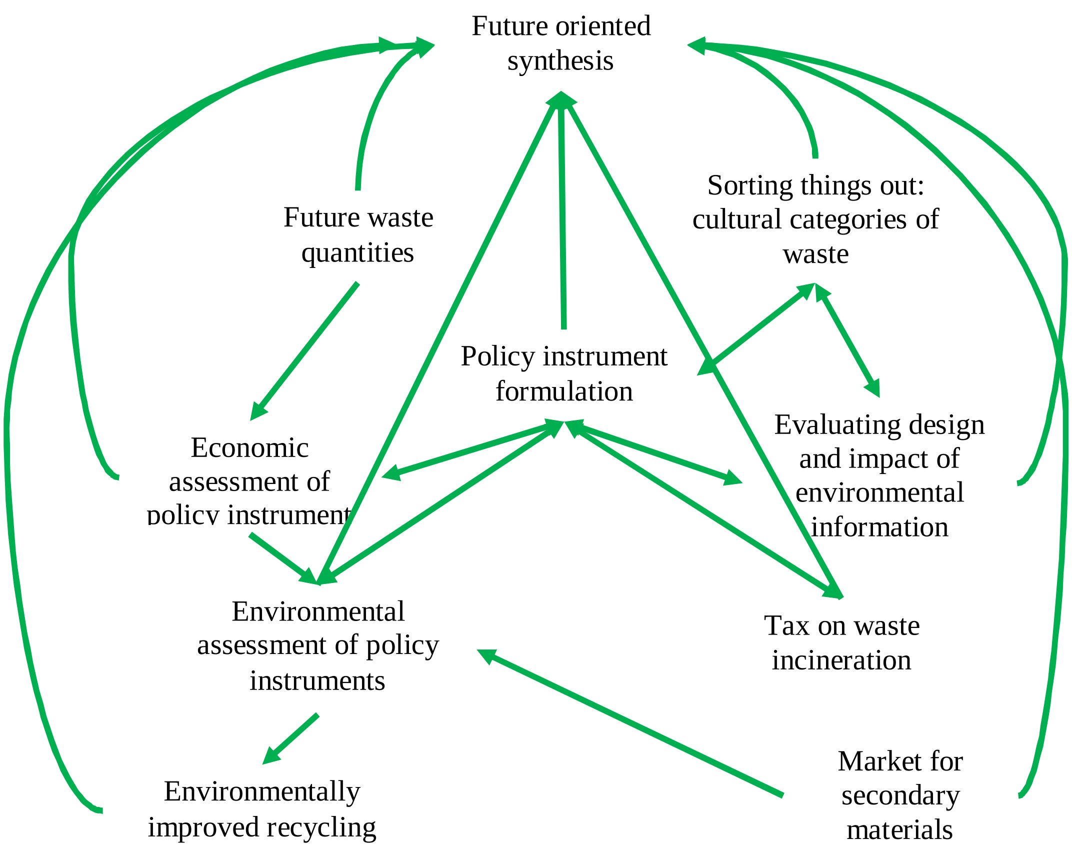


Figure 41. Potential reasons which can have an effect on textile waste adapted and modified from [58]

There are different policies behind any change in input parameters such as, for example, disposing rate or number of donated items and there are many complex reasons and logic behind any factor. Therefore, based on the assumptions taken in the base model it is tried to anticipate the outcome. Some of the factors that can vary from one scenario to another are production rate of used material, switching machines, or applying a new sequence of operations. The results of running the model provide details regarding the number and variety of finished products and the time each product spends in the system.

Policies and measures are needed to reduce the consumption of raw textile and increase the rate of recycling, but there is not enough knowledge and evidence to discuss this matter. Improving the textile waste management system can reduce the final price of recycled materials. We are also aware that the environmental costs are not inclusive to the production of raw textile. This could be one of the reasons why currently most of the raw materials are cheaper than recycled materials [58]

Appendices 3. Environmental aspects of textile waste

As it was mentioned in the second chapter a product lifecycle can be defined to two-phase; use and after use phase. From the aspect of sustainability, the second phase of a product life is more important. The reason behind this matter is the environmental effect that a product can have. A T-shirt just takes about 226 grams of cotton to be made but this is its environmental issues such as energy and fresh water consumption, carbon footprint, the amount of fertilizer and insecticide which have impact on the environment. For every kilogram of virgin cotton displaced by second-hand clothing approximately 65 kWh is saved [40].

Appendices 4. Pricing analysis

Virgin materials and raw textiles are harvest and produced in low-cost countries while collection for reusing and recycling occurs in countries like Sweden, Denmark, The United Kingdom and The United States of America where the wages for workers are higher [58]. Moreover, the region of production, quantity, and quality of input material, recycling facilities and efficiency of the process need to be considered for price analysis. In this study due to lack of data, these factors are not considered.

All the mentioned reasons can have an impact on the textile waste management system. Based on available recourses if the final price of a T-shirt assumes to be $5.67 so, this includes six different components:

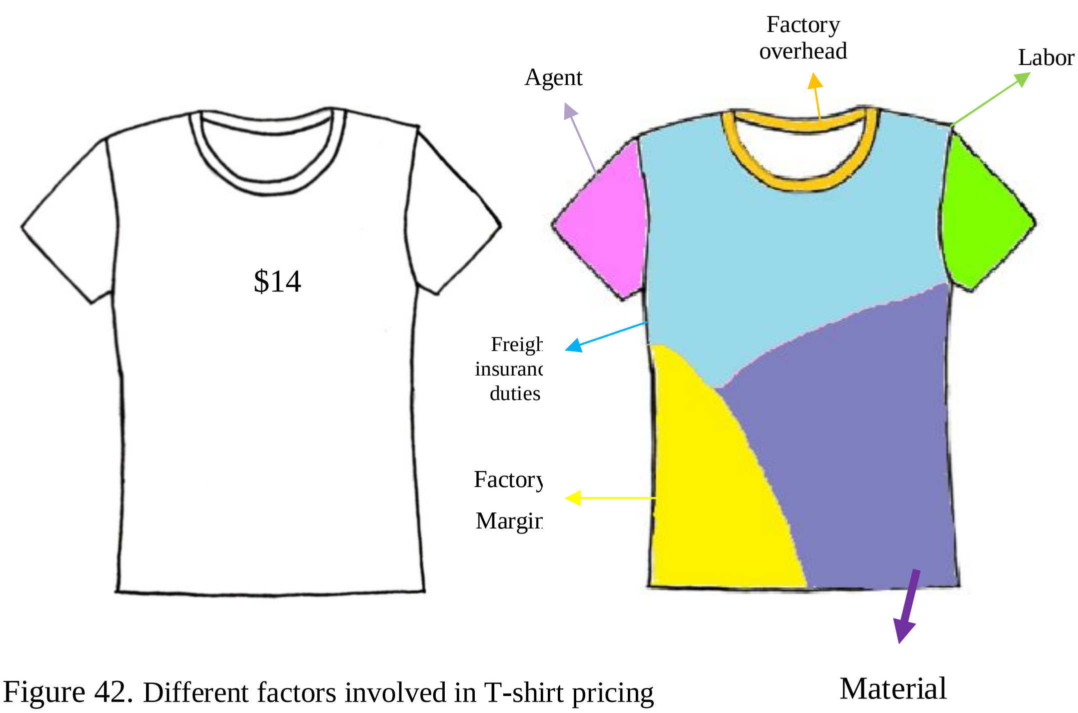


Figure 42. Different factors involved in T-shirt pricing

Different components in T-shirt pricing	Price in US Dollar
Factory overhead	0.07
Labor	0.12
Agent	0.18
Factory margin	0.58
Freight insurance duties	1.03
Material and finishing	3.69

Table 11. Pricing analysis

These numbers might change based on the location of the production factory for instance in the U.S the total price is around 13.22 dollars which $7.74 is labor cost, and just $5 is for used materials. On the other hand, most of the T-shirts which are made in Bangladesh or India, (where the labor cost is cheap) sold in developed countries with a higher price ($14). Hence, it is possible to assume that %65.07 of the total cost is related to the materials. Therefore, by applying low-cost materials, it can be possible to reduce production costs. So, by saving one monetary unit, the total price is reduced by 21%. [58].

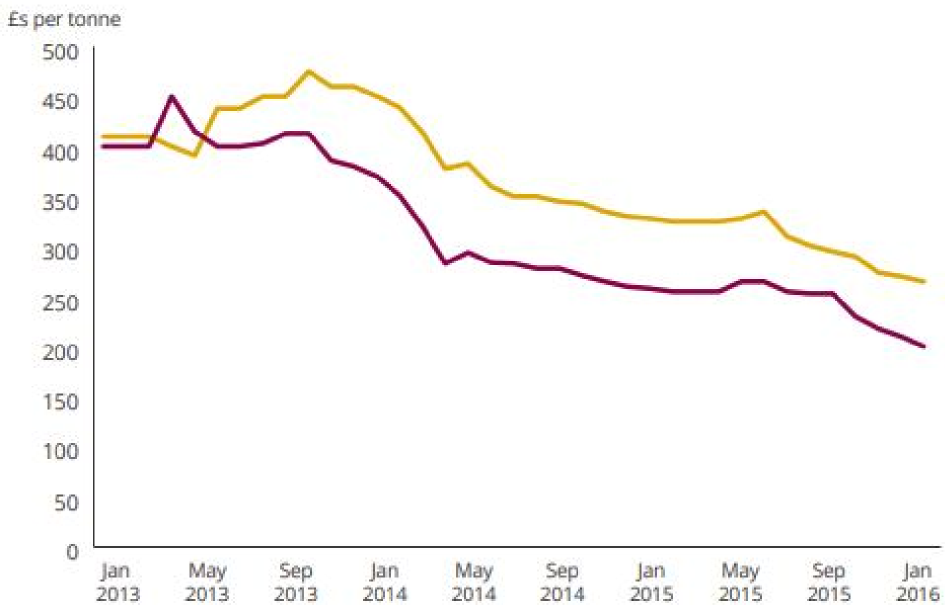


Figure 43. Recovered textile price [7]

In recent years due to the desire for recycling textile is increasing and recycling plants are using new technologies and methods to recover used clothes, it is expected to have less recycling cost. Figure 19 illustrates the pricing data for two years (from January 2013 to January 2016).

Appendices 5. Related figures and tables

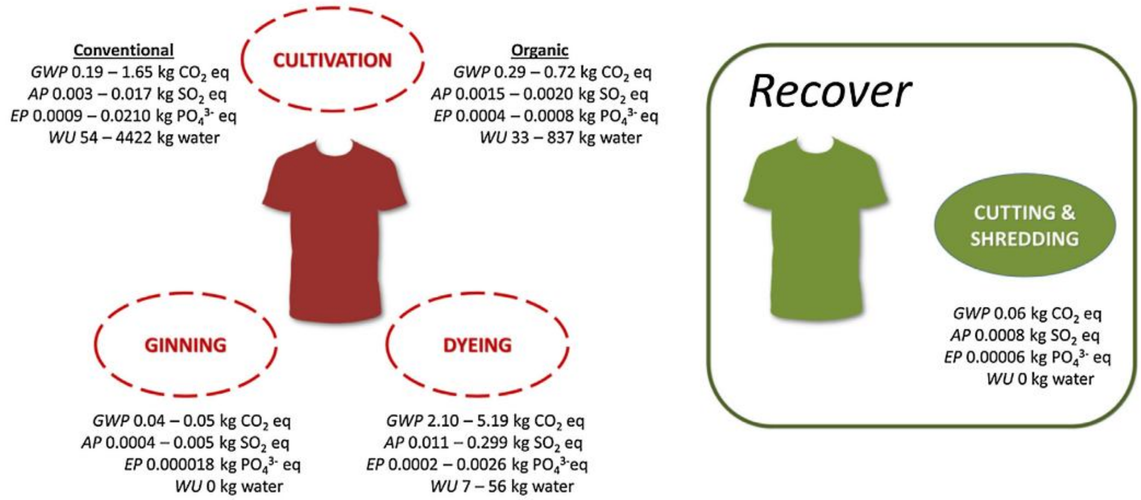


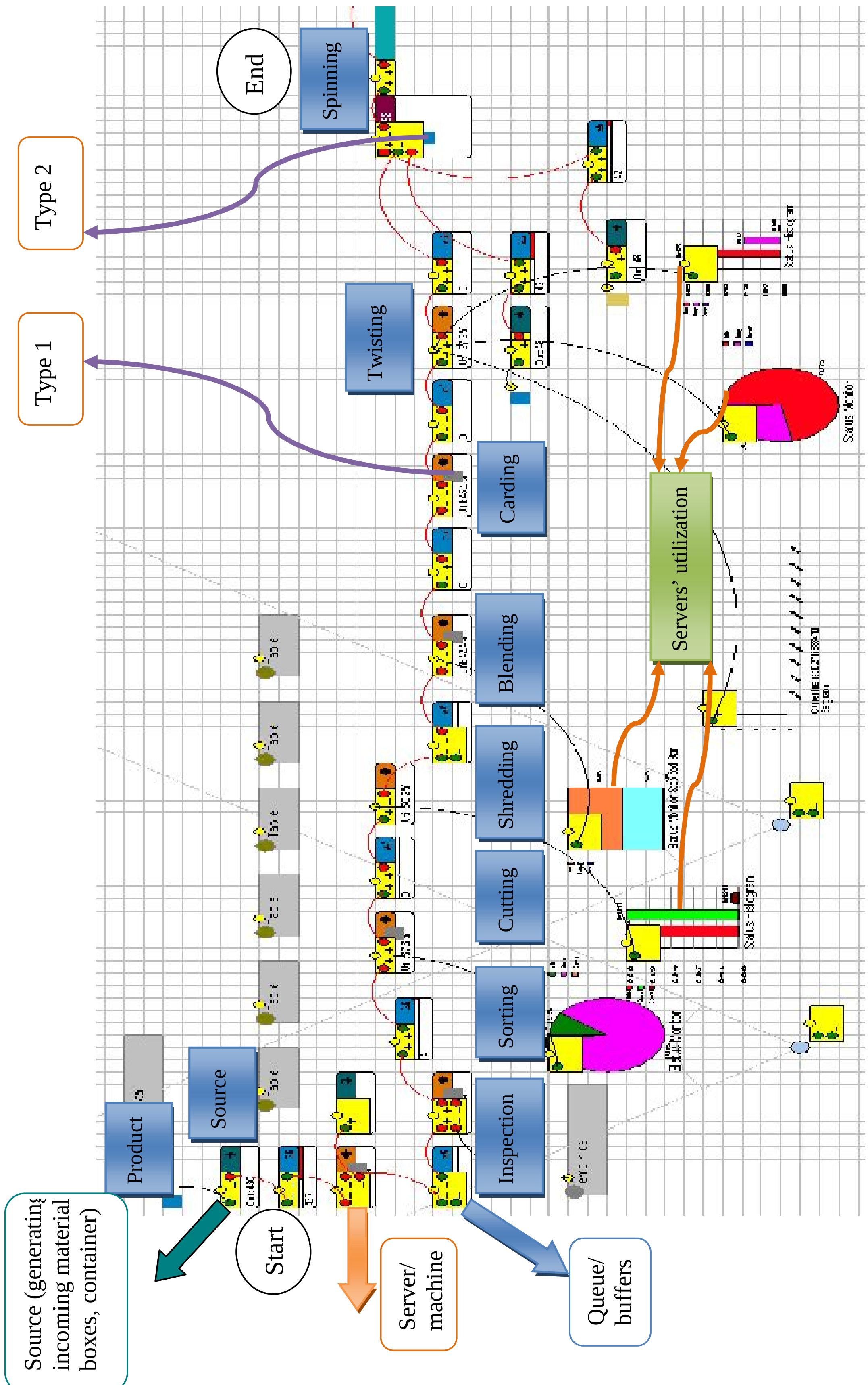
Figure 44. Environmental impacts of a cotton T-shirt (0.3kg) and a recovers T-shirt [40].

Figure 45. Main steps to produce recycled cotton [40].

Table 12. The results of 316 replications from the base model

14	14	14	14	14	14	14	14
14	14	14	14	14	14	14	14
16	14	14	14	14	14	14	15
14	14	14	14	14	14	14	14
14	14	14	14	16	14	15	14
14	14	14	14	14	14	14	14
14	14	14	14	15	14	14	14
14	14	14	14	14	14	14	14
14	13	14	14	16	14	16	14
14	14	14	14	14	14	14	14
14	14	14	15	14	14	14	14
14	14	14	14	14	14	14	14
14	14	16	14	14	14	14	14
15	14	14	14	14	14	14	14
14	14	14	14	14	14	14	14
14	14	16	14	14	14	14	16
14	14	14	14	14	14	14	14
14	14	15	15	14	14	14	14
14	14	14	14	14	14	14	14
14	14	14	14	14	14	14	14
14	14	14	14	15	14	14	14
14	15	14	14	14	14	14	14
14	14	14	14	14	14	14	16
14	14	14	16	14	14	14	14
15	14	14	14	14	14	14	14
14	16	14	14	14	16	14	15
14	14	14	14	14	14	14	14
14	14	14	14	15	16	14	14
14	16	14	14	14	14	14	14
15	14	14	14	14	14	14	14
14	14	15	14	14	14	15	14
16	14	14	15	14	14	14	14
14	14	14	14	14	14	14	14
14	14	14	14	14	14	14	16
14	14	15	16	14	14	14	14
14	14	14	14	14	14	14	14
14	15	14	15	14	14	16	14
14	14	14	14	14	14	14	14
14	14	14	14	14	14	14	14
14	14	14	14				

Figure 46. Mechanical textile recycling for cotton fibers is presented with the simulation



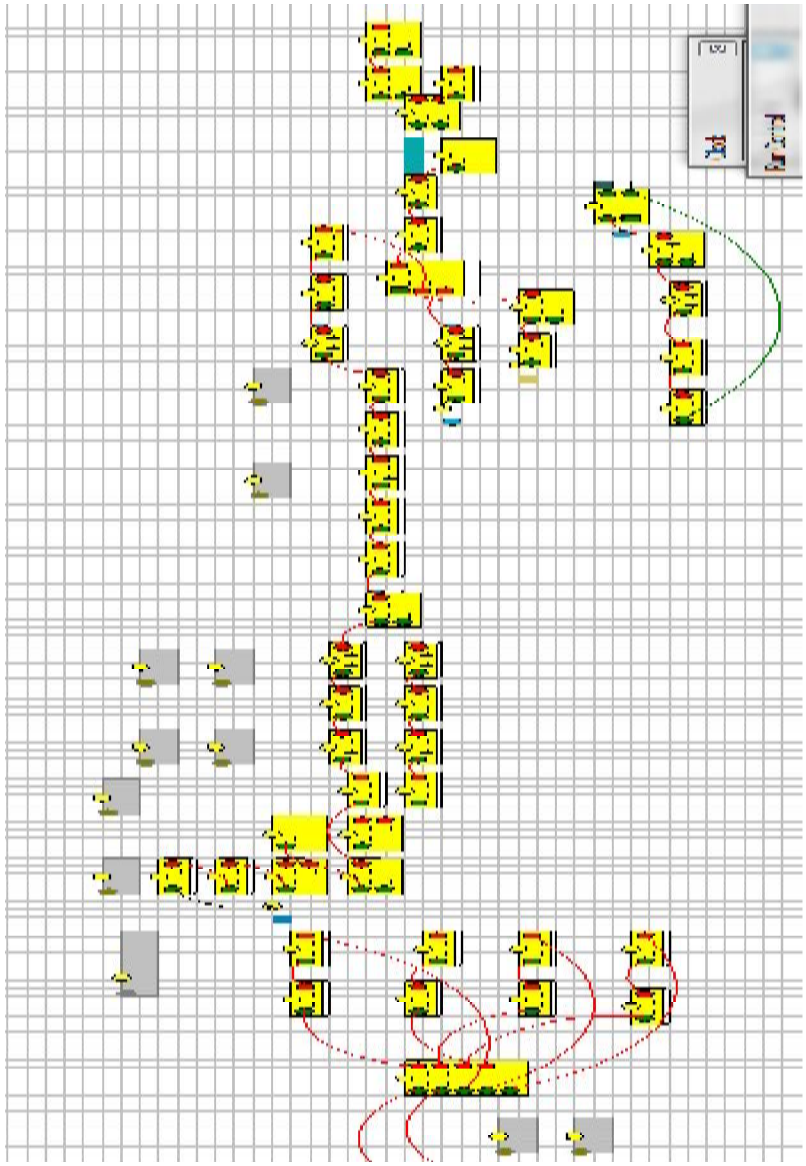


Figure 47. Recycling process model

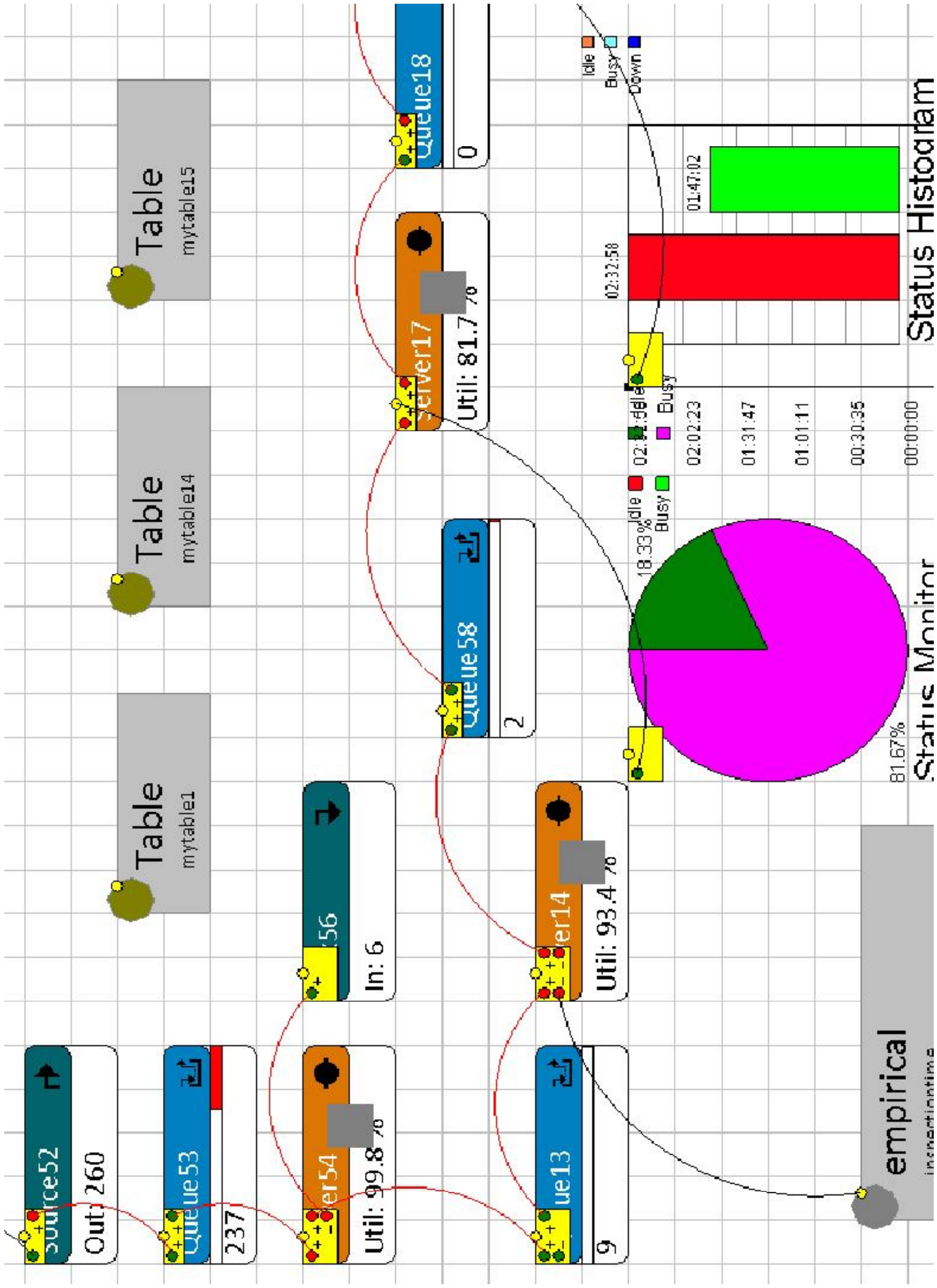


Figure 48. Details in the recycling process model (1)

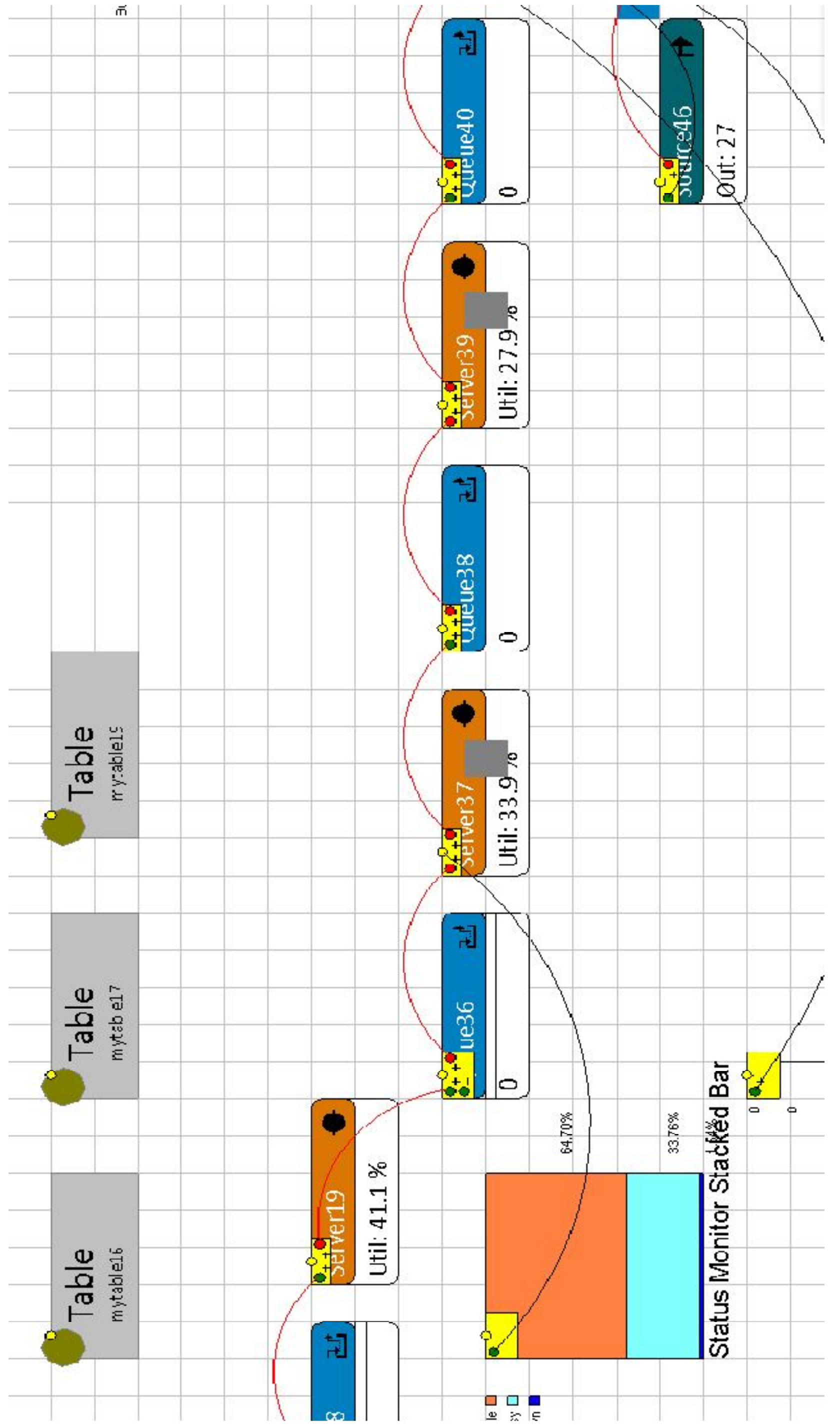


Figure 49. Details in the recycling process model (2)

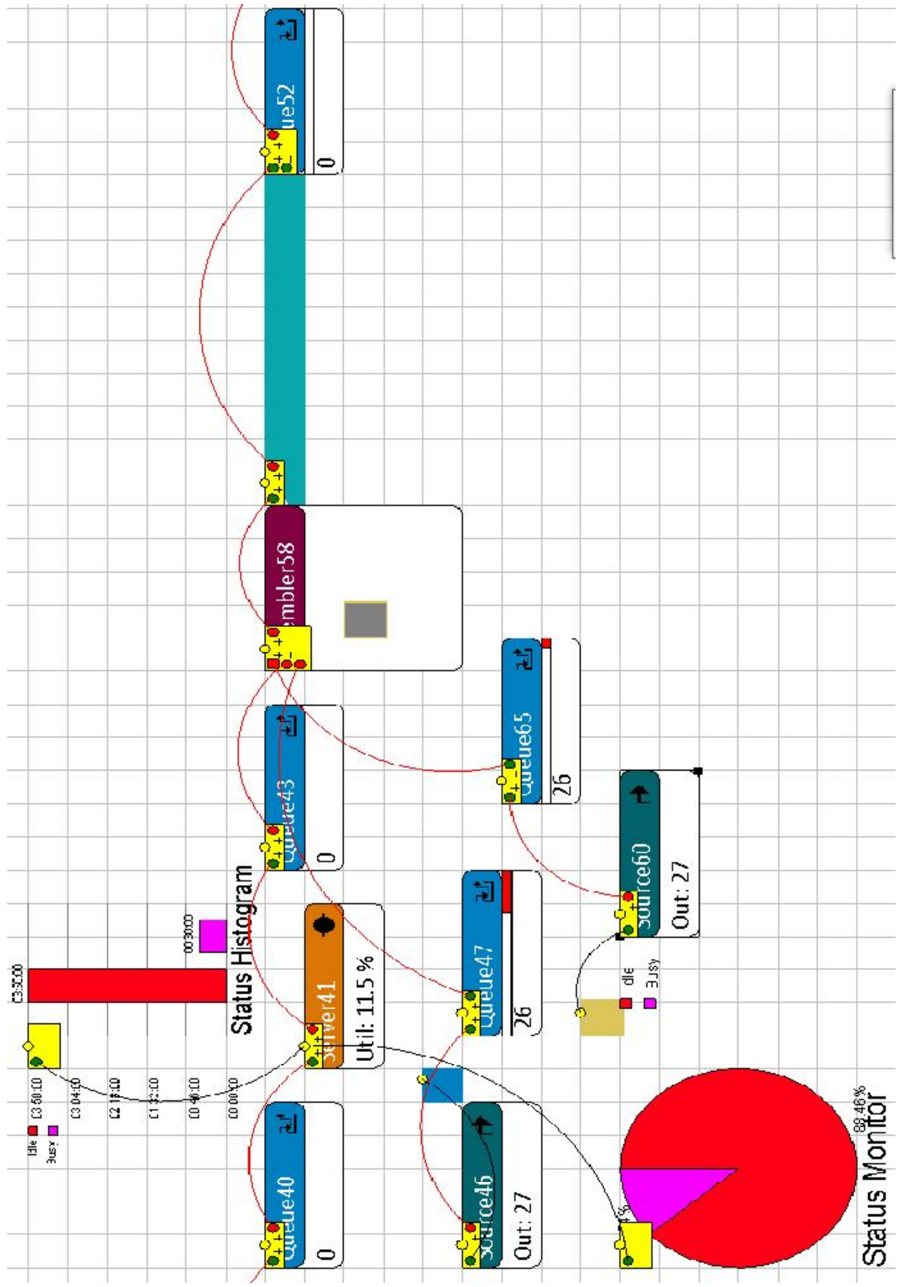


Figure 50. Details in the recycling process model (3)

Summary report

	content		throughput		staytime
name	**current**	**average**	**input**	**output**	**average**
mytable19	0	0.000	0	0	0.000
mytable17	0	0.000	0	0	0.000
inspectiontime	0	0.000	0	0	0.000
mytable16	0	0.000	0	0	0.000
mytable15	0	0.000	0	0	0.000
mytable14	0	0.000	0	0	0.000
kkk1	0	0.000	0	0	0.000
mytable1	0	0.000	0	0	0.000
c_time	0	0.000	0	0	0.000
p_plan	0	0.000	0	0	0.000
Queue13	56	28.012	82	26	18754.740
Server14	1	0.990	26	25	2273.351
Server17	1	0.950	18	17	3180.317
Queue18	0	0.000	17	17	0.000
Server19	1	0.578	17	16	2038.813
Product	0	0.000	0	0	0.000
Ground Storage7	0	0.000	0	0	0.000
Queue32	0	0.000	0	0	0.000
Server33	0	0.000	0	0	0.000
Server34	0	0.000	0	0	0.000
Queue35	0	0.000	0	0	0.000
Queue36	0	0.000	16	16	0.000
Server37	0	0.067	16	16	240.000
Queue38	0	0.000	16	16	0.000
Server39	0	0.003	16	16	9.250
Queue40	0	0.000	16	16	0.000
Server41	0	0.007	16	16	26.889
Queue43	0	0.000	16	16	0.000
Source46	0	0.000	96	96	0.000
Queue47	79	40.791	96	17	26727.480
Product48	0	0.000	0	0	0.000
Queue52	0	0.000	16	16	0.000
Advanced Accumu	0	0.003	16	16	10.000
Product	0	0.000	0	0	0.000
Queue54	16	6.689	16	0	0.000
Source52	1	0.068	895	894	4.083
Queue53	800	431.238	894	94	26457.577
Server54	1	0.999	94	93	615.378
Product	0	0.000	0	0	0.000
Sink56	0	0.000	11	0	0.000
Queue58	7	3.650	25	18	8833.424
Assembler58	1	1.000	50	49	1162.341
Container59	0	0.000	0	0	0.000
Source60	0	0.000	96	96	0.000
Queue65	79	40.791	96	17	26727.480
Camera46	0	0.000	0	0	0.000

Model start time	Monday, September 24 2018 12:25:02
Model end time	Tuesday, September 25 2018 04:25:02
Runlength (seconds)	57600.00

End of report.

Figure 51. Summary report after running the base model for 16 hours

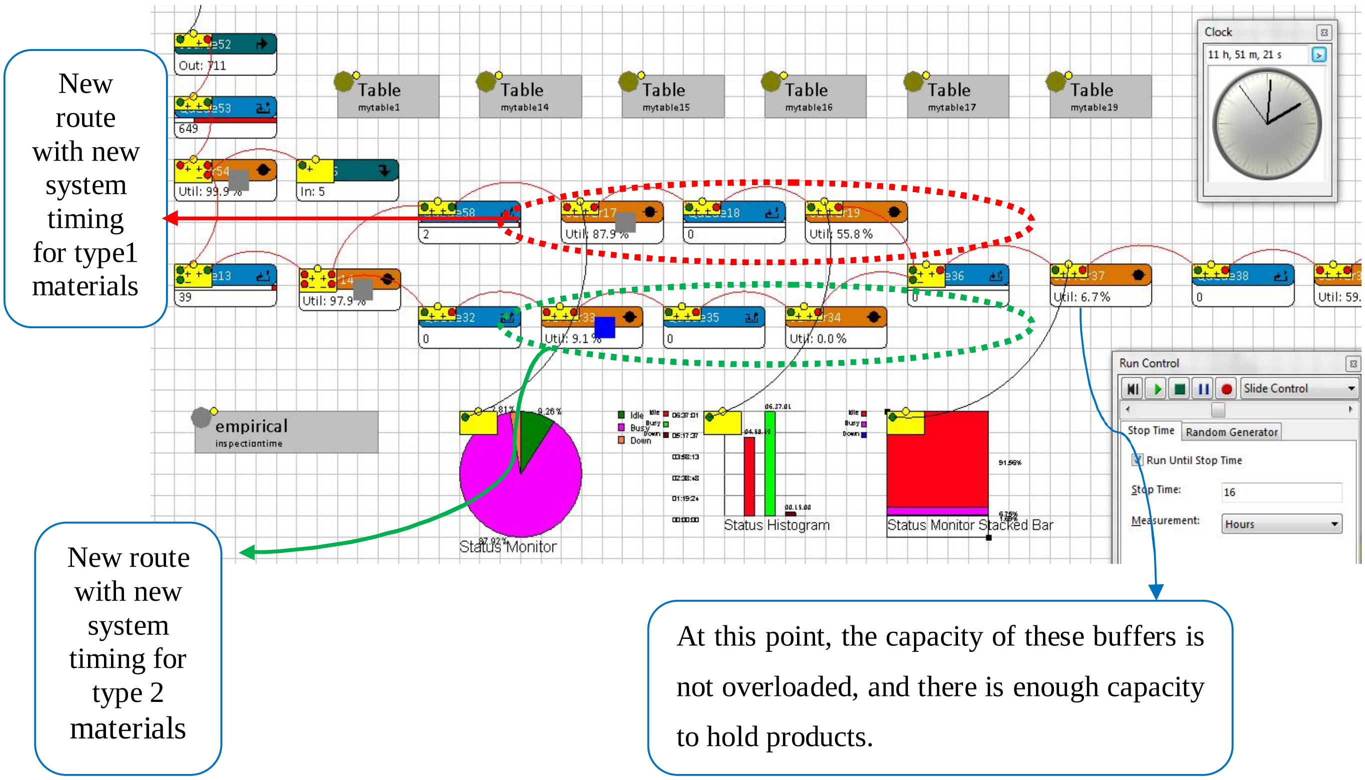


Figure 52. Proposed model after using the new sorting system and using a new process flow for different types of materials

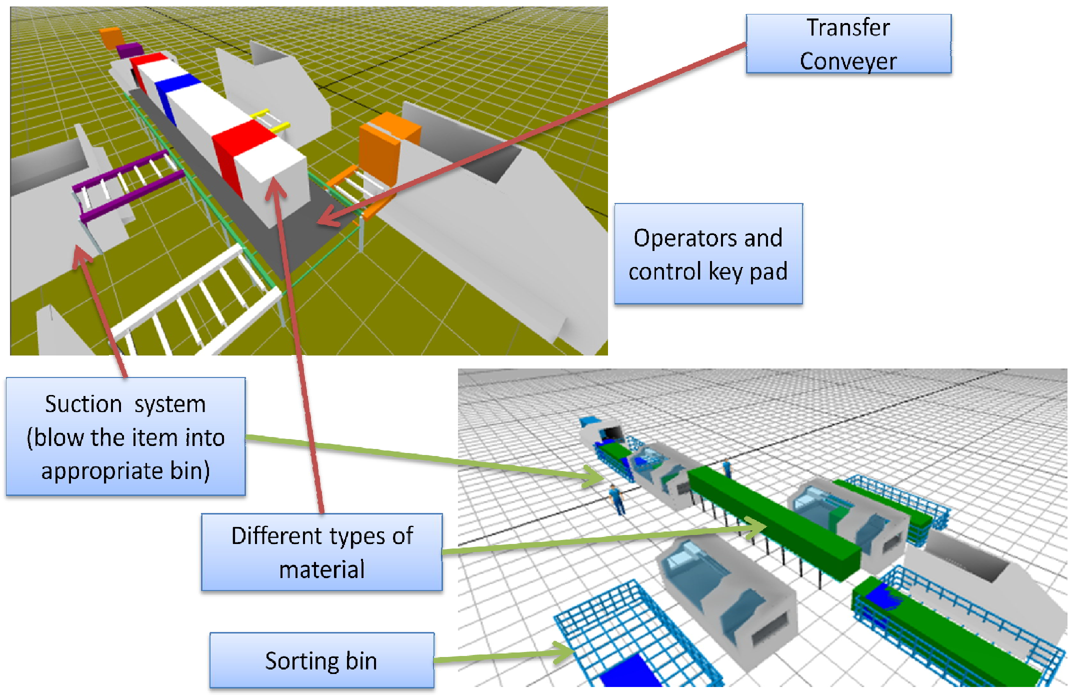


Figure 53. 3D view of the new inspection and sorting system

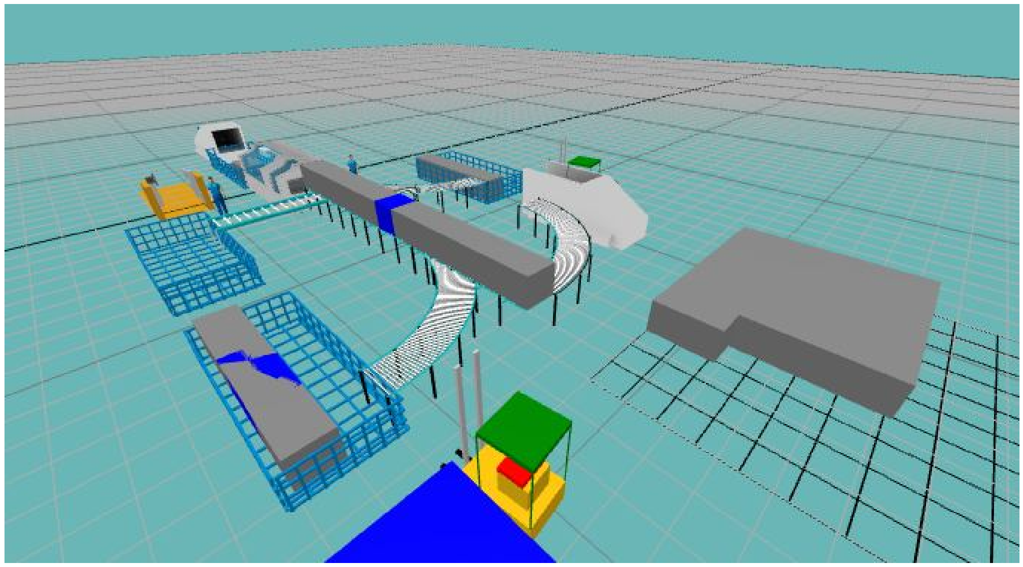


Figure 54. The 3D view of improvement model (The inventory behind cutting machine)

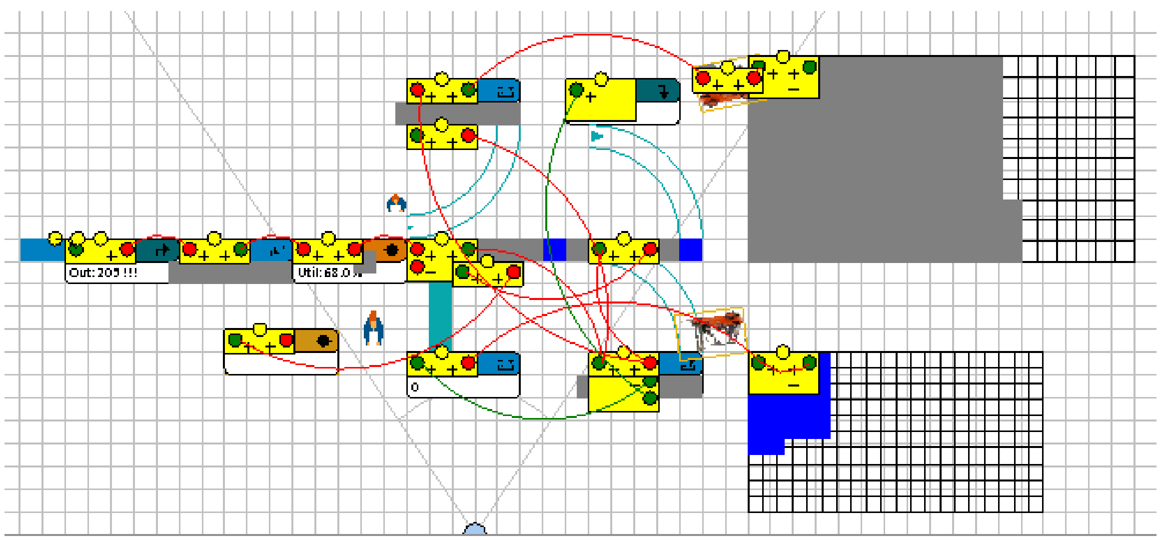


Figure 55. 2D view of sorting and inspection stations for the proposed model

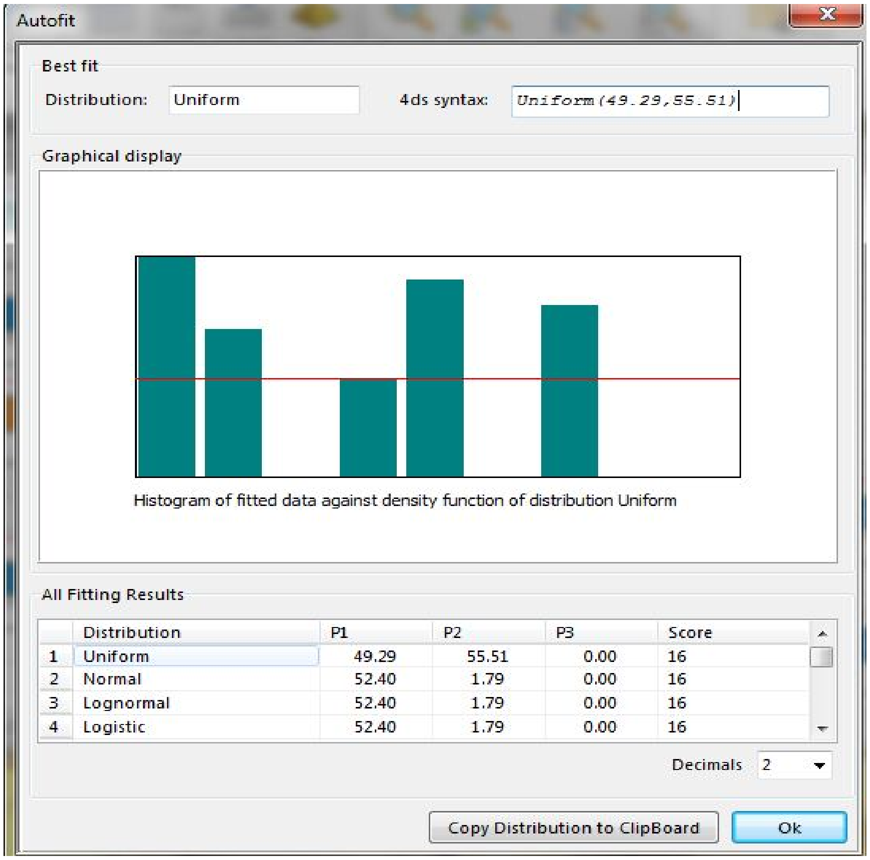


Figure 56. Cycle time for cutting machine for the first type of material

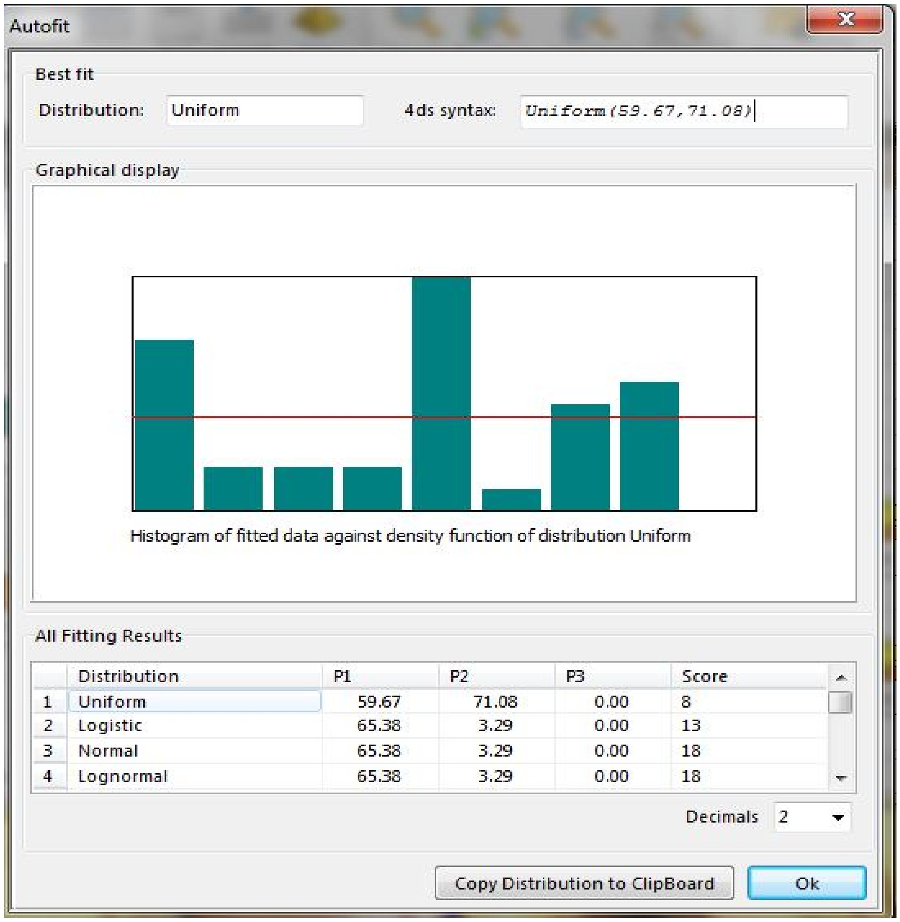


Figure 57. Cutting machine cycle time for the second type of material

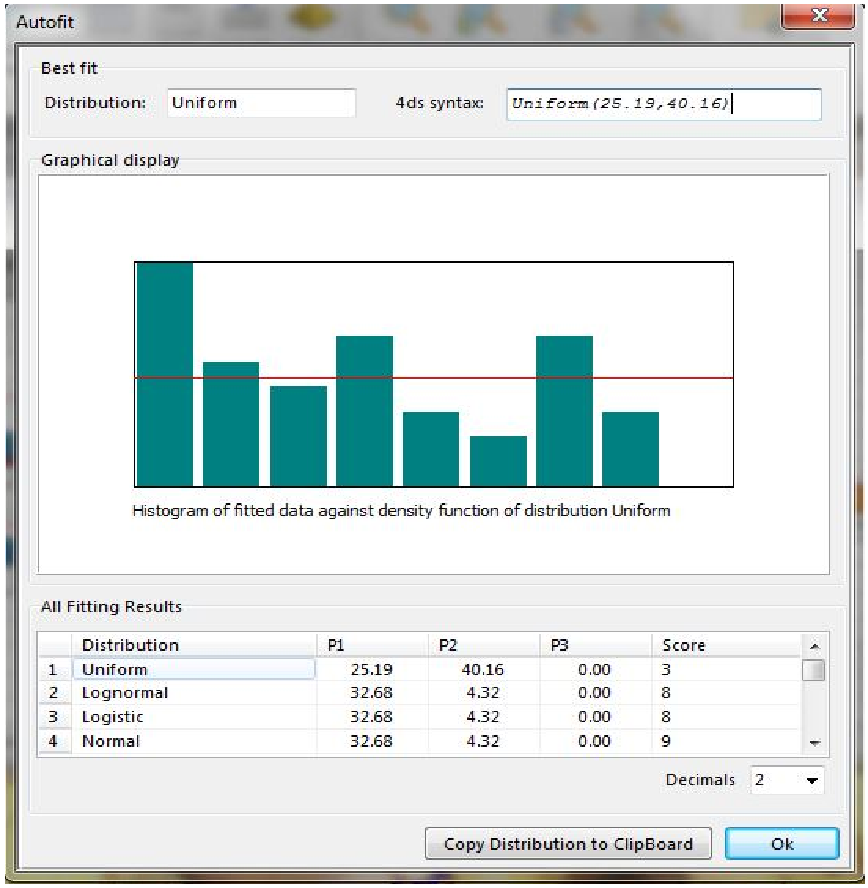


Figure 58. Inspection time for 70% of initial products

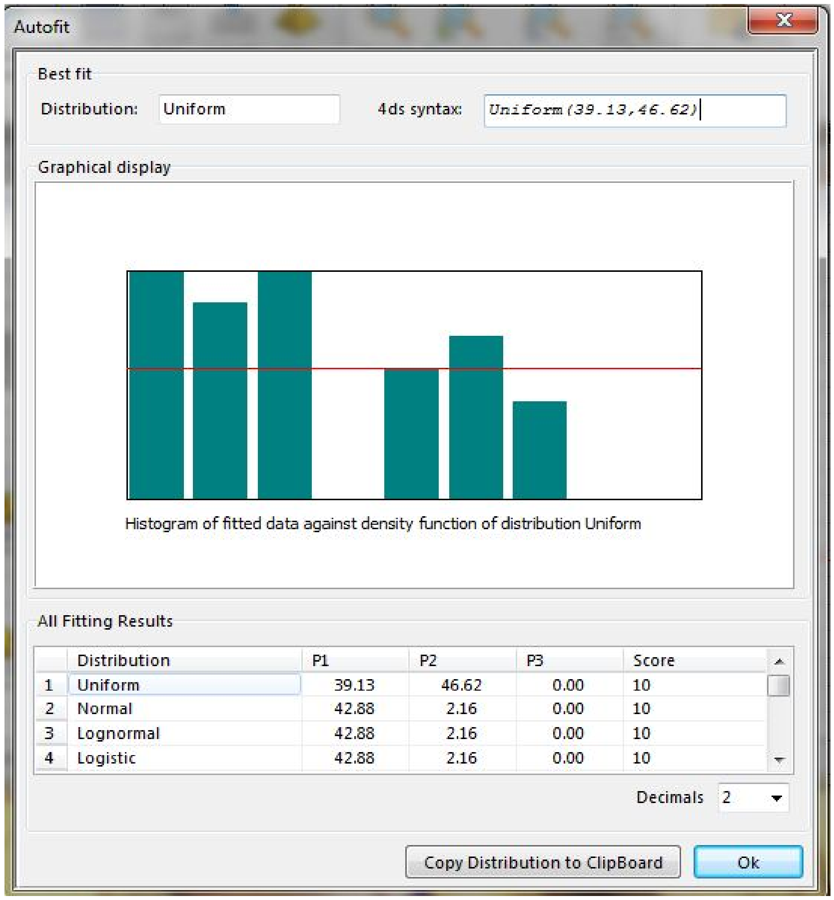


Figure 59. Inspection time for 20 percent of materials

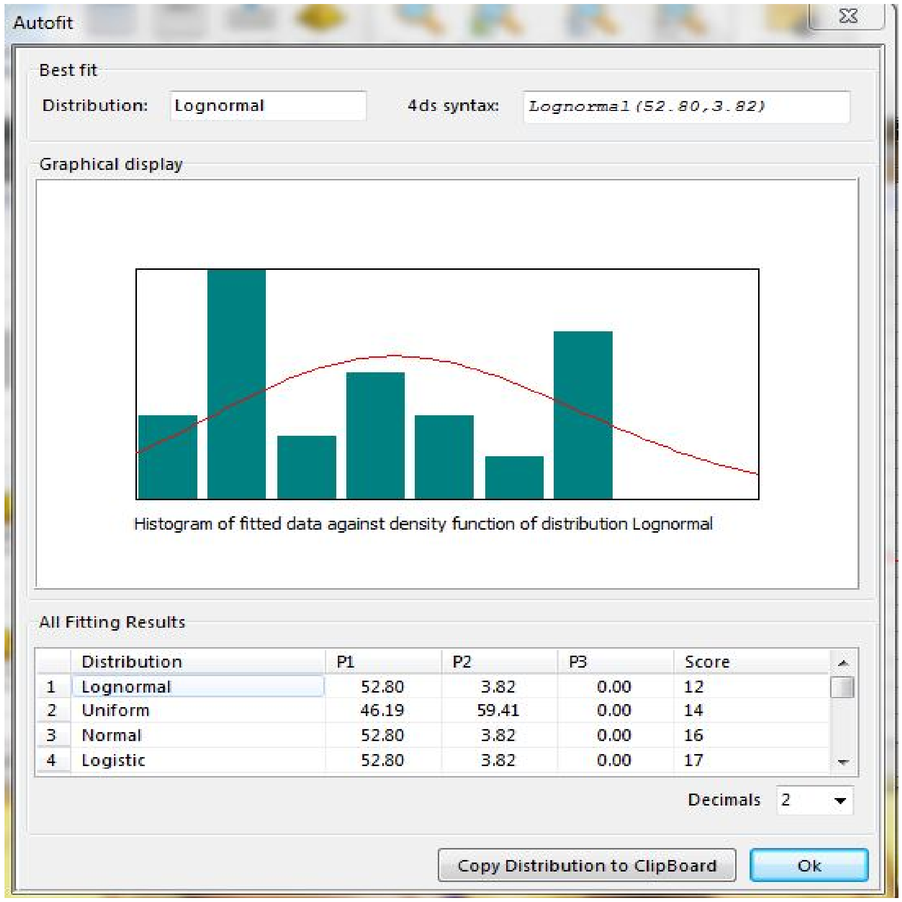


Figure 60. Inspection time for 10% of the material

Table 13. Queue capacities

Queue	Capacity
Queue 2 where the initial material should wait to be processed	100000 Bags
Queue 7 Distributor queue	1000 bags
Queue 10 and 11 temporary warehouse for initial products from whole seller and charity shops	100000 Bag
Queue 13 after inspection and quality check	800 pieces of cloth
Queue 14 and 15 after before sorting	5000 kg
Queue 18 and 22 for cutting and shredding stations	2000 kg

Table 14. Data used in the simulation model and range of input parameters

Type of operation	Cycle time for all type of materials (type 1 and 2)
Inspection	70%: mins(Uniform(25.19,40.16)) 20%: mins(Uniform(39.13,46.62)) 10%: mins(Uniform(52.80,3.82))
Sorting	Normal(130.56,217.48) Uniform(300.03,1000.17) Uniform (3.03,10.17)
Cutting	mins(Uniform(49.29,55.51)) mins (Uniform(59.67,71.08))
Shredding	mins (Uniform(40.46,30.50))
Blend	mins(Uniform(59.52,70.65))
Carding	Normal(101.10,5.93)
Twisting	mins(Uniform(63.94,77.61))
Spinning	mins(20)

Table 15. 4D Script syntax of input parameters

Workstation	MTTF	MTTR
Inspection	-	-
Sorting	-	-
Cutting	hr (uniform(6,5.5))	Mins(10)
Shredding	mins (Uniform(40.46,30.50)) mins (Uniform(30.46,25.50))	Mins(10)
Blending	hr(uniform (4,3))	Mins (4)
Carding	-	-
Twisting	-	-
Spinning	Hr(Max(0, Normal(2, 1)))	Mins(3)

Table 16. The capacity of each machine

Machine/working station	Capacity
Cutting	800 kg per load
Shredding	700 kg per load
Blending	700 kg per load
Carding	500 kg per load
Twisting	100 kg per load
Spinning	100 kg per load

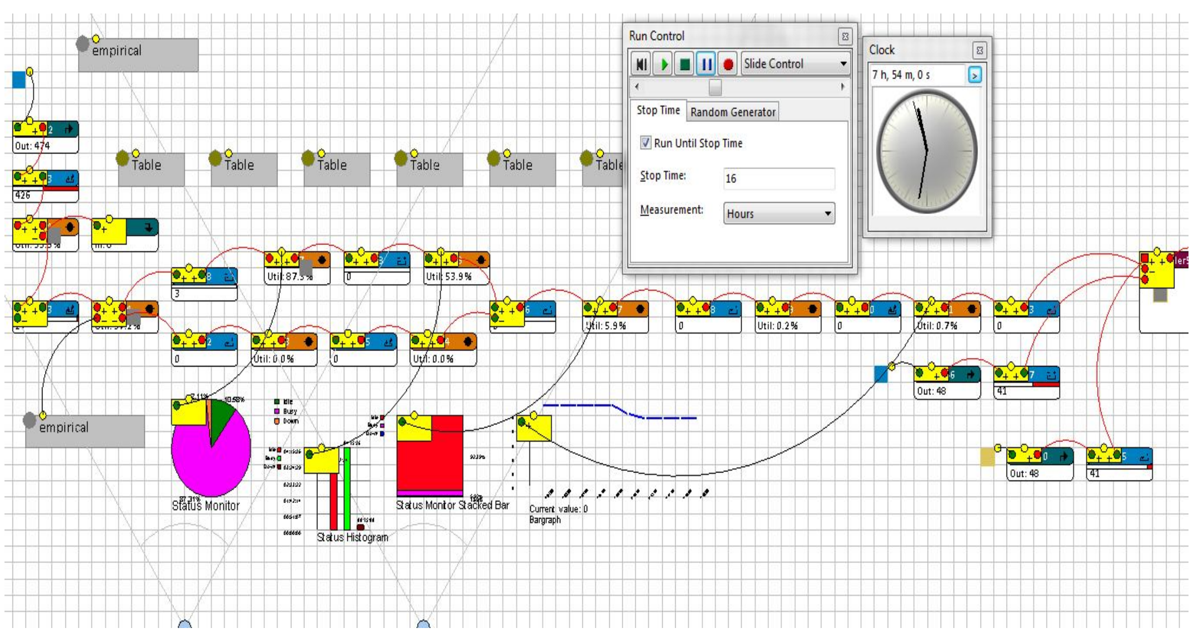


Figure 61. Screenshot of the model after 7 hours of run

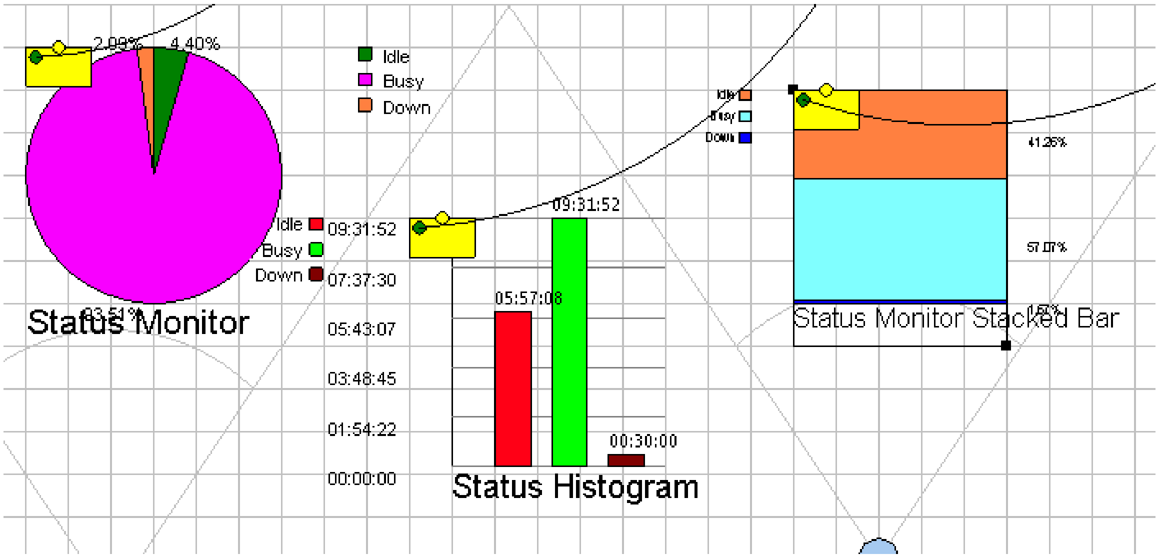


Figure 62. The performance of sorting, cutting and shredding server

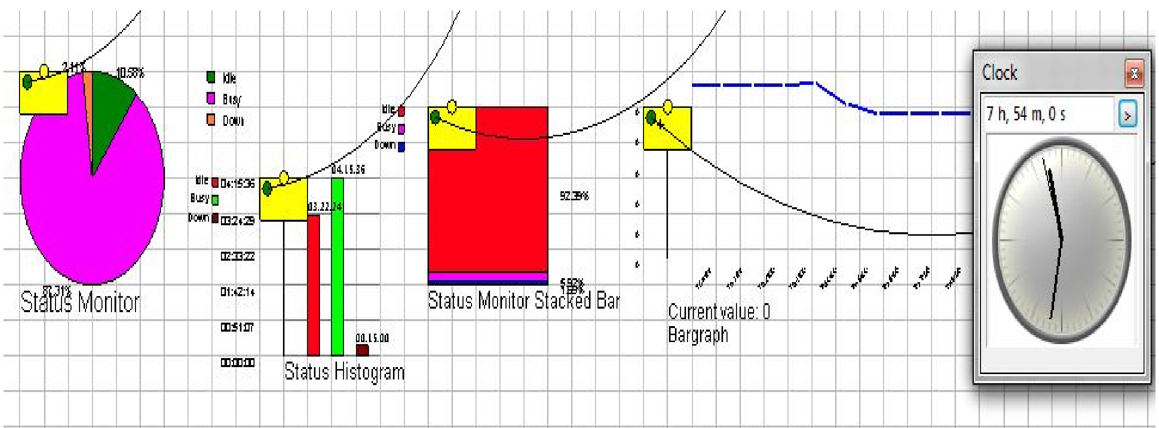


Figure 63. Performance of Cutting, Blending and Spinning machine

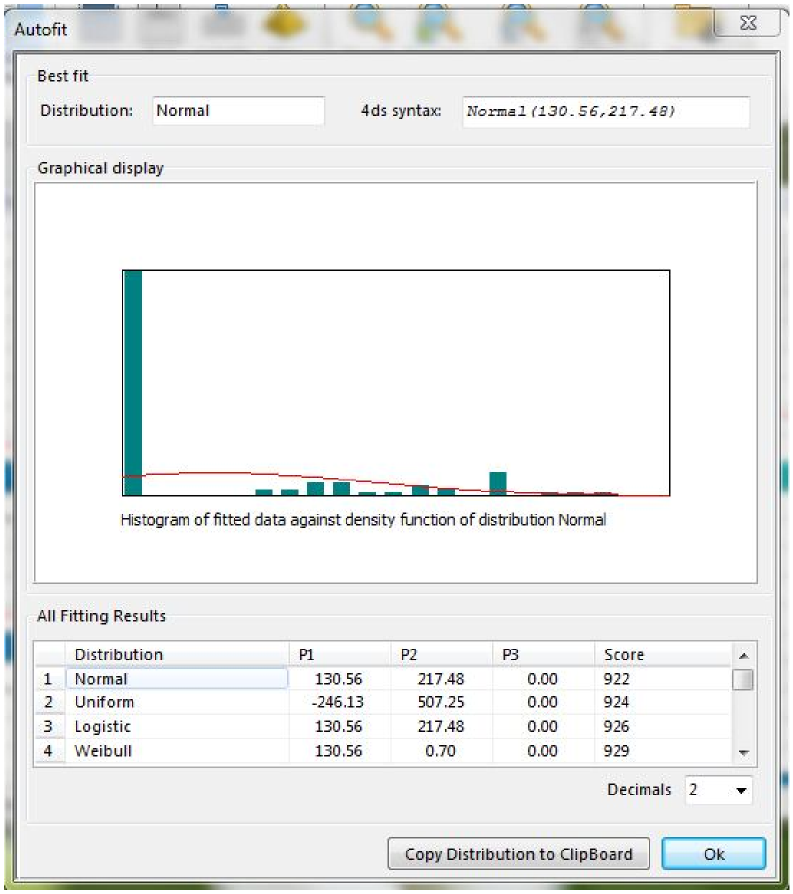


Figure 64. Sorting time

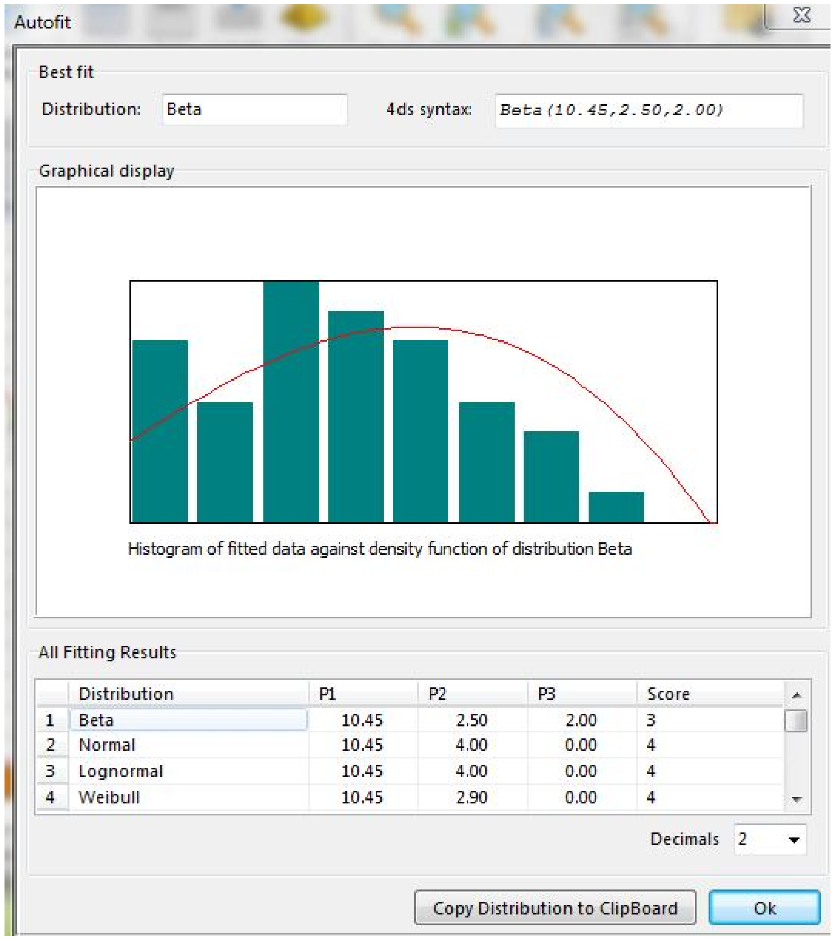


Figure 65. Cutting machine cycle time

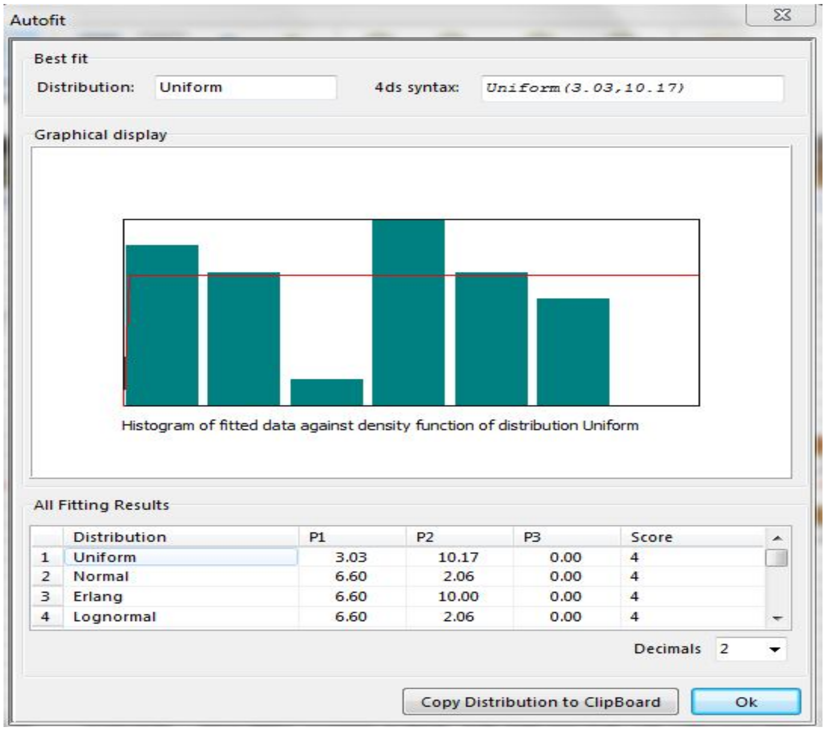


Figure 66. Inspection time

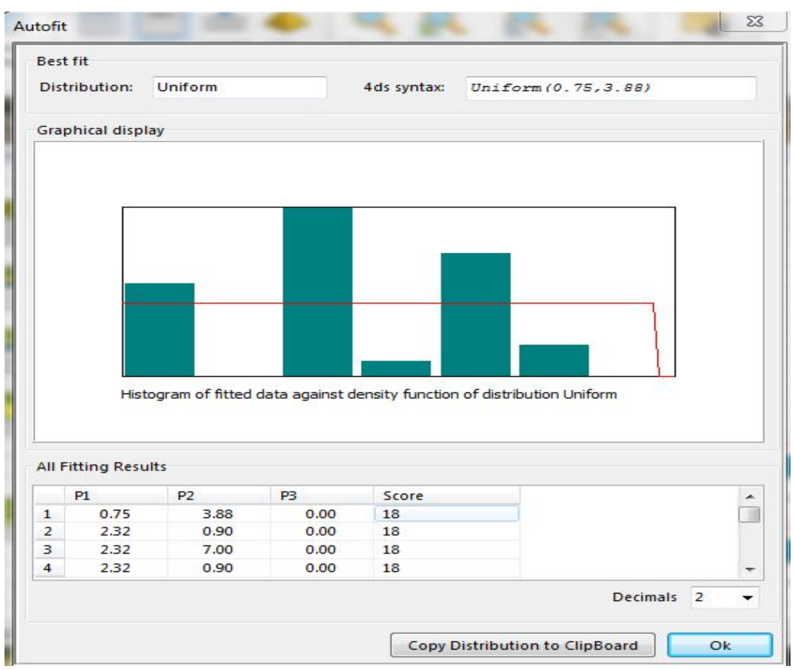


Figure 67. Separation of different type of material based on their label

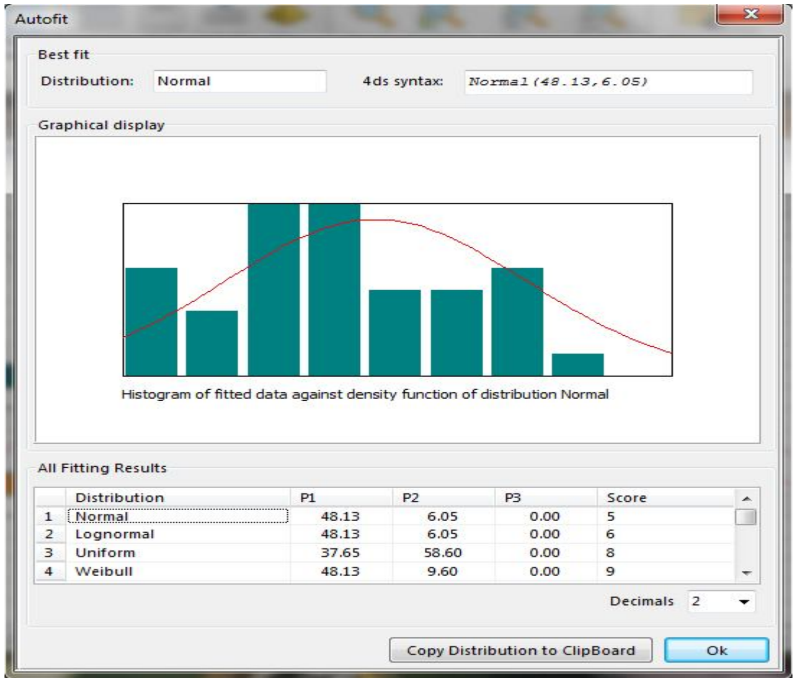


Figure 68. Cycle time for cutting type 1 products

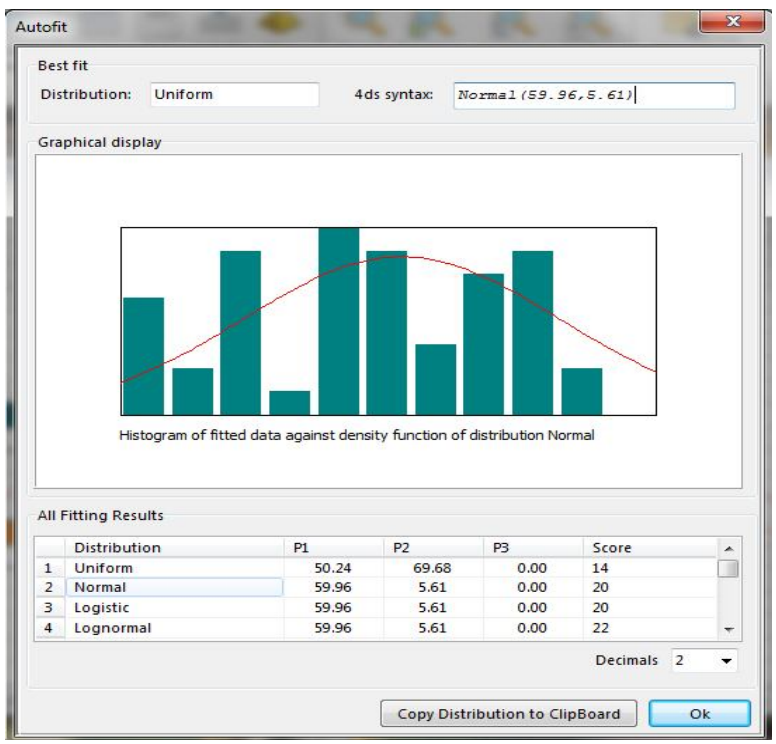


Figure 69. Cycle time for cutting type 2products

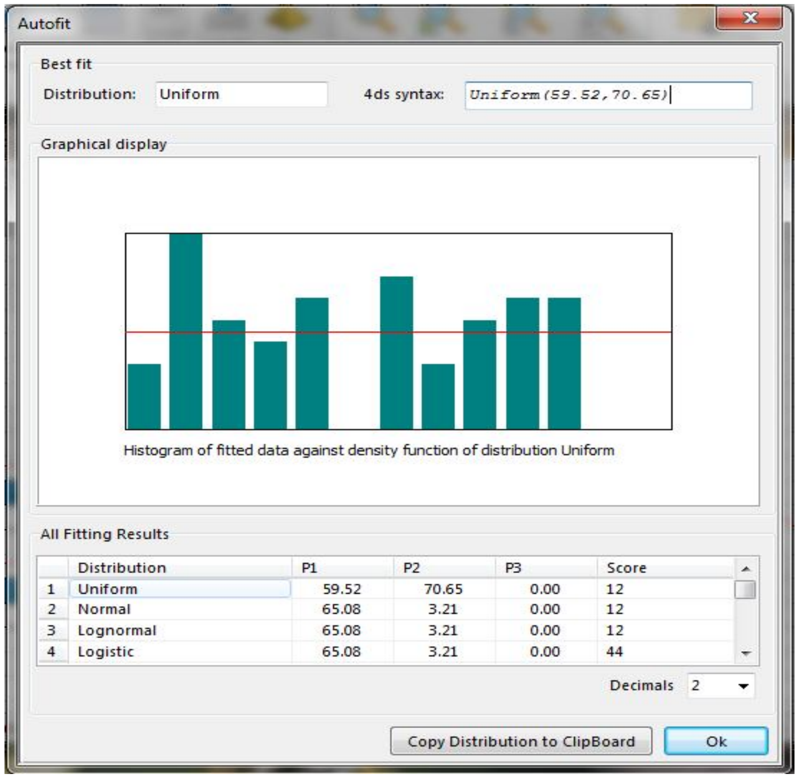


Figure 70. The cycle time of pulling machine

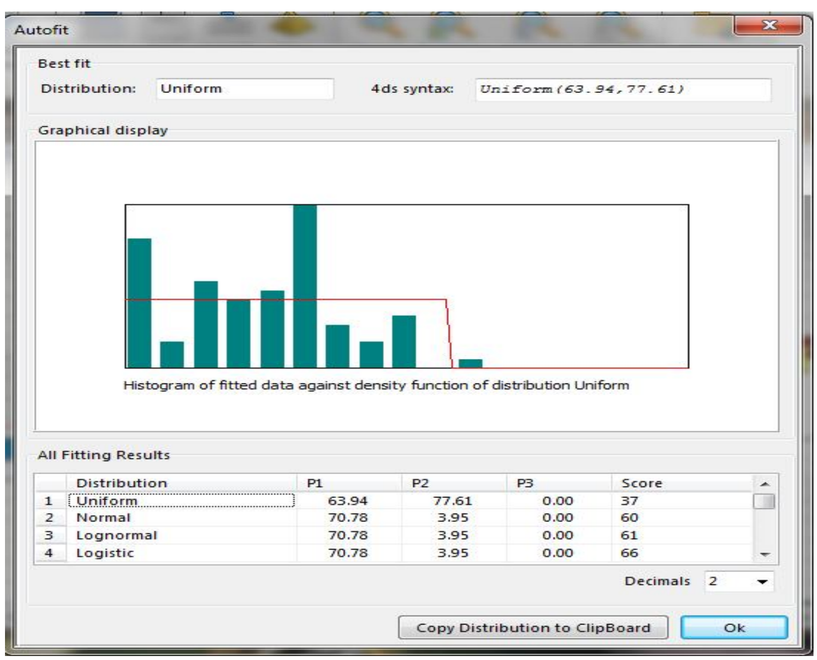


Figure 71. The cycle time of final twisting

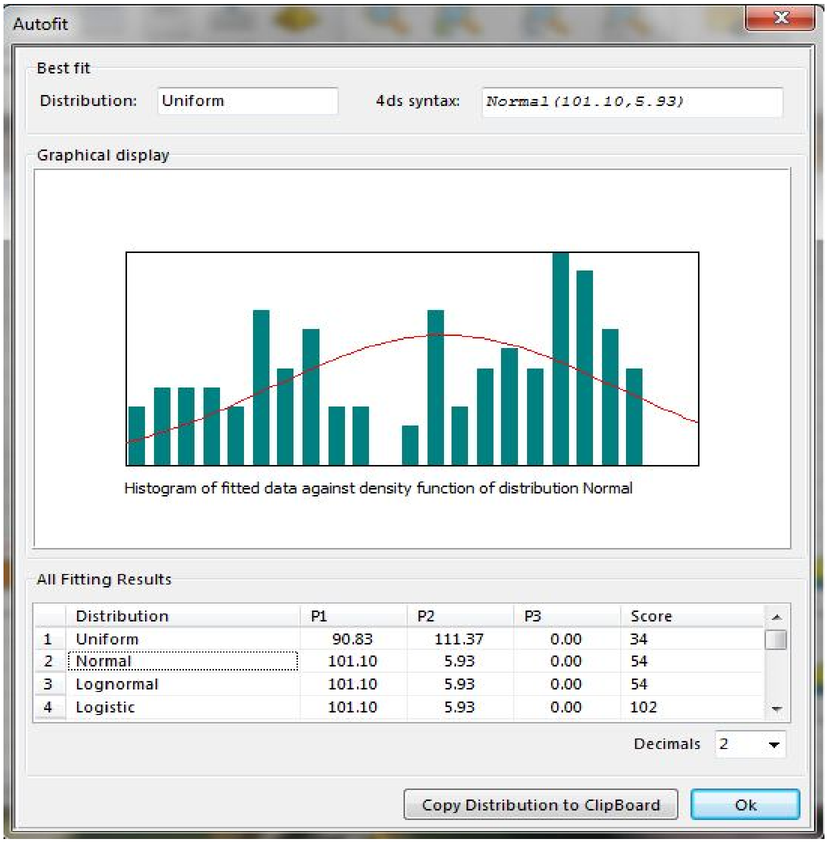


Figure 72. The cycle time of the first pulling process

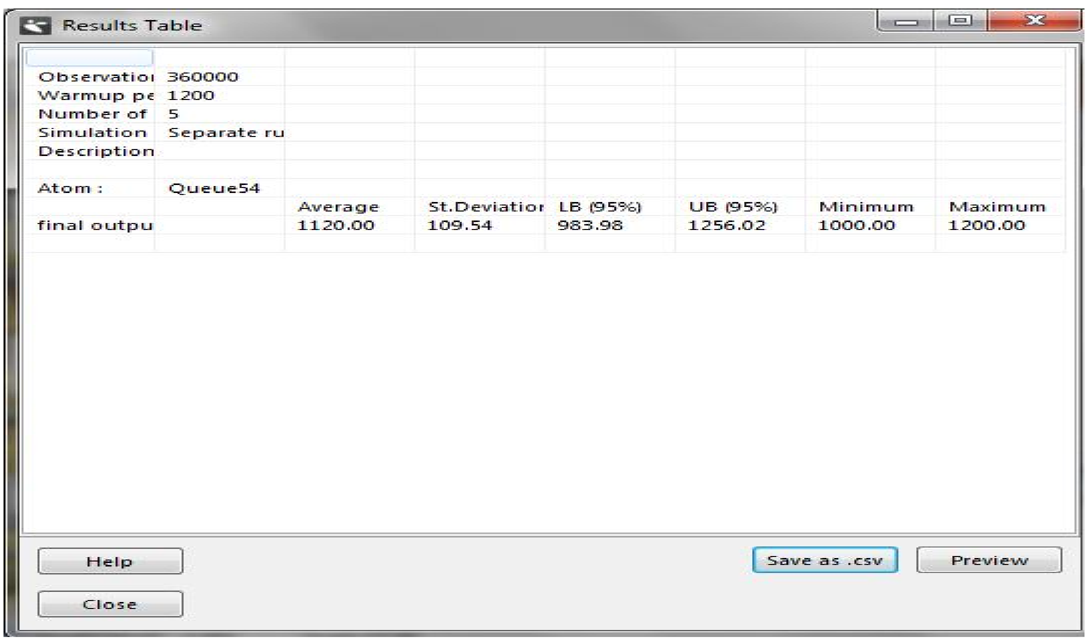


Figure 73. The results of 5 replications in kilograms

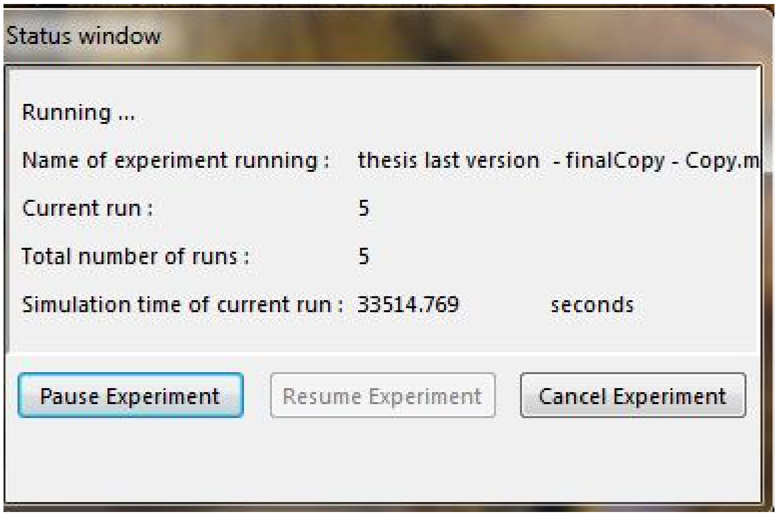


Figure 74. Run length for 5 replications

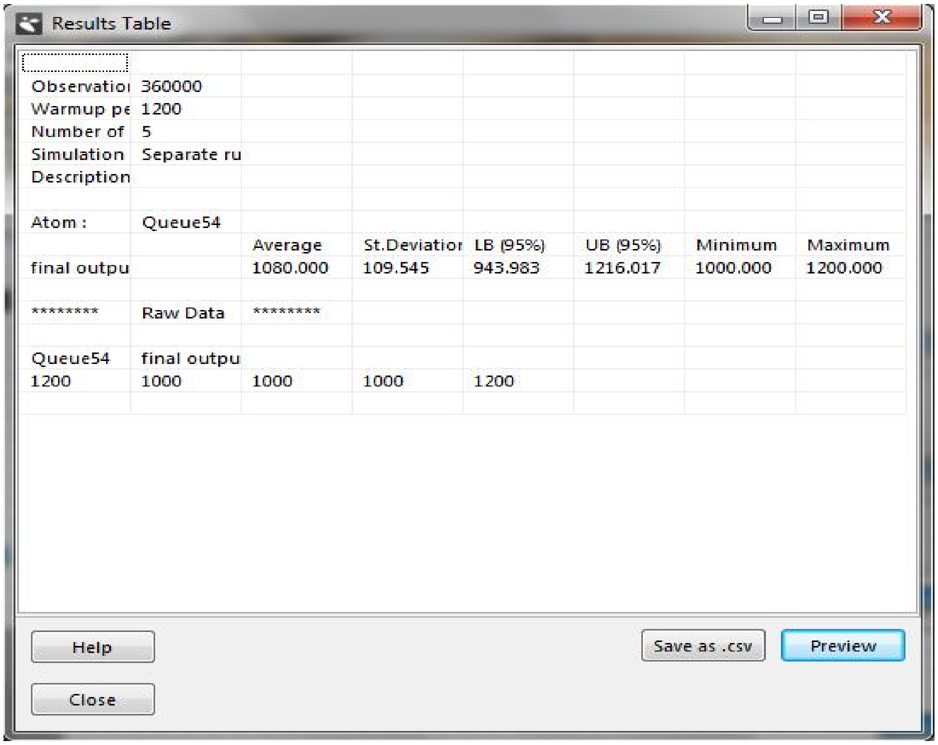


Figure 75. The average number of final products (kilogram) for 5 replications

VITA AUCTORIS

NAME:	Reyhaneh Yavari
PLACE OF BIRTH:	Iran
YEAR OF BIRTH:	1992
EDUCATION:	QIAU, B.Sc., Industrial Engineering, Iran University of Windsor, M.Sc. Industrial and Manufacturing Engineering, Windsor, ON, 2019