STUDY ON DESIGN AND MODELLING OF PAPER FIBRE RECOVERY NETWORK

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ABSTRACT

This work presents the development of a *Model for Optimal Design for Paper Fibre Networks (MODPFN)* applicable for urban case study. This can be achieved by implementing the mathematical approach on design and modelling of paper fibre recovery network. The purposes of this study are to design a mathematical model for paper fibre recovery network and implement the model in an urban case study. This work involved few steps, firstly, extraction of limiting data on paper fibre, followed by representation of superstructure, developing of mathematical formulation and next application of model in GAMS software in order to get optimal maximum fibre recovery and lastly, implemented the model in the urban case study. *MODPFN* develop can simultaneously target and design of paper fibre recovery network. It is less tedious and more effective compared from previous method from previous researches. The results show that the potential of maximum fresh fibre reduction of 32.48% for high quality paper and 48.66% for low quality paper.

ABSTRAK

Kerja ini membentangkan pembangunan *Model for Optimal Design for Paper Fibre Network (MODPFN)* untuk pemulihan maksimum kertas serat bagi kertas terpakai yang akan diaplikasi dalam kajian kes bandar. Ini boleh dicapai dengan melaksanakan pendekatan matematik bagi reka bentuk dan model rangkaian pemulihan kertas serat. Tujuan kajian ini adalah untuk mereka bentuk model matematik untuk pemulihan rangkaian kertas serat dan melaksanakan model dalam kajian kes bandar. Kerja ini melibatkan beberapa langkah, pertama, mengekstrak data terhad ke atas gentian kertas, diikuti oleh perwakilan mahastruktur, membangunkan rumus matematik dan seterusnya model diaplikasi dalam perisian GAMS untuk mendapatkan pemulihan serat yang optimum dan akhir sekali, model diaplikasi dalam kajian kes bandar. *MODPFN* yang dibangunkan pada masa yang sama boleh mensasar dan reka bentuk rangkaian pemulihan kertas serat. Ia adalah kurang membosankan dan lebih berkesan berbanding kaedah yang diperkenalkan oleh penyelidik sebelum ini. Keputusan yang didapati diakhir projek ini menunjukkan bahawa nilai maksimum serat segar yang dapat dikurangkan ialah 34.48% bagi kertas berkualiti tinggi manakala sebanyak 48.66% bagi kertas berkualiti rendah.

TABLE OF CONTENTS

CHAPTER 3 FUNDAMENTAL THEORY

CHAPTRER 4 METHODOLOGY

CHAPTER 5 RESULTS AND DISCUSSION

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

i	-	Index for high quality paper fibre source
j	-	Index for low quality paper fibre source
k	-	Index for high quality paper fibre demand
l	-	Index for low quality paper fibre demand
Da_1	-	Demand on high quality paper fibre, Magazine
Da_2	-	Demand on high quality paper fibre, Manila Card
Db_1	-	Demand on low quality paper fibre, Newspaper
Db_2	-	Demand on low quality paper fibre, Tissue
Db_3	-	Demand on low quality paper fibre, A4 Paper
Db_4	-	Demand on low quality, Corrugated Box
FF	-	Fresh Fibre
Sa_1	-	Source on high quality paper fibre, Magazine
Sa_2	-	Source on high quality paper fibre, Manila Card
Sb_1	-	Source on low quality paper fibre, Newspaper
Sb_2	-	Source on low quality paper fibre, Tissue
Sb_3	-	Source on low quality paper fibre, A4 Paper
Sb_4	-	Source on low quality, Corrugated Box
WF	-	Waste Fibre

LIST OF ABBREVIATIONS

MSW	-	Municipal Solid Waste
PCA	-	Property Cascade Analysis
NAPAP	-	North America Pulp and Paper
SSCC	-	Source Sink Composite
SSAC	-	Source and Sink Allocation Curve
NAD	-	Network Allocation Diagram
LP	-	Linear Programming
MILP	-	Multi Integer Linear Programming
MTB	-	Mass Transfer Based
NMTB	-	Non-mass Transfer Based
GAMS	-	General Algebric Modelling System
ISRI	-	Institute of Scrap Recycling
MODPFN	-	Model for Optimal Paper Fibre Network

CHAPTER 1

INTORDUCTION

1.1 INTRODUCTION

This chapter provides the overview of the current local and global waste paper outlook. The background of the research will describe next followed by the problem statement. This followed by the objective and scope of the study which involves the development of new systematic technique for designing and modelling a paper fibre recovery network based on mathematical modelling. This chapter also addressed the contributions of this work.

1.2 WASTE PAPER OUTLOOK

One of the most treasured resources of world is forests. It plays an important part in our daily life but nowadays, forests are disappearing day by day because of the pulp and paper production. Global production in the pulp, paper and publishing sector is expected to increase by 77% from 1995 to 2020, so we must act now to preserve our forests. Using post-consumer recycled paper reduces the need to log forests (Print Net Incorporated Website, 2008). World's primary raw-material for paper manufacture are 75% forest woods, 20% waste paper and 5% other fibrous waste materials, including agricultural residues (Paper Mart Website, 2006). The paper production has increased year by years because of the high demand on it. Most of the paper production demand is on containerboard 31%, followed by printing or writing paper 28% and boxboard 21% (Figure1.1)

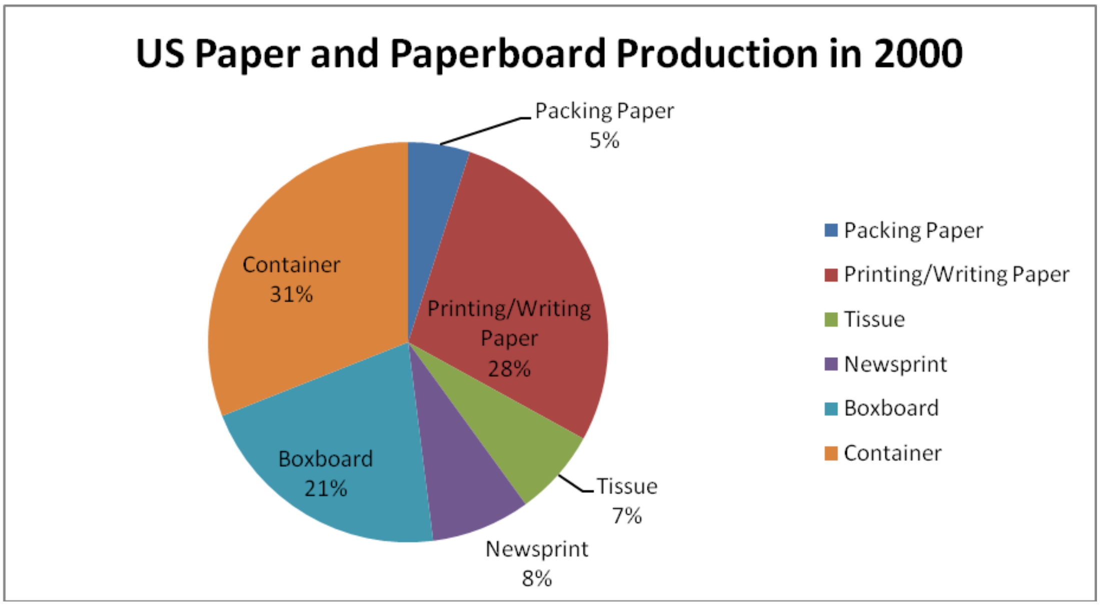

Figure 1.1: US paper and paperboard production in 2000

Source: Paper Mart Website (2006)

Based on research conducted by U.S. Environmental Protection Agency in 2009, the Municipal Solid Waste (MSW) or commonly known as trash or garbage that consists of everyday items that we use and then throw away, 54.3 % of MSW was straight away discarded, meanwhile 33.8% from them was recovered back and the rest, 11.9 % was combusted (Figure 1.2)

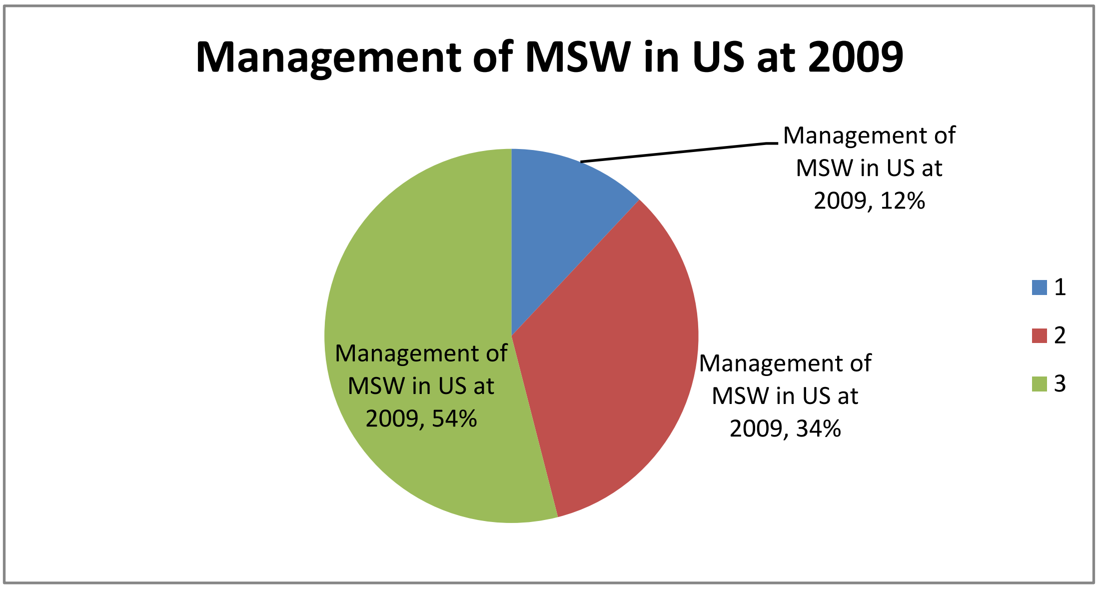

Figure 1.2: Management of MSW in US in 2009

Source: US Environmental Protection Agency (2009)

Out of the MSW generation in 2009, 28.2% of total MSW contain paper and paperboard. Food scraps compromise 14.1% followed by yard trimmings 13.7% (Figure 1.3).

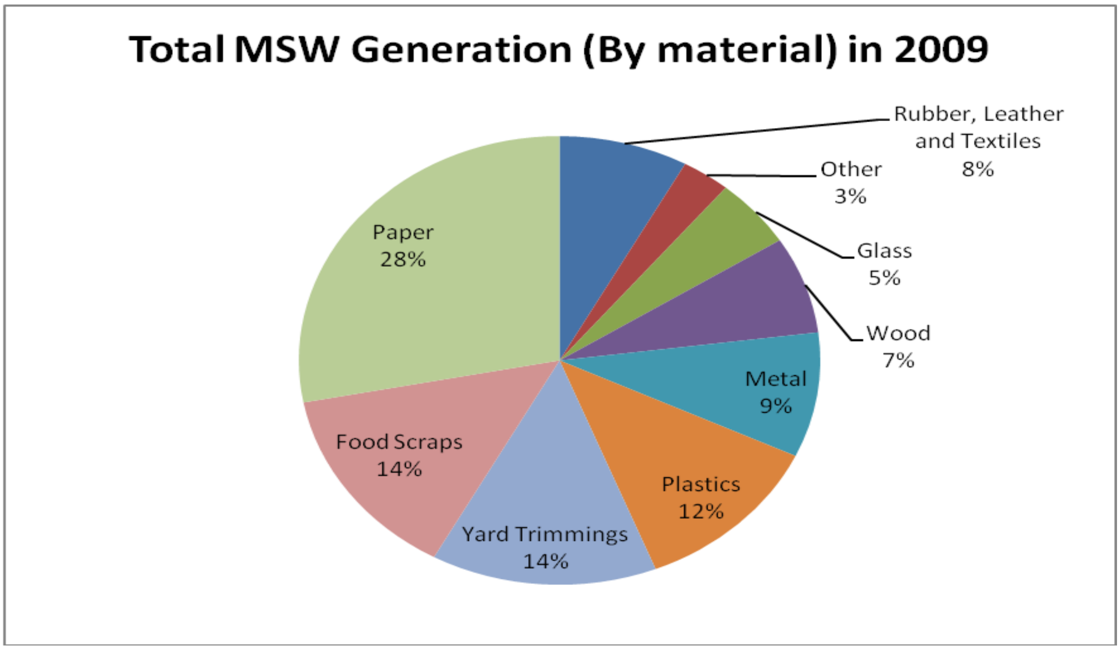

Figure 1.3: Total MSW Generation (by material) in 2009

Source: US Environmental Protection Agency (2009)

From the previous Figure 1.3, it is clearly shown that paper has become the fundamental of our life and its existence has taken for granted. If there is no proper action taken to manage this waste properly, the extinction of forest will become serious. This situation will leads to other problem such as green house effect,

1.3 RESEARCH BACKGROUND

The demand on paper has steadily increased since paper was invented. The world consumption of paper has grown 400% in the last 40 years or in other word, nearly 4 billion of trees are cut around the world for use in paper industries. Natural forests are being destroyed at an unsustainable pace with most surviving forests degraded by roads, agriculture, pollution and invasive species. In a year, about 30 million forested acres or an area about the size of Pennsylvania, United States are lost (Paper Consumption, 2011). This situation has become a major concern to the world as forests play important role to the world. To overcome this situation, recycle have been introduce in order to reduce forests extinction. This method has been a major concern world-wide, involving government bodies, large corporations and organizations. Waste paper can be disposed in three ways that are buried, burnt or recycled (Debunking the Myths of Recycle Paper Website, 2000). Out of the three methods that mentioned, recycle is the most viable alternative solution. This is because, the increasing shortage of landfills make burying an unfeasible long-term solution meanwhile, burning can cause air pollution.

In the recent years, several researches have been done on the synthesis of paper fibre recovering network by using several techniques. The techniques that have been introduced are pinch analysis by Kit et al. (2011) and Property Cascade Analysis (PCA) by Foo et al. (2006).

Property Cascade Analysis (PCA) introduced by Foo et al. (2006) was only focused on recycling paper broke from a paper plant to satisfy the relevant paper demand on paper machines. However, Kit et al. (2011) has come out with a method that focused on post-consumer waste paper recycling. His worked applying the pinch analysis concept to determine how post-consumers waste paper recycling can be maximized to produce various types of recycle paper. Although the technique have provide an interactive, quick and efficient guidelines to conduct paper fibre recovery network, but the method is quite tedious and complicated. Hence, in order to overcome this limitation, the development of a new systematic approach by using mathematical programming technique is proposed in this work.

1.4 PROBLEM STATEMENT

Back to ancient days, paper have been innovating for nearly 2000 years now and today it have become an integral part of our daily life from a print medium for communication and knowledge, packing material, daily hygiene and also become as a special material from the banknotes to medical filters. Each year, nearly 400 billion of trees worldwide are cut down for paper or in other words, 35% of the harvested trees (Martin, 2010). Deforestation can causes negative impact for the environment and world. The result may increase the global temperature, raising the level of sea and cause the change in weather pattern and ecosystem around the world. This activity often cited as the major causes enhanced the green house effects. To overcome these problems, recycling is one of the possible ways to reduce deforestation.

Given a set of paper fibre data with different value of fibre content, it is desired to design and develop a mathematical model in order to achieve maximum paper fibre recovery.

1.5 OBJECTIVE

The main objective of this study is to develop a mathematical model for designing and modelling a system in order to get the maximum paper fibre recovery network.

1.6 SCOPE

The main purpose is to develop a mathematical model to achieve maximum paper fibre recovery. This study only focus on how the post-consumer waste paper recycling can be maximized to produce various recycles paper types. This study will overcome the tedious graphical approach of the previous research Kit et al. (2011) by presenting a simultaneous target and design of paper fibre recovery network.

1.7 RATIONALE AND SIGNIFICANCE

This study will provide an easy way to determine the recycle fibre that we can obtain from the post-consumer waste paper fibre instead of other method that is more inconvenient.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter summarises all the researched and worked that have been done by previous researches. A general view on the study and design of paper fibre recovery network is described in section 2.1. Next, the previous worked on paper fibre recovery network is described next followed by the review on previous worked on mathematical modelling.

2.2 A GENERAL REVIEW ON STUDY AND DESIGN OF PAPER FIBER RECOVERY NETWORK

Paper is a thin material mainly used for writing upon, printing upon or for packaging. It is produced by pressing together moist fibres that can be obtained from woods, rags or grasses and then drying them into flexible sheets. 95% of the raw material used for making paper comes from the trees which can be obtained from the forests. The paper was widely used in our daily life. The various types of paper are from tissue until the corrugated box. In order to reduce the usage of the fresh fibre, recycling has been introduced. By applying this method, the forests products chain can be sustain for long period of time as well as the greenhouse effect from the deforestation can be minimised. Consumers use paper to meet many different needs and each requires different properties such as strength, brightness and absorbency. In order to achieve different kinds of needs and properties, both of fresh and recycled fibres are blend together in varying proportions. The demands on paper keep increase years by years, so it is impossible to sustain long-term demands without fresh fibre. Hence, recycling method should implement to overcome this situation.

In this paper, a mathematical model has been introduced to find an easiest way to obtain the recycling fibre from post-consumers waste paper. Modelling is defined as a process of application of fundamental knowledge or experience to simulate or describe the performance of a real system to achieve certain goals (Nirmalakhandan, 2002). Meanwhile, mathematical modelling is a transformation of the system under study from its natural environment to a mathematical environment in terms of abstract and equations (Nirmalakhandan, 2002).

2.3 PREVIOUS WORKS ON PAPER FIBER RECOVERY NETWORK

Recycling is a common practice among us, but somehow researches and published literatures that deal with the paper mixing is very limited (Kit et al., 2011). Some of the relevant researches have been done by Byström and Lönnstedt (1997). They introduced a linear programming technique on the optimal combination of energy recovery and recycling of waste paper for paper and board production. Their work also considered the impact of paper recycling on environment and economics. In addition, they designed a model with a function to maximise the profit, waste paper distribution and energy recovery. The proposed model was successfully implemented in paper fibre industry.

Zhang et al. (1997) have introduced linear programming of paper industry. They studied on the impacts of increased paper recycling on the U.S pulp and paper sector by using North America Pulp and Paper (NAPAP) model. This model was consisted of two phases; static and dynamic. In static phase, it computes a multi-region, multi-commodity equilibrium at a given time. Meanwhile in dynamic phase, it forecasts the amount of pulp, paper and paperboard exchanged in multi-region market and the corresponding prices.

Property Cascade Analysis (PCA) has been introduced by Foo et al. (2006). This method was proposed in order to overcome the iterative steps associated with graphical method. PCA was implemented in pulp and paper industry process which the rejected products from machine were recycled back as feed to the process after treated. Hence, by recycling the broke paper, the resource usage can be maximised and fresh fibre consumption can be reduced. Foo et al. (2006) also introduced the application of pinch analysis in paper fibre recovery network. Pinch analysis have been introduced as a systematic tool for optimal design of resource utilization networks including heat, water, mass and gas (Kit et al., 2011). In their work, Foo et al. (2006) was only focused on paper broke from rejected waste fibre in papermaking plant.

Later, Kit et al. (2011) proposed a graphical approach for simultaneous targeting and design of a paper fibre recycling network. There were two main steps involve in this method. Firstly, a graphical approach called source-sink composite curve (SSCC) was used to establish the maximum paper recycling network. Next, from the SSCC, a source and sink allocation curve (SSAC) and Network Allocation Diagram (NAD) were constructed to design the maximum paper recovery network. This work has extended the concept of pinch analysis that was introduced by Foo et al. (2006) by applied it on the post-consumers waste paper recycling. Their work focused on how the post-consumers waste paper recycling can be maximised to produce the different kind of recycle paper types.

2.4 PREVIOUS WORKS ON MATHEMATICAL MODELLING

Since the researches and published literature review on paper fibre recovery network were limited, the review on mathematical modelling was done on water and heat recovery network. Mathematical programming technique has emerged primarily to overcome the limitations encountered by the graphical approaches particularly for large-scale and complex problems as well as cost optimality. Mathematical programming is effective tool for minimising or maximising an objective function subjects to constraint relationships among the independent variables. It is typically done by simultaneously considering all factors contributing to overall network cost effectiveness and operability. In recent years, several mathematical programming approaches has been widely implemented in order to minimise utilities in a plant such as heat (Chuei and Lien, 1996), water (Hul et al., 2007) and hydrogen (Halale and Liu, 2001).

2.4.1 Review on Heat Recovery Network

Heat recovery network usually apply in industry in order to minimize annual utilities cost of the plant and hence optimizing the energy consumption rate. Youting et al. (1989) have introduced a multi objective zero-one linear mixed integer programming problem that used Dongfanghong Refinery, China as their practical example. There were a number of steam sources like boiler and catalytic process, and steam consumers like air blower, gas compressor and other process that need heat to operate in the refinery, thus a reasonable modification in order to retrofit these steam system is a need. Their work also included several objective functions in the model. The objective functions that considered were comprehensive energy consumption of the steam system, capital investment cost for modification of the steam system, annual calculative cost and oil consumption of the steam.

Later, Chuei and Lien (1996) considered the heat integration in heat exchanger design. In heat exchanger network (HEN) design, merging process stream originated from different units is often a feasible alternative in addition to the conventional synthesis techniques. Conventionally, there are three steps involved in mathematical programming of HEN. Firstly, the minimum consumption rates of utilities were determined by using linear programming (LP). Secondly, mixed integer linear programming (MILP) was used in order to determine the minimum number of matches and heat duties. Lastly, cost-optimal network was obtained by using nonlinear programming (NLP). In their work, Chuei and Lien (1996) proposed modification in LP, MILP and NLP models incorporated of mixing and splitting streams from multiple origins in process synthesis. They have proved that the modification made can be used in order to cut down the capital investment and utility cost of heat recovery systems.

Afterwards, Pettersson and Söderman (2007) introduced a heat recovery system (HRS) that recovers heat from drying section in papermaking industry. They presented a hybrid method consist of generic algorithms (GA) and nonlinear programming (NLP). In GA, an investment cost was determined by making decision about the matches stream and size of heat exchanger area. Meanwhile, NLP is used in order to determine the amount of annual operation costs corresponding to the minimization of utility amount needed.

2.4.2 Review on Water Recovery Network

Besides heat, minimisation of water also has become concerns to researches. Study on water recovery network is widely applied not only in plant but also in post consumers' problem. Rabie (2007) has done a work for optimal design of water recycle networks in batch process. The fresh water and wastewater discharge are determined by eliminating scheduling constraints. This work also provided formula to minimize total annualized cost of the system by trading off capital versus operating costs.

Hul et al. (2007) also introduced a crisp and fuzzy optimisation approaches for water retrofit. They work used LP and MILP model that includes piping cost and constraints that were applied in paper mill industry. They compare five types of scenarios. First scenario was maximum water recovery. In this scenario, they want to maximise the wastewater recovery by reused/recycled water sources to the water sink from water that supposedly sent for discharge. Second scenario was capital investment limits. When they maximise the water recovery, the amount of capital investment get higher. In order to maximise the capital investment, the amount of water recovery should be minimise and vice versa. Third scenario was wastewater reduction percentage. Sometimes, there is a situation where amount of wastewater reduction needed in plant is limited. This situation arises due to the bottleneck wastewater treatment system in the plant. Fourth scenario was forbidden matches for self-recycling in order to prevent some contaminants building up in the systems. Lastly, fuzzy model for reconciling conflicting objectives was the fifth scenario considered in their work. In this scenario, the different objective functions were optimising simultaneously by using fuzzy model. The maximisation of water recovery and minimisation of capital cost were done simultaneously.

In other work, Kim et al. (2008) introduced a simultaneously optimization that combines problems of wastewater and heat exchanger network in a single step. Wastewater and heat exchanger network for process industries involving effluent stream that contain multi contaminants was proposed in their work. They used MILP formula to achieve their objective function of minimization the total amount of annual cost of wastewater and heat exchanger network design. They have proved their MILP formula by implement it to the oil refinery industry.

Later, Handani et al. (2009) have done a research on optimal design of water networks involving single contaminant. The objective of this worked was to developed a systematic technique to target freshwater consumption and wastewater generation to achieve the maximum water recovery systems involving the single contaminant. They categorized the water-using operation into two broad categories; mass transfer-based (MTB) and non-mass transfer-based (NMTB). The mathematical programming was said more suitable approach for optimum water networks for both grassroots and retrofit application.

Hashim et al. (2010) have conducted a research on formulation of mathematical modelling for the design of maximum water recovery. In this research, the optimization of water was involved multi contaminant and multi utilities. The water management hierarchy and the cost constraints to select the best water minimisation schemes were considered.

From Handani et al. (2009) and Hashim et al. (2010), the steps involved in order to get the maximize water recovery network was implemented in paper fibre recovery network. The steps involving in the paper fibre recovery network were firstly, the limiting of paper fibre data extraction, followed by the superstructure representation and mathematical modelling. After that, the mathematical formula obtained were going to implemented in programming then lastly, the minimum paper fibre targets and design was produced.

Although Foo et al. (2006) was introduced PCA on paper fibre recovery network. Their worked only focus on paper broke recycling at papermaking industry. The target for this paper work was on post-consumer waste paper recycling at Universiti Teknologi Malaysia. This worked will overcome the tediousness and drawbacks from graphical approach by Kit et al. (2011).

CHAPTER 3

FUNDAMENTAL THEORY

3.1 INTRODUCTION

This chapter present the fundamental theory involves in order to generate mathematical model that can be applied to the urban case study. The conventional method involve in paper recycling described in section 3.1 followed by the waste paper grading next. The steps involve in implementing model in GAMS described next in section 3.3.

3.2 CONVENTIONAL METHOD OF PAPER RECYCLING

Recycling requires clean recovered papers that are free from contaminants such as food, plastic, metal and other trash. This is important in order to produce recycle paper that have the same standard as the one produced from virgin pulp. The contaminant paper which cannot be recycled was composted, burned for energy or dumped at landfills. Usually, before recycling process takes place, papers are sorted according to their grades or types. There are three basic steps involve in recycling process; re-pulping, removal of contaminants and de-inking (Forstall, 2002).

Firstly is the re-pulping of waste paper into individual fibres by mechanical agitation (Forstall, 2002). Waste paper was first moves to pulper that contain water and chemicals where the waste paper is chops into small pieces. Later, the small pieces of paper are break down into tiny strands of cellulose called fibres by heating process. At some time later, the waste paper will turn into a mushy mixture called pulp. The pulp then was forced through screen that contains holes and slots of various shapes and size (Tappi Website, 2011).

Next, the contaminant in waste paper is removed by mechanical removal systems. There are two types of mechanical removal, screens and centrifugal cleaners. In screening process, the pulp is forced through screens to remove small contaminants such as bits of plastics and globs of glue. Meanwhile, in centrifugal cleaners, the pulp was spin around in a large cone-shaped cylinder. Heavy contaminants include metal, sand, rocks and glass will throw to the outside of the cone fall through the bottom of the cylinder. Meanwhile light contaminants like plastics, Styrofoam, and wood will be collected at the centre of cone and removed.

After that, de-inking process took place where printing ink and sticky materials like glue residue and adhesives are removed. Usually, de-inking process is a combination of two de-inking processes. First is the dispersion process whereby the systems will wash the ink from pulp with large amount of water. Second is the flotation process where it will be used when ink is in suspension. During this process, pulp is fed into a large vat called flotation cell air and surfactants are injected into pulp. The surfactant will cause ink and stickiest to loosen from pulp and stick to the air bubble. The air bubble will carry ink and sticky material to the surface away from fibre creating froth which can remove from the top surface of vat and leaving the clean pulp behind.

The clean pulp is now ready to be made into paper. The recycled fibre can be used alone or blended with a portion of fresh fibre from wood to give extra strength or smoothness. Usually the recovered paper can be recycled back into a grade similar to, or lower quality than, the grade of the original product.

3.3 WASTE PAPER GRADING

Grading of waste paper is necessary in order to determine how the waste paper can be used. Almost of the household waste paper can be recycled back including used newspaper, cardboard, packaging, magazines, catalogues and wrapping paper. Before paper can be recycled and transported to the mill, it needs to be collected, sorted, graded