Department of Mechatronics

Chair of Mechatronics systems

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Waste paper sorting module

Vanapaberi sorteerimismoodul

MSc thesis

MHK70LT

The author applies for
The academic degree
Master of Science in Engineering

Tallinn
2017

Author's declaration

I declare that I have written this graduation thesis independently.

These materials have not been submitted for any academic degree.

All the works of other authors used in this thesis have been referenced.

The thesis was completed under ________________________ supervision

Author

________________________ Signature

The thesis complies with the requirements for graduation thesis.

Supervisor

________________________ Signature

Accepted for defense.

________________________ Chairman of the defense committee

________________________ Signature

TUT Department of Mechatronics

MSc THESIS TASK SHEET

2017 spring semester

Student	Artur Baisev 143859MAHM
Study program	Mechatronics
Specialty	-
Supervisor	Leo Teder
Consultants	Igor Penkov

THESIS TOPIC:

(In Estonian) Vanapaberi sorteerimismoodul

(In English) Waste paper sorting module

Assignments to be completed and schedule for their completion:

No.	Task description	Deadline
1.	Existing solution overview	01/03/2017
2.	Conveyor calculation	01/04/2017
3.	3D model design	01/05/2017
4.	Developing compressed air solution	14/05/2017

Engineering and economic problems to be solved:

The problem to be solved is to make it easier for future student of mechanical department to create application on android device which will communicate with Matlab/Simulink models.

The work will prevent extra expenditures required to make standalone applications or build actual devices.

Language of the thesis: English

Deadline for submission of the application for defense: 15/05/2017

Deadline for submission of the thesis: 20/05/2017

Student Artur Baisev signature: date: 12/02/2017

Supervisor Leo Teder signature: date: 12/02/2017

Supervisor Igor Penkov signature: date: 12/02/2017

Confidentiality requirements and other corporate terms and conditions shall be set out on the reverse side.

Abstract

The main goal of this project is to sort out the waste paper from the waste flow, assuming that the waste is moving on a conveyor or other feeder and before entering the sorting module it comes thru recognition module which provides us with cordinates of each paper piece (also its type) , we assume that recognition module already exists. Flow of waste contains : white paper, newspapers,brown paper and also non-metals . It is also known that size of each piece does not exceeds 100mm, the paper has no overlaps and there is a sufficient distance between the pieces (distance between the piece can be chosen by author). Main criteria is to be able to sort out 2 tons per hour. Waste is devided in such way: 40-60% white paper, 30-50% coloured paper, 10% of other paper and 5% other waste (metals,plastics etc). The task is design a waste paper sorting module and a conveyor or other infeed construction.

Contents

LIST OF FIGURES

FOREWORD

This thesis represents the work done by me for a Master’s degree in Mechatronics at Tallinn University of Technologies. The main aim of this project was to create a paper sorting module.
The task was provided by Ahti Põlder. The design was done in Solid Edge ST9 . Simulation was done in MATLAB R2015b.
The supervisors were Leo Teder from faculty of mechanical engineering and Igor Penkov.
I would like to thank my family and friends for support during the work period. Would like to thank my supervisors for their help and guidance.

EESSÕNA

See töö on tehtud Tallinna Tehnikaülikooli magistrikraadi saavutamiseks. Peamine eesmärk selles projektis oli proekteerida vanapaberi sorteerimismoodul.

Ülesanne selle töö jaoks andis Ahti Põlder. Mudelid tehtud programmis Solid Edge ST9. Simmuleerimine on teostatud MATLAB R2015b süsteemidega.

Juhendajad olid Leo Teder Mehaanikateaduskonnast ja Igor Penkov.

Tahaksin tänada oma pere ja sõpru toetuse eest projekti kallal töötamise ajal. Suur tänu ka juhendajatele kes olid abiks töö tegemisel.

1. INTRODUCTION

Yearly in Estonia is produced about 70 000 tons of paper waste. Almost this entire amount in a short period of use is converted into waste. For the most efficient processing of paper waste is required to sort by types of paper. Sorting automation is a rational solution to increase productivity and reduce costs. It is possible to use different technologies to automate the process. The purpose of this study is to find out the best solution system and to evaluate its effectiveness for sorting different types of paper.

Efficient waste paper recycling has a significant role in the sustainable environment. Recyclable waste paper as a fundamental ingredient of municipal solid wastes (MSWs) is indeed an ‘‘urban ore’’. Waste papers are considered as the solid recovered fuel which is recovered from MSW. Recyclable waste papers are segregated into various grades to produce high-quality products. Moreover, sorted paper streams save energy, chemicals, and water, as well as reduce sludge and rejects. Information technology is widely integrated with the waste management industry into its operations such as recycling, reuse, segregating based on categories and so on. This review article focuses on the life cycle of waste paper and existing waste paper sorting techniques. In the paper industry, many types of sensors are used in different mechanical and optical waste paper sorting systems [1].

Estonian recycling companies are facing the same sorting problem as well as others all around the world. They are interested in creating the system which would eliminate the problem of sorting paper on the line.

During this project we assume that recognition system already exists and fully working, machine vision system determines the waste piece location coordinates and its size by x, y scale coordinates. Waste can include:

- White paper
- Newspapers
- Magazines
- Brown paper
- Non fiber (plastic, magnet cards etc)

The waste piece size is defined by the maximum size of 100mm, the material appears as a flat layer on the conveyor line. Sorted material should be separated as quickly as possible after going through the machine vision system. The main criteria is productivity which should be not less than 2 tons per hour. Waste is divided into 4 groups which are:

White paper (40-60%)

Colored paper (30-50%)

Other types (10%)
Non paper (5%)
For this project it is necessary to sort only one type of paper, a white paper waste is picked up.

1.1 Background

Nowadays most spread automated sorting systems are divided into 2 types which are mechanical and optical. Mechanical sorting system is 2 times less efficient and 2 times more expensive. Optical systems include such sensors as:

- lignin
- gloss
- stiffness
- mid-infrared
- infrared
- color sensors

Sorting system for paper includes conveyor, coarse sleeve, fine sleeve, NIR device, sorting cabin, chain conveyor and press.

The mixed recycling goes through four main processes to separate out the different materials, these include the use of compressed air, magnets and infrared technology. Before entering the automated processes the materials are hand checked and anything such as plastic bags, textiles and glass are removed, these are then recycled elsewhere where possible. The ‘trommel’ is a very large drum which spins and separates out some of the materials such as cans and plastic bottles. The ‘air knife’ uses jets of compressed air to separate out paper. Paper and brown cardboard are then sorted into separate areas. A large magnet is used to attract and remove steel cans and electromagnetic technology repels and removes aluminium cans. Infrared cameras scan items passing on the conveyor belt. They recognize plastic bottles and determine their type. Precision jets of air then move the different plastic items into separate areas. This process can happen thousands of times a minute [2].

There are 2 main sorting approaches – manual one and using air streams. Modern approach based on identifying the optical properties of paper at speeds of up to 1200 ft/min (6 m/s). Up to 99 different grades can be set up as individual categories: white, colored, newspaper, magazines, brown OCC, etc. The incoming material is distributed over the full machine width and travels underneath the sensor array, which is mounted on top and at the end of a high-speed acceleration belt. State-of-the-art electronics process the signals from sensors and activate corresponding air valves, which eject the targeted material [3].

1.2 Determination of automation process

One of possible options for automation of the paper sorting process is using several robot manipulators. Delta robot appears to be most efficient manipulator for this kind of process [2]. Delta robot is a type of parallel robot and perfectly fits for sorting line. Distinctive feature for delta robot is high speed and accuracy. Some delta robots achieve speed up to 300 pics per minute. [2] Primary disadvantage of this option is high cost of each robot. The price offer from one of leading company in pneumatics and automation is equal to 48 700 euros

1.3 Methodology

Air streams and mechanical devices for sorting the paper are going to be overviewed. Aim is to develop a cheap and reliable sorting system which will be fast and accurate. There are several why the air streams and mechanical additional devices will be used in this approach. Main advantages of pneumatic system are simplicity in use, service, as well low cost of components, reliability and fast cost recovery [4]. Principle of work of the pneumatic system is to install pneumatic tubes on the end of the conveyor and with directed airflow push away needed paper wastes. With the help of the valve system air flow will be regulated at the right time. Pneumatic valves have fast response time, around 30-50 milliseconds. Durability exceeds 300 million cycles. Due to those characteristics pneumatic valves better choice for the needs [5].

1.4 Existing patent research

During the research it was found a variety of patented apparatus and systems used for waste paper sorting. In most cases air flow is used to separate paper. Below are mentioned main patents which could handle the problem of sorting waste paper. Used methods and systems lie very close to the research. Some of the future developed systems will partly rely on the previous inventions.

Paper sorting system:

Publication number	US6250472 B1
Publication type	Grant
Application number	US 09/301,992
Publication date	26 Jun 2001
Filing date	29 Apr 1999
Priority date ?	29 Apr 1999
Fee status ?	Lapsed
Inventors	Michael R. Grubbs, Garry R. Kenny, Paul G. Gaddis
Original Assignee	Advanced Sorting Technologies, Llc
Export Citation	BiBTeX, EndNote, RefMan

Patent Citations (119), Non-Patent Citations (9), Referenced by (41), Classifications (29), Legal Events (10)

External Links: USPTO, USPTO Assignment, Espacenet

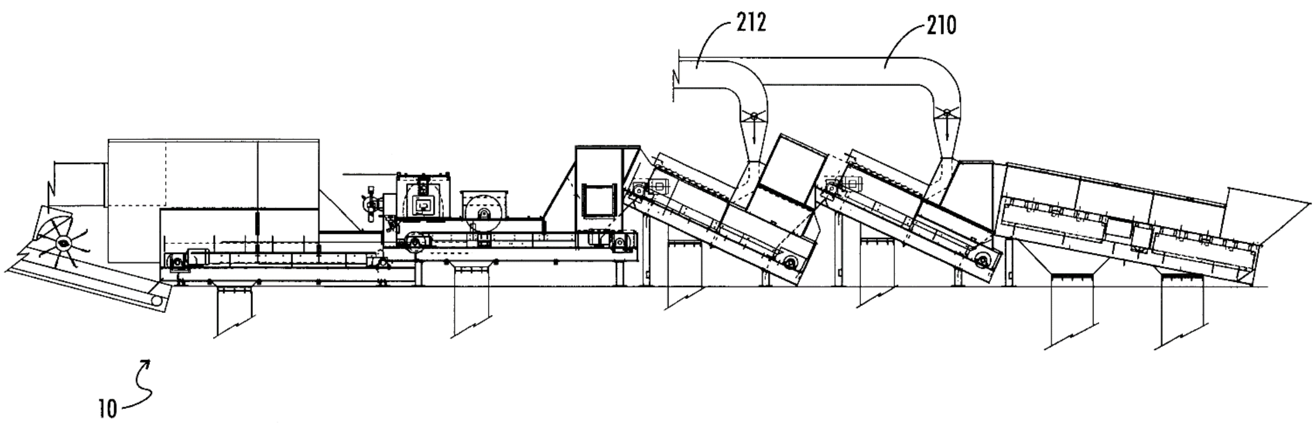

Figure 1. Principle schema

The systems uses several inclined conveyors, each conveyor speed is higher than the previuos one. Rotor blades situated above the conveyor belt provide additional friction force between the paper sheets and the rubber conveyor belt. Targeted material is ejected by air streams.

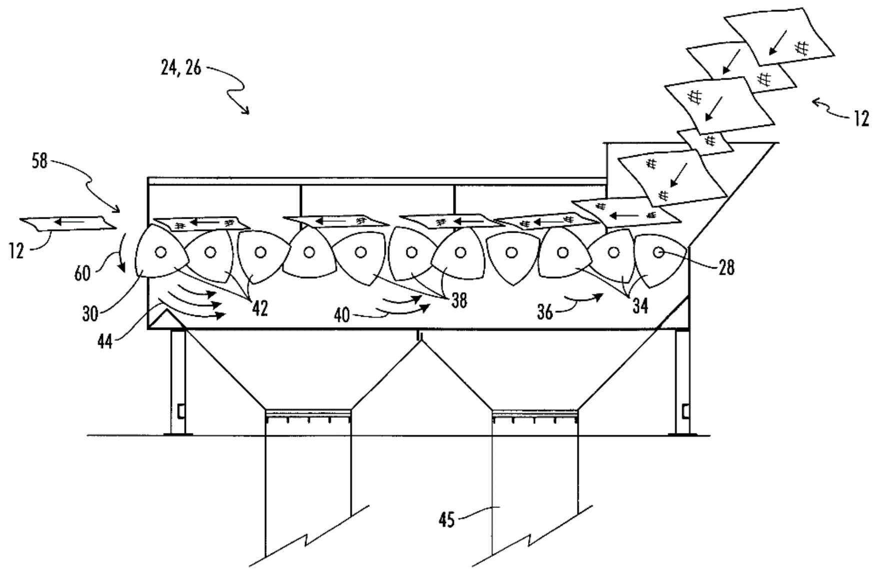

Figure 2. Principle schema 2

A device for separating office paper and computer printout from cardboard waste material is provided. Non-cardboard paper can fall between the disc rotors as the paper flows through the machine. A single counter-rotational disc rotor is provided which inverts cardboard and empties boxes. The drive for each deck of the device is independent and variable speed, allowing for quick reconfiguration between input streams.

Method and apparatus for sorting waste paper of different grades and conditions is given below

Publication number	US6506991 B1
Publication type	Grant
Application number	US 09/559,634
Publication date	14 Jan 2003
Filing date	28 Apr 2000
Priority date ?	30 Apr 1999
Fee status ?	Lapsed
Also published as	DE50009892D1, EP1048363A2, EP1048363A3, EP1048363B1
Inventors	Rainer Eixelberger, Peter Friedl, Karlheinz Gschweitl
Original Assignee	Binder & Co. Aktiengesellschaft
Export Citation	BiBTeX, EndNote, RefMan

Patent Citations (16), Non-Patent Citations (2), Referenced by (25), Classifications (12), Legal Events (7)

External Links: USPTO, USPTO Assignment, Espacenet

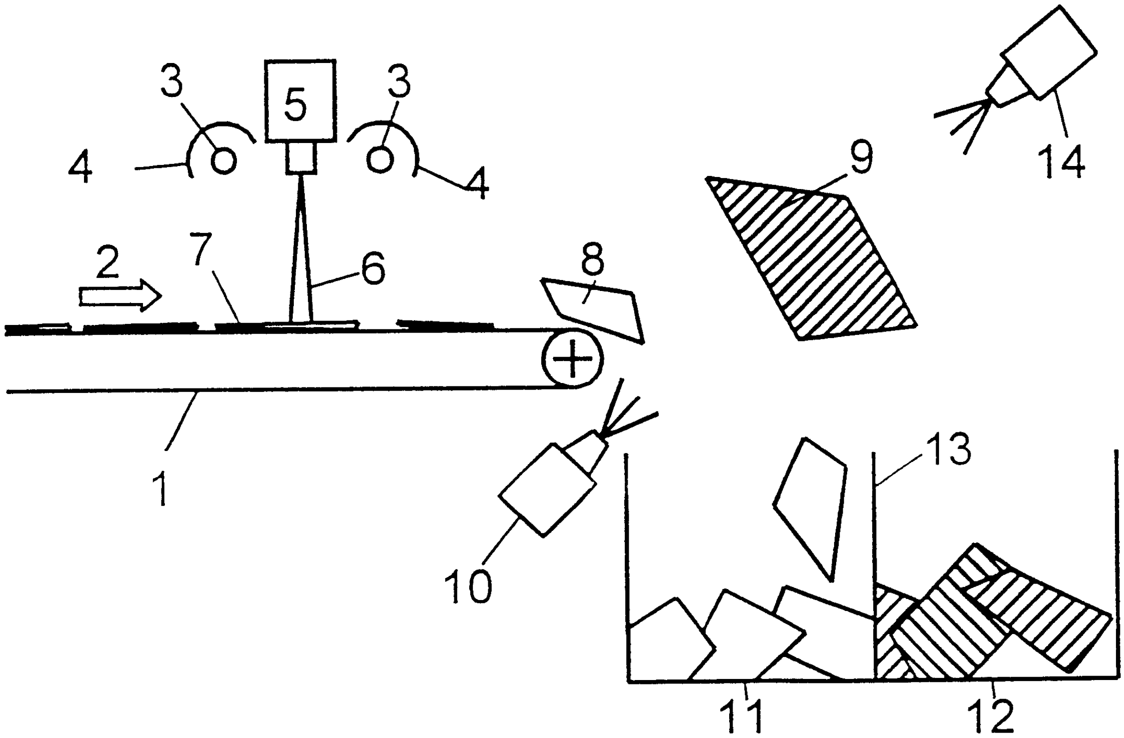

Figure 3. Principle schema 3

The method includes moving waste paper on at least 1 sorting conveyor belt. Each piece moves under the irradiating device, which irradiates surface and registrate reflected radiation. Piece continues moving in the direction of conveying, in the end a separation device is attached (air stream nozzles) which eject the piece with a concentrated air flow.

2. HUMAN-OPERATED SEGREGATION

2.1 Working principles

From the point of current thesis human-operated segregation is not being taken into consideration as a technical solution. Therefore author points it out to support the economical expediency of the automated systems.

The usual human-operated waste segregation consists of an input funnel, conveyor, operator’s platform, side containers for separated materials, container or module for non-segregated waste.

Although the human-operated waste segregation is less effective and more costly then automated waste segregation it is still being popular at segregation sites with capacity up to 100 thousand tons yearly. Which means, that it can be a solution for smaller districts with good self-discipline of people, who preliminary segregate their waste on a systematic basis.

The usual human-operated segregator can provide the separation of about 40% paper waste, about 15% of metal waste and 20-25% on plastic waste. Which is way less effective, then simple automated segregator. Therefore, human recognition of materials is way better and the separated paper is clean and well sorted considering the colors and type of paper, which makes it way easier to process further on.

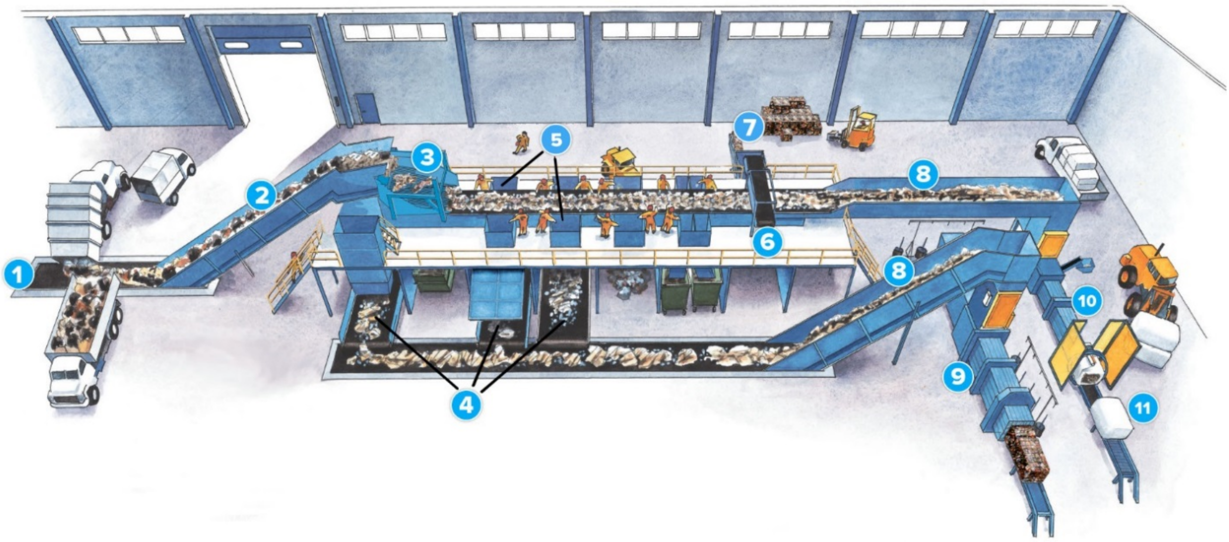

Figure 4. The example of human-operated waste segregation facility with separate conveyor line for paper waste.

2.2 Cost Calculation For Human Operated Solution

In the current case there is no additional equipment besides conveyor, which means that the initial investment contains only the cost of the facility, conveyor, containers for segregated waste.

The maintenance cost comes together from 5 aspects:

- Operators salary (considering the type of work it can be near to minimum wage)
- Conveyor technical maintenance cost
- Heating
- Electricity
- Water

For normal work the paper segregation conveyor line needs at least 5 operator (one operator for one container) working simultaneously. Otherwise the operators would have to be moving besides containers, which would create time loss, and result in lowering the speed of conveyor and overall productivity loss. If we need the facility to be working 24/7, then it means that yearly expenses on workforce would be at least 2,78 EUR per hour considering the minimum wage in Estonia (RT I, 22.12.2015, 51).

Additionally to it there are additional fees to be paid for working at night shift, on a public holiday, or weekend. So we should consider 12 public holidays, when operators should get double payment according to the Labor Act of Estonian Republic (RT I, 07.12.2016, 12): 12•24•5•2•2,78 = 8006,40 EUR, and 2920 hours of night work, paid at 1,25 rate: 2920•5•1,25•2,78 = 50735, and the usual work hours paid (365-12) •16•2,78•5 = 78507,20. Also the worker have the right to get 28 days of paid holiday per year, which raises the expenses by (365+28)/365 = 1,077

So the real numbers of the workforce brutto salary, if the operators get minimum wage are (8006,4+50735+78507,2)*1,077 = 147816,75 EUR per year
Where on the social tax 33% and the unemployment insurance fee 0,7%
So the real workforce expenses are 147816,75•1,337 = 197631 EUR.

And considering the fact, that working at minimum wage is not really attractive for people, then it means that the salaries can rise significantly higher. As a result author thinks, that this is not an effective way of waste management, because the expenses during the first year of work of the facility could cover a simple automated system.

3. SIMPLE AUTOMATED SINGLE LINE SEGREGATOR

3.1 Working principles

While the speed of human-operated segregators is quite low and cost-ineffective the simple automated single line segregators have another negative issue – the quality of segregation. To achieve the good quality of segregation it is required that the material recognition would be at high level. When using simple automated single line segregators it is possible to use the controlled recognition modules, which can be recognize the basic properties of material. The segregation is run only using physical properties of processed material. In the case of current thesis the material to be separated is paper. In principle the variety of paper materials is very big. Which means that separating the paper can only be made by removing other waste materials.

Figure 5. The outcome of simple automated single line segregator

The simple automated single line segregators are often used as the starting point of the whole big system, or as an intermediate between High-end automated modules. The quality of separation provided by automated single line segregators is relatively low, and if the paper picked out by these is to be processed later on according to its properties, then this type of segregation is not final. For instance, if the segregated paper materials are going to be burned, then there is no particular need to continue separation.

The schematic model of simple automated single line segregator is shown on next figure.

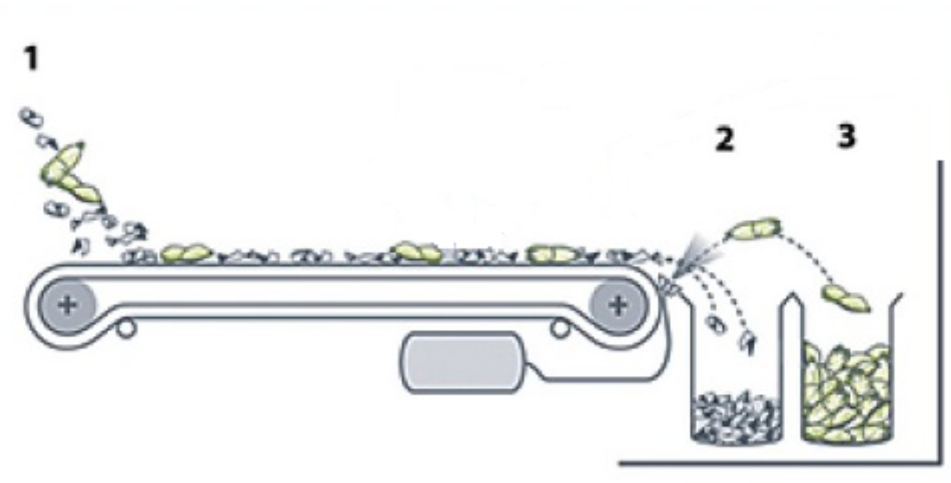

Figure 6. Schematic model of simple automated single line segregator.
Where: 1 – waste income, 2 – container for heavy waste, 3 – for light-weight waste

The conveyor shown on the figure shows the separation of plastic bottles and heavy waste using so called “air knife”, which is a high velocity air blower, which blows away all the light-weight waste. The same system can be applied for preliminary paper separation. By adding an electromagnet on the conveyor it would also be possible to remove metal from waste. But, it should be mentioned, that this type of segregator is not eligible to separate paper waste by its color and type. Therefore it can be used as a preparatory segregator, from where paper waste clean of plastic and metal proceeds to the main segregator – the high end solution which can “pick out” the paper by other properties.

As soon as the air knife on this kind of systems does not need nozzles to create spot jet, here “line jet” air knifes are used, for example the one on figure 7. This one does not need a pneumatic compressor, but only a blower.

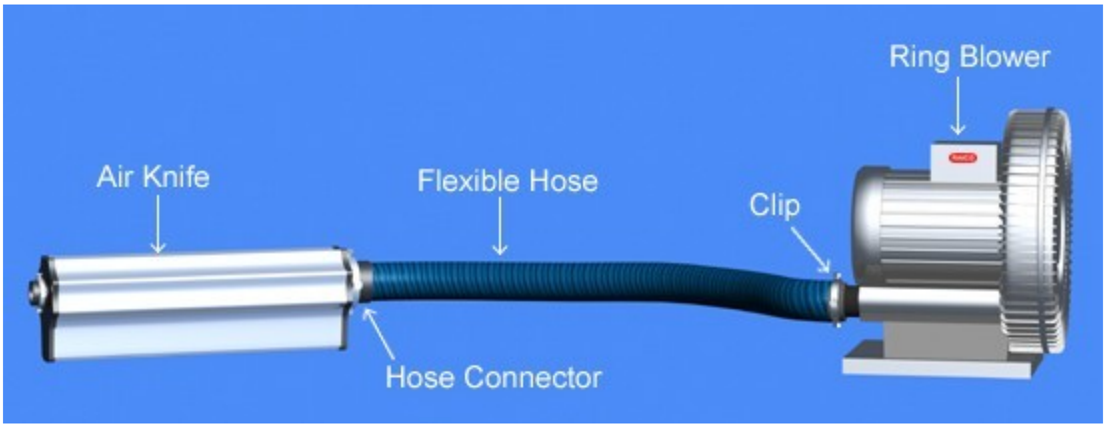

Figure 7. Simple air knife.

3.2 Cost calculation for simple automated system

The cost for simple automated system additionally to conveyor contains:

- Blower – for example Shengshi & Cyes (next figure), net price 425 eur – productivity 40 m3/min,

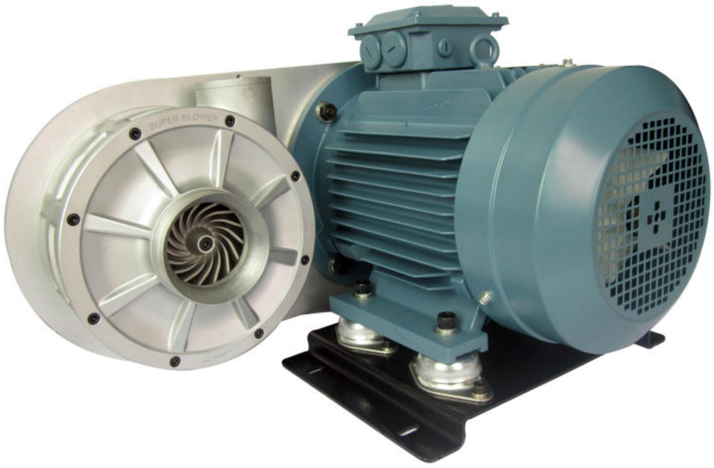

Figure 8. Shengshi & Cyes Industrial air blower

- Air knive – for example Vabs (next figure), net price 89 eur.

Figure 9. Vabs air knife

- Containers or bunkers for separated waste. Carbon fiber container price range is form 78 to 225 EUR depending on the volume.

Which makes the total initial investment around 600-800 euros besides conveyor.

Simple automated single line segregator is an effective pre-processing unit and it is likely to compete with high-end automation units in case if the required segregation facility productivity is low and separation quality demands are not high.

4. HIGH-END SOLUTIONS FOR MECHANICAL SEGREGATION (FLIPPING PLATFORM)

4.1 Technical solution

The current system was designed by Indian scientists, whose aim was to create a very cost effective system to segregate the trash locally. Author includes the overview of this system to the paper for comparison to other proposed systems.

4.1.1 The working principles

System starts when the waste material is put into the system. Waste is pushed through a flap into the inclined plane having the inductive proximity sensor. An upper enclosure ensures waste does not fall out of the sensing area. When the waste is dumped, the object slides over the incline to roll over the inductance coil which is used to sense any metal object. If the object is metallic a change in parallel resonant impedance of the metal detection system is observed. The object again continues and drops into the resistive sensing module. An IR and photodiode combination is placed here to check the presence of other waste. As and when waste falls between resistive plates, a change in IR value is detected. That change is used as the threshold to start the calibrations. Here, a decision is made if the waste paper is wet or dry based on its relative permittivity. After the identification of waste, a circular base which holds containers for paper and metallic waste is rotated. The collapsible flap is lowered once the container corresponding to the type of garbage is positioned under it. The waste falls into the container and the flap is raised. The waste in the containers now can be collected separately and sent for further processing [7].

4.1.2 Entry system and initialization

The waste is dumped into the Automatic Waste Segregator which marks the entry of the waste and starts up the system. It then initializes the sensor modules. The initialization of all modules ensures that any dynamic changes in the environment do not affect the sensing [7]. The advantage of the system is that it does not have any additional intermediate controllers between the main controller and servo-drives.

4.1.3 Metal detection system

The object moves over the incline and falls on the inductive proximity sensor] which contain an inductive coil. The inductive coil is a part of a parallel inductance and capacitance (LC) circuit. This measures the parallel resonance impedance of a parallel LC circuit and returns data as a proximity value. This data changes whenever another metallic object is introduced in the vicinity of the coil. When an alternating current is passed through a coil it generates a magnetic field. When a metallic object is introduced in the vicinity of the coil, eddy current is induced on its surface. The eddy current is a function of the distance, size, surface area and composition of the target. This generates a magnetic field which opposes the original magnetic field which is generated by the coil. The inductive coupling between the coil and the object creates a mutual inductance effect on the coil which decreases the parallel resonant impedance of the circuit which in turn is reflected by an increase in the proximity count value. Magnetic fields do not affect the metal detection system. It can detect any conducting material irrespective of its magnetic properties. The waste continues down the incline towards the resistive sensing module [7].

4.1.4 Resistive sensing module

Two pairs of copper cladded plates of size 10*7 cm are placed along the walls of the structure which are inclined to each other at an angle of 60°. This arrangement is made to ensure that waste of all sizes can be sensed. The area between each pair of plates increases as it moves away from the apex of the structure. The sensitivity of the plate decreases with its increase in area, hence smaller plates would accurately sense objects of smaller size. Even though the sensitivity of the larger plate is decreased, it is designed to detect larger objects which will yield a change sufficient to be identified. The property used for segregation of waste is the relative dielectric constant. Once a dielectric is introduced between the plates the resistance value between the plate's changes and subsequently a voltage change is detected. Wet paper waste has a higher relative dielectric constant than that of dry paper waste because of the moisture, or oil and fat, content present in kitchen waste and food package. If the change in the voltage is greater than threshold then the type of garbage is inferred as dry waste, else it is wet waste. Thus, the type of waste is identified as either wet or dry. Wet paper waste proceeds through the drying conveyor before being processed [7].

4.1.5 Segregation module

To achieve the segregation, two servo motors are used. The containers are placed on a circular base which is mounted on the axle of a servo motor. The circular base rotates as the axle of the servo motor rotates. If the container corresponding to the type of garbage is not under the flap then the motor is rotated clockwise or anticlockwise. The servo motor is given three different positions or angles for the three types of wastes detected. The motor thus always comes to the required position according to the signal obtained. The default bin at the circular base is the dry bin. To avoid overshooting of the container due to the momentum of the base, the servo motor is rotated at lower speeds by using pulse width modulation (PWM) which is generated from the microcontroller's timer. Once the required container is positioned under the flap, a second servo motor lowers the collapsible flap by rotating the motor clockwise by 180° it then waits for 2 seconds to ensure that the waste falls down and finally raises the flap back to the initial position by rotating the motor anti clockwise by going back to 50°. PWM is used to rotate the motor. Thus the segregation is completed. Rotation of circular base is as shown in figure 10 [7].

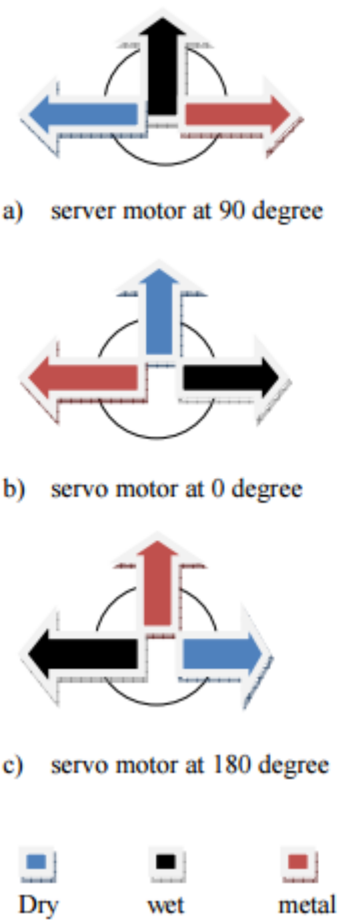

Figure 10. Rotation of circular base of servo [7]

The current solution uses the Arduino Nano microcontroller for the operational lead and recognition module. It is important to mention, that the net price of Arduino Nano microcontrollers begin with 18 euros, which makes it an extremely cheap control device, if being compared to well-known controller brands like Siemens (list price beginning with 56 EUR) or Danfoss (list price beginning with 118 EUR) etc.

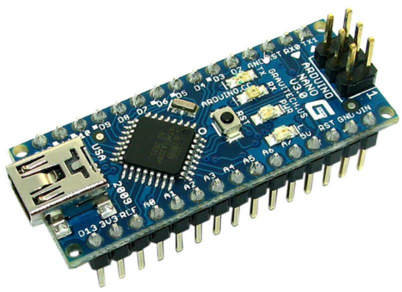

Figure 11. Arduino Nano microcontroller

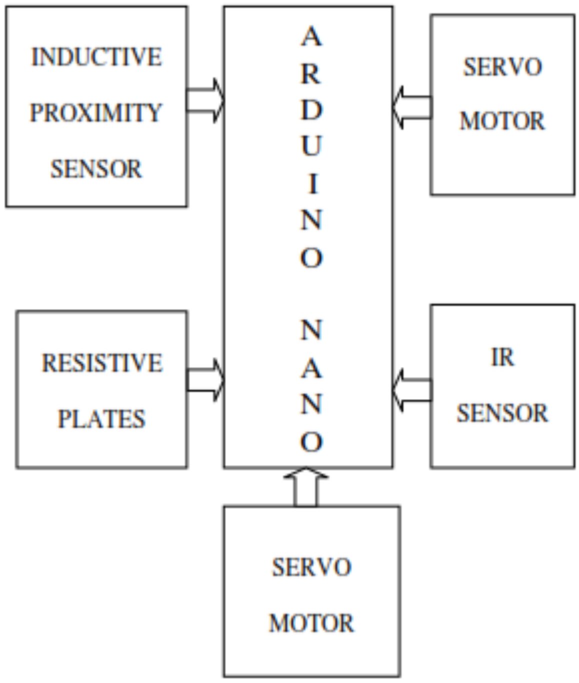

Figure 12. Block diagram for AWS [7].

The logical scheme of control software is shown as a flowchart on diagram below (figure 13). This can be implemented to any type of microcontrollers. For instance if ones objective is to make system more highly durable and reliable, to work in strong magnetic environment, then instead of using Arduino Nano the preferred solution would be Danfoss Plus+1 microcontroller, which uses the maintenance tool supporting the same graphical logic constructor [7].

From the flowchart one can see that the logic chain begins with recognition module feedback if IR sensor detects the material or not; If the inductive indicator detects metal, the position of segregation module is turned to 0 degrees, which make the waste fall to the container for metal waste; if not, the resistance is checked, where two options arise – wet paper waste has lower resistance and dry paper has high resistance. If the resistance measured is higher the threshold setting, then the waste is considered dry paper, and it goes to the “dry” container. If the resistance is lower than threshold setting, then the waste is considered wet, and is being moved to the container or module, where it will be dried with either a fan or other possible options. That is the end of logic scheme [7].

Only after the wet paper waste is dried it can be mixed with dry paper and processed further.

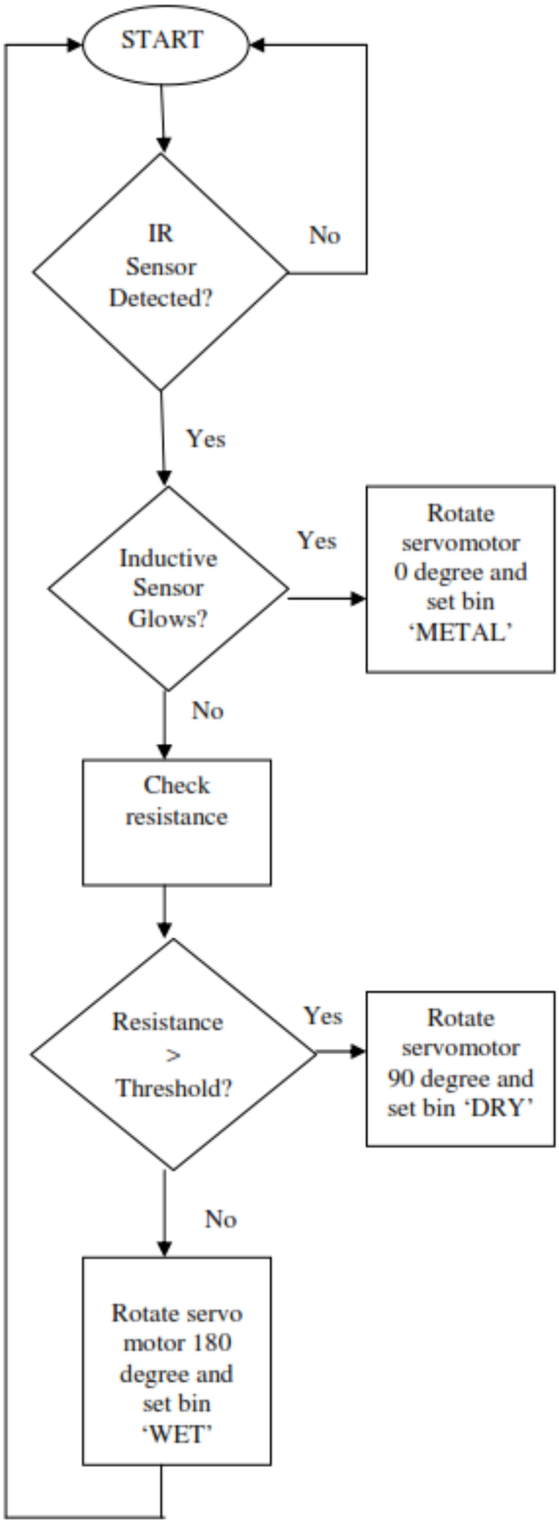

Figure 13. Software implementation [7].

4.2 Cost calculation for “flipping platform” solution

It is hard to calculate the cost for flipping platform solution, because it is just a concept, and there can be multiple technical designs for that one. The cost of servo-motor would be in between 300-800 EUR depending on it power, momentum, and speed. As a result one can get different productivity.

The price of controller varies from 18 to about 200 EUR.

Making the mechanical part of the segregation module including the design and product development would be around 5000 EUR. The price is proposed by company Eksamo AS based on their previous engineering experience and median prices of metal works in Estonia at the current moment. The price is valid although there is no official price offer to present.

Which means that the start-up price would vary in between 5000-6000 EUR

The exploitation cost would only consist of electricity consumed by the module, which depend straight on the power of servo-motor.

5. HIGH-END SERVO-ELECTRIC MANIPULATOR SOLUTION

5.1 Technical solution

5.1.1 The working principles

All servo-electric manipulator solutions are microcontroller based. It means that the recognition module, the conveyor encoder, the manipulator servo-motors are all connected to the controller, which analyses the surface of material. For instance the properties to be analyzed can be the thickness, the color and the surface finishing of paper fed to the segregator.

The manipulators are based on a beam or a console, hanging above the conveyor. The manipulators require 3 servo-motors of which two actuate on Y and Z axis, and one on A axis, which is the grabber on the end of manipulator. The X axis parallel to the length of the conveyor, and it is not being actuated, but the controller receives feedback of the position changes of the conveyor line.

Figure 14. Schematic model of manipulator on linear axes

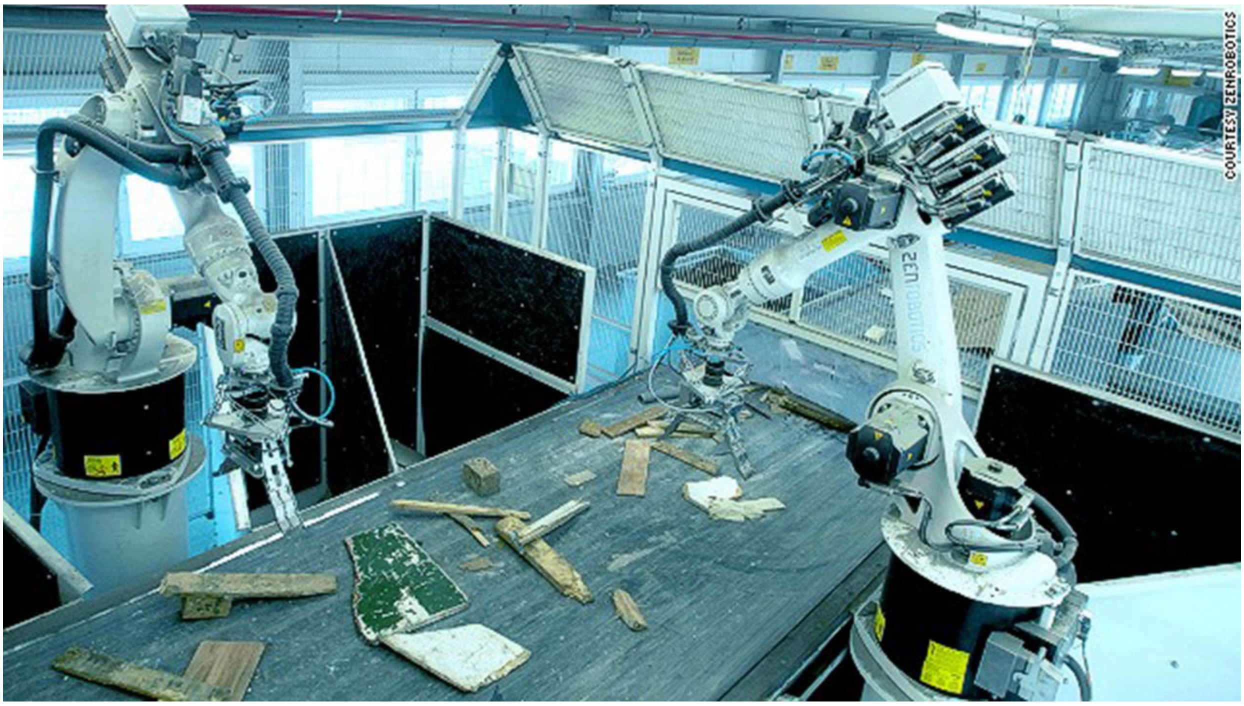

Figure 15. Alternative solution for manipulator segregation module on rotary axes

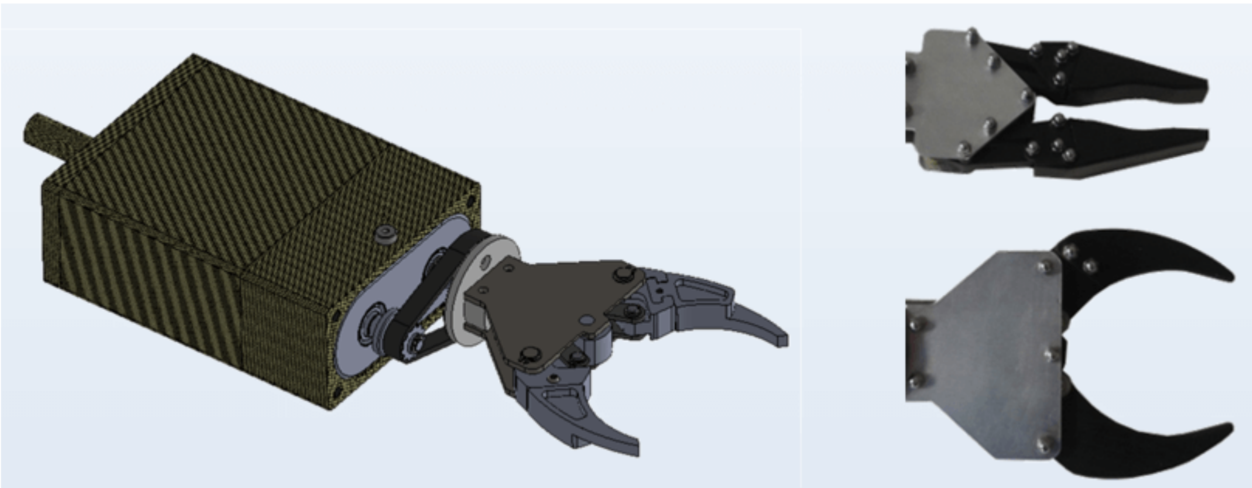

Figure 16. The grabber of manipulator

As the material to be picked out of the conveyor is paper, then additional rotary axis is not required for effective work of manipulator grabber. Therefore a rotary axis in the base of grabber would be an advantage if in time there would be reason to reorganize the segregation module to work with other solid waste with strong shapes.

5.1.2 Control

The controller must have the ability to read and actuate all positions simultaneously. Also a factor to be considered is the working capacity of manipulators. One manipulator can handle only one object at time, which means that a conveyor running at full capacity requires more than one manipulator. The controller should be also able to decide which manipulator to use to pick a specific object, to ensure that the object is picked with a manipulator that has to make the shortest traveling for that. For instance – if the object is on the left edge of the conveyor, then it should be picked by a manipulator, that is the closest to the left edge at the current moment. This is meant to avoid “useless moves” and make the system more energy efficient. Considering the fact, that the automated waste segregator should be running 24/7, “useless moves” can be a great economic issue. Typical PLC controllers are not eligible to this type of situation, therefore author recommends to use the Danfoss Plus+1 controller or similar.

Figure 17. Danfoss Plus+1 50 pin controller [15].

The manipulators have a lot of moving details that makes their start-up cost high. But the maintenance cost will be significantly lower than high-velocity air flow solutions which are the focus of next chapter of current work.

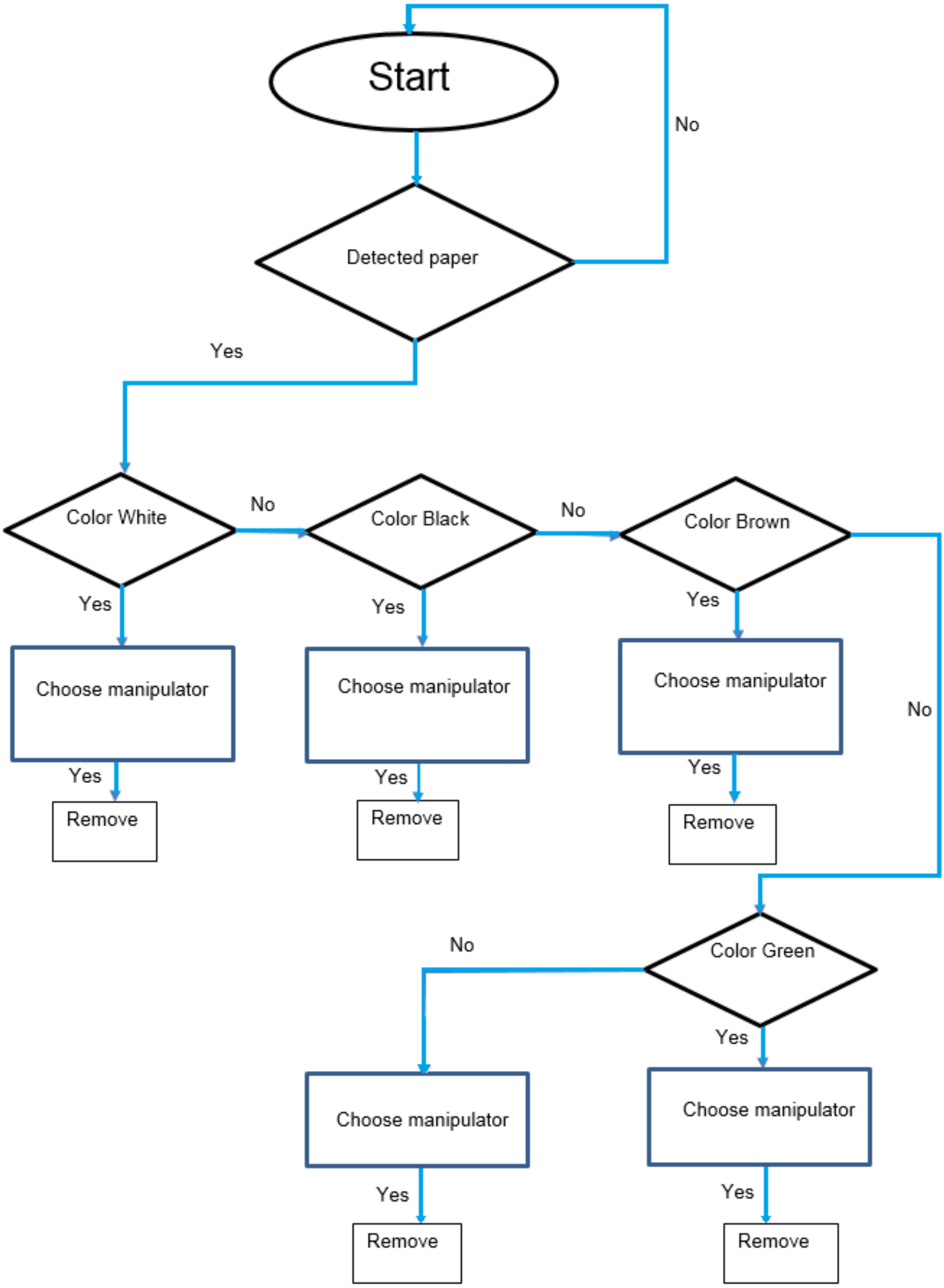

Figure 18. Control software logic chain

5.2 Cost calculation

For this type of solution the facility should have one technician to service the systems. The technician does not have to be necessarily a fulltime worker. The position can be connected to any other job on the facility, or be a part of supervisor obligations. Let us presume that the workforce expenses on the technician are around 8400 EUR per year (or 700 per month) which is reasonable to pay for part time work in conditions of 24/7 readiness.

The initial investment for such system would be:

- 24500 EUR per one manipulator
- The industrial controller (for example Danfoss Plus+1) - 118 EUR (according to price offer in attachment)
- The software for controller (according to price offer in attachment) 5500 EUR
- Assembling an wiring (according to price offer in attachment) 3500 EUR

Total: 131618 EUR

The maintenance cost of the system therefore contains:

- Electricity consumption 27 kw power, which makes 8822,20 EUR yearly, at price 0,0373 EUR/KWh (march 2017, Eesti Energia)
- Technician salary expenses 8400 EUR
- Possible unexpected expenses for spare parts

Which makes around 17220 EUR yearly, if no unexpected situation occur.

6. HIGH-VELOCITY AIR FLOW SOLUTION

Upon analysis of previously mentioned possible solutions for separating the waste paper it is obvious that air knife is the most cheapest and reliable. Also pneumatic systems are long life and cost effective. Since air knife is not accurate it is decided to develop an idea with compressed air streams and go to controlled valve and nozzle system.

6.1 Technical solution

6.1.1 Working principles

High-velocity air flow solution with multiple nozzles on the block of an “air knife” could provide us a possibility to pick out the specific type of paper from the overall waste flow on the conveyor line, and shoot it to the gathering point, which could be either a container or a bunker. Unfortunately due to circumstance that air jet in the atmosphere has highly turbulent flow it means that it is not possible to choose multiple different types of paper and shoot those in different directions to different gathering points. But, it is possible to make multiple steps on conveyor line, and each would “pick out” the specific type of paper.

In current thesis we are observing the separation of paper by color, so for the current chapter we would choose white paper separation as an object for research. The possible way to make it is shown on next figure.

Figure 19. Paper separation with air jet

On the figure 19 one can see paper waste approaching the separation module. Under the drum of the conveyor line there is a block of air nozzles, which shoot air jets at the objects specified by the recognition module. The recognition module chooses the white paper on the conveyor, measures its geometry, and finds its geometrical center point, and forwards the information to the controller of the separation module. The controller actuates the nozzles according to the position of the paper.

When an air jet is shot to the sheet of paper it jumps up over the drum of the separation module, which can be seen on next figure. From that point the paper sheet is being vacuumed to the bunker. All the remaining materials contained in the waste fall down lower conveyor line, from where the waste is being moved for further procession to other places.

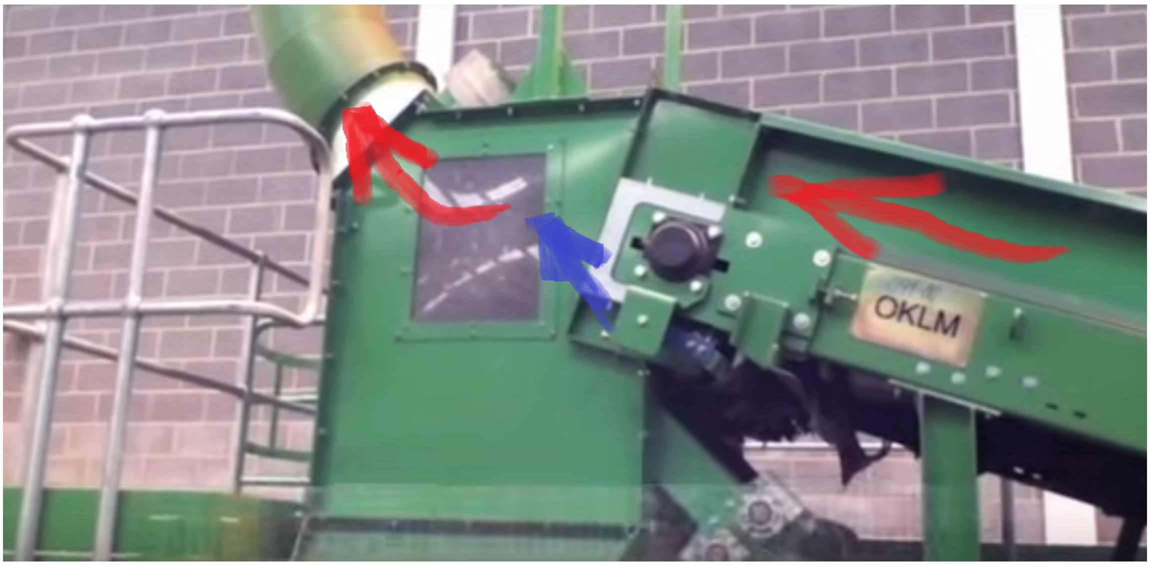

Figure 20. High-velocity air flow separation module. White paper moves shown with red. Air jets shown with blue.

For smaller systems it is possible to use multiple conveyor lines instead of vacuum. Like on figure below.

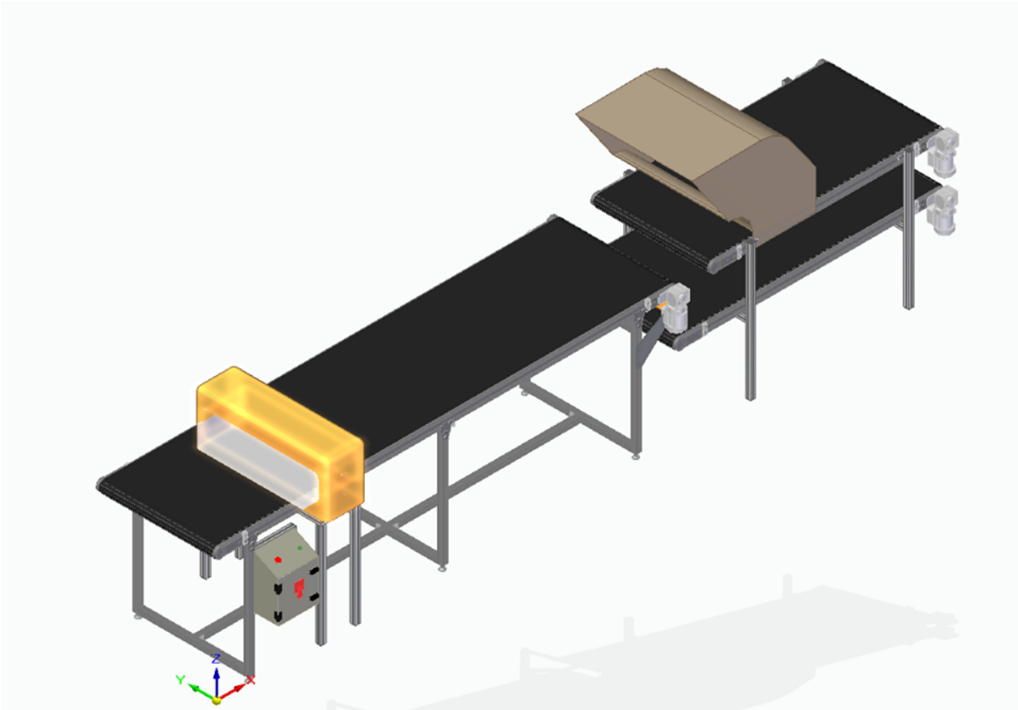

Figure 21. Conveyor line assembly. 3D model.

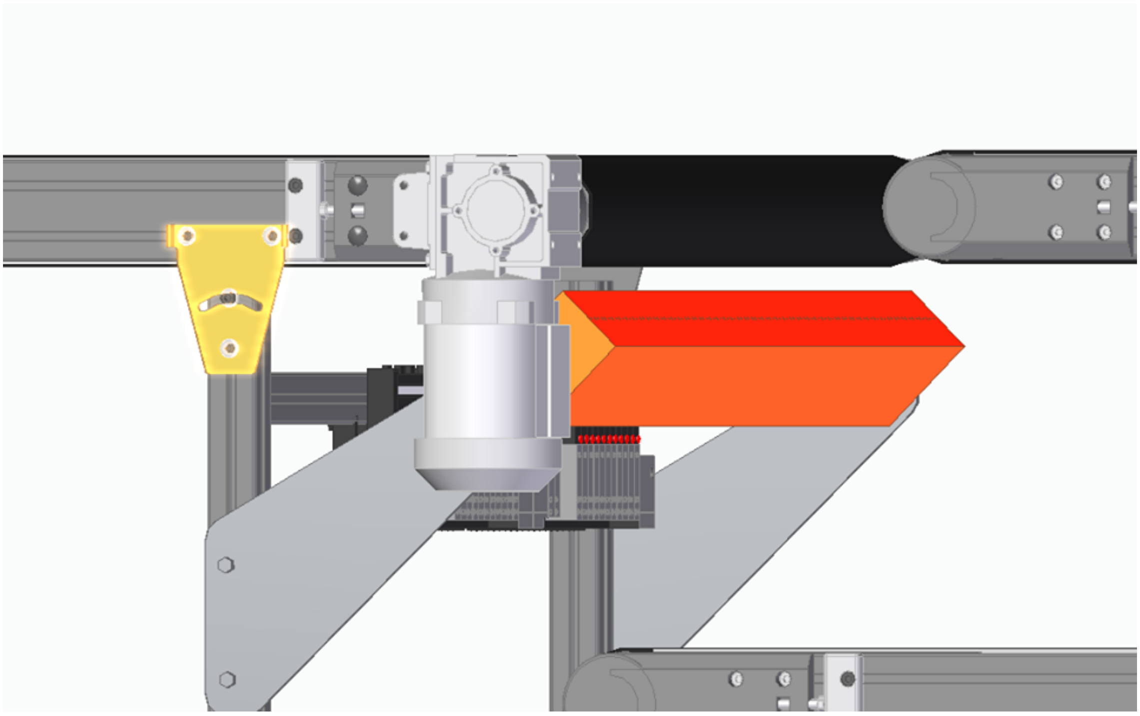

Figure 22. 3D model of separation module. On the right there are two conveyor lines, upper for separated white paper, and lower for other materials. The nozzle block is in the middle right under the end of first conveyor.

As soon as the air has turbulent flow the air jets can move also unnecessary objects with the selected paper to the vacuum pipe and to the bunker with white paper. Therefore human processing would still be needed on the outcome of the bunker with white paper, so that human operators would be able to pick out the unnecessary object from white paper conveyor line.

After that the white paper is pressed together with a hydraulic press, and being shipped out for recycling.

6.1.2 Pneumatic engineering

High-velocity air solution is likely to have the lower start-up price, but most probably higher maintenance cost over time. The main parts of high-velocity air flow solution are the compressor, the valve stack and the nozzles, which create the air jet to blow away the paper from the conveyor.

Now a great many enterprises of various specificities use the pneumatic system in the technological processes. The durability of equipment and the income of the enterprise directly depends on reliability of the pneumatic system and on the quality of products. In light of this, the installation and design of pneumatic systems are of particular importance.

Factors to be considered

- Careful approach to the selection of the type of compressor equipment and site for its location;
- The calculation of the necessary volume and number of receivers, the choice of a location for the placement of the latter;
- Calculation of the degree of purification of air under pressure from compressor oil, moisture, various particles, reasoned from a technical point of view, the choice of the location of filters, steam traps and dehumidifiers;
- Selection of the method for removing heat energy generated during operation of the compressor unit;
- Calculation of pipe sections, selection of their location, selection of material, observance of necessary deviations, correct connection of equipment;
- Condensate recovery

Improper calculation and installation of a pneumatic system often cause significant losses in production. Such losses can be expressed in frequent outages of compressor units, breakdowns of compressed air devices, idle automatic lines. Sometimes losses can be very noticeable. In addition, the design of a pneumatic system that takes into account the above factors will lead to energy savings of up to fifty percent, in comparison with obsolete methods.

The design of the pneumatic system should be approached with particular gravity, since the acquisition and installation of inexpensive but low-quality equipment is likely to cause frequent breakdowns, and the purchase of overly expensive and expensive equipment will increase the cost of the purchase and subsequent investments in it Electricity during work cycle.

When designing the pneumatic system, and the high-velocity air flow solution is a pneumatic system, one has to avoid the main mistakes brought next:

- Installation of an air-cooled compressor on the site, where cooling air is not possible or difficult to remove. The lack of this in the design will cause frequent overheating and breakdown of compressors.
- Wrong choice of the location of the steam trap and low-level dehumidifier. Currently, a number of domestic companies offer "dehumidifiers", which, in practice, are steam traps. They are able to remove only droplet moisture, while the water vapor remains in the compressed air. It makes sense to remove condensate in the only place where the condensate is formed. Condensation, in fact, occurs at the cooling point of the compressed air. Imagine an outdated model of the compressor, with missing equipment for cooling compressed air. The compressed hot air produced by such a compressor is cooled in the pipes connected to the consumer. As a result, condensate accumulates along the length of the pipeline. When after such a compressor connect the steam trap or the above-mentioned "desiccant", moisture will not be removed from the compressed air.
- Incorrect slopes of the pipeline. This defect is caused by two variants of the consequences. The best of them involves getting a small amount of condensate to the consumers of air under pressure. A more unfavorable development of the situation will lead to filling the whole pipe with condensate and throwing out its entire volume to consumers. If, in this case, the pipes are made of usual steel, they will undergo corrosion during the condensate sedimentation stage. Corrosion products will directly fall into the system (irrespective of the quality of air purification when exiting the compressor) and quickly make it incompetent.

Highlights at the initial stage of work

Before one gets pneumatic system in production it is necessary to go through the next steps:

1. Select the most suitable compressor and site for its installation;
2. Calculation of the required number of receivers and their volume;
3. Determination of the cross-section of pipes and the material from which they are made
4. Careful calculation of the route, slopes, checking the strength of their joints;
5. Determination of the methodology for the utilization of condensate and thermal energy.

Based on the data received in the process of operations performed, the calculation is carried out, which is compulsorily agreed with the control bodies.

Pneumatic engineering includes:

- Calculation of required compressed air volumes for the enterprise;
- Preparation of the air preparation system;
- Determination of possible pressure drops;
- Development of the project of the compressor room.
- Creating a pneumatic network

Pipeline is a device for distributing and transporting prepared air, with the adjustment elements and shut-off valves installed therein. It is important at the design stage not to make mistakes. They can adversely affect the performance and economic feasibility of using this equipment. One of the most common errors is the wrong choice of the basis of manufacture. Along with plastic and steel, aluminum pipes are not corroded, they do not create resistance to the flow of air. Their weight is minimal, which eliminates the need to install special structures for support.

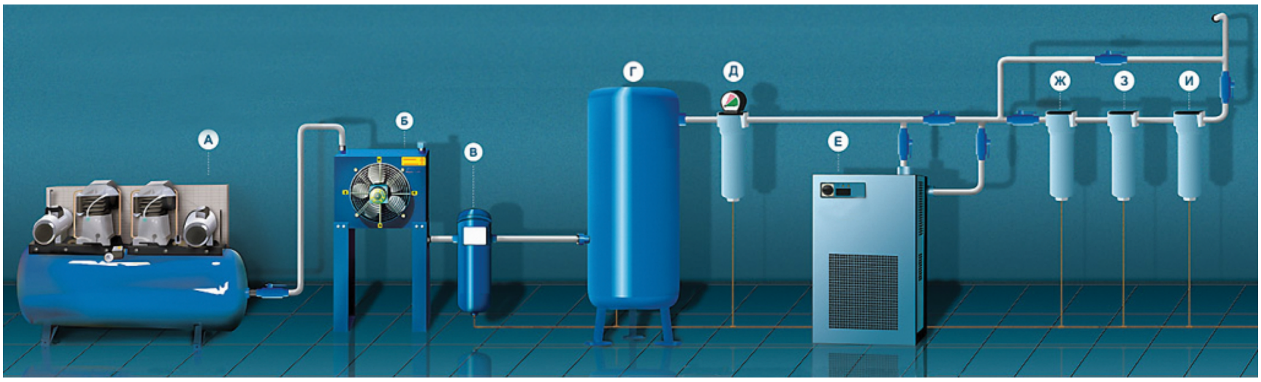

Figure 23. Pneumatic system air preparation module, in which (form left to right: Compressor; air cooler; cyclone type separator; reservoir; preliminary filter; air drier; intermediate with condensate remover; oil catching filter; coal filter) [13].

When choosing compressors, the question often arises: to acquire one powerful compressor and from it to conduct a branched network to different consumers, or at each work site to install its own small compressor. Each scheme has its advantages and disadvantages.

Centralized settings:

- Reduce energy consumption;
- Require less expenditure on ongoing monitoring and maintenance;
- Reduce the necessary area;
- Are easy to provide noise insulation and equipment selection.

A system with several decentralized compressors:

- Allows to create a simpler compressed air system;
- Sharply reduces the loss of compressed air and is cheaper to operate;
- For each consumer, a compressor with the necessary pressure and capacity can be installed;
- Small compressors do not require foundations, which simplifies and reduces the cost of their installation and commissioning.

The decision in favor of a centralized or decentralized installation of compressors is best taken after a detailed analysis of the air distribution system: the length of the air main, the possibility of installing receivers, pressure losses, leaks, total consumption and the nature of compressed air consumption by individual parts of production.

In case of garbage segregation system the decentralized compressor setting provides multiple advantages:

1. System becomes Fail Safe due to multiple compressors working in parallel. In case if one compressor needs to be maintained or repaired then others can supply the system with critical amount of pressurized air. That is a critical issue for an automatic conveyor that is supposed to work 24/7 without operator's participation.
2. Small compressors are cheaper and more cost effective in exploitation.
3. It is definitely much easier to cool down multiple small compressors using the usual ventilation, then a big one.

In order nozzles provide enough powerful air jet to blow away the paper from the conveyor pressure and air flow should be appropriately chosen. Herein one has to consider the pneumatic system losses. As soon as actuator used in the system are electric, then low pressure line air consumption does not have to be considered in our case. The remaining losses are:

- Leakage (usual leakage is supposed to be under 10% of effective air flow; in formula 5.3 coefficient "k_1");
- Multiple element simultaneous work pressure drops (in formula 5.3 "k_2", 0,8…0,95);
- Flow resistance doe to pipeline geometry (in formula 5.3 "k_3", 0,95…0,99);
- Air volume change due to temperature drop (in formula 5.3 "k_4", for our case around 0,9).

The air flow in the cross-section of the pipeline is calculated according to the formula 5.1.

$$Q_1 = \frac{V_1}{\Delta t} = \frac{S_1 \cdot \Delta l_1}{\Delta t} = S_1 v_1 \quad . \qquad (5.1)$$

In ideal situation Q_1=Q_2 which means that the system has no leakage on no losses, where Q_2 is the flow in another cross-section, calculated a0ccording to the same formula

$$Q_2 = \frac{V_2}{\Delta t} = \frac{S_2 \cdot \Delta l_2}{\Delta t}.$$

Which basicly means that the speed of air in different cross-sections of the system multiplied with the cross-section is the same in any point of the system.

$$S_1 v_1 = S_2 v_2 = const. \quad (5.2)$$

Where S_1 and S_2 are the cross-sections, and v_1 and v_2 are the flow speeds.

But as already mentioned above that is not the case for our system, and we have to consider the losses. The formula considering the losses would look like this:

$$Q_2=Q_1 \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \,. \quad (5.3)$$

Where Q_1 is specified by the compressor, in our case the preliminary choice is 28,4 m^3/h

$$Q_2=28{,}4 \cdot 0{,}9 \cdot 0{,}95 \cdot 0{,}99 \cdot 0{,}9=21{,}63\ m^3h$$

or

$$0{,}006\ m^3 = 6\ L/s$$

Where in Q_2 is the total flow on the output of the system, Q_1 is the total flow in the cross-section between the compressor and the air preparation module.

The total airflow on the output Q_2 in our case contains 100 nozzles (one per 10 mm of width).

$$Q_2=q_1+q_2+\ldots+q_n\,. \quad (5.4)$$

Where in $q_1 \ldots q_n$ is the flow through one nozzle.

Although all nozzles are not likely to operate simultaneously, it can still occur in some cases. It means, that the right amount of air can be provided for short time using the air reservoir. In this case we would need to calculate the total effective output flow:

$$Q_2=q_1 \cdot i1+q_2 \cdot i_2+\ldots +qn \cdot i_n\,. \quad (5.5)$$

Where in $i_1 \ldots i_n$ is the effective cycle of one nozzle. Counted as operational time divided with overall time.

Running forward it is necessary to mention, that the effective cycle of one nozzle would be approximately 1/3 of a time. And the total productivity of compressor station would be calculated like for chargeable pneumatic systems.

The reservoir calculation comes under formula 5.6.

$$V(l) = (Q \cdot t \cdot Kpr) / (60 \cdot \Delta P)\,. \quad (5.6)$$

Where in:
V is the volume of reservoir;
Q is the flow;
Kpr is the coefficient of productivity of compressor (0,65 … 0,75);
ΔP is the allowed pressure drop is the reservoir (in our case 2 Bar).

The working pressure in the pipes should be in between 6,5 and 13 Bar (the usual pressure for industrial compressors). To simplify the calculations and gain more cost effectiveness of the system herein author proposes to go on with 6,5 Bar pressure. Here in we should find the required cross-section of the nozzle, to be able to blow away the paper from the conveyor with an air jet.

Here the gas mechanics of the jet should be considered. The flowing air jet moves along a spiral trajectory, while particles are separated from it. The strength of the impact of a particle on an object depends on many parameters, it is important that upon impact it receives a back impulse, pushing away from the object, and then, under the action of the centrifugal force, again moves to the object. Thus, the particle makes a sudden movement at the object, and in our case - at the surface of the conveyor line, while object on it are displaced along the Y axis in the stream of the air jet, and also changes its axial coordinate in the jet under the action of gravity.

To effectively move paper and cardboard and save energy the recognition module of the conveyor forwards the sizes of the object on the conveyor to the controller, which controls the actuators of proportional pneumatic valves. This means we can control the amount and the flow of air used to move the objects. The nozzle block at its full throttle should be able to produce about up to 6,0 L/s flow, which means that the system should be able to produce 21,6 m^3/h flow on the output. That would provide 20…23 m/s flow depending on the temperature drop, which would be the flow required for normal operation. Detailed simulation is show in next paragraph.

6.1.3 Nozzle block construction and suitability check

The common question in case of air nozzle usage is the power it provides. Would the airflow and the velocity be high enough to provide reactive force to move the object fast enough. For this multiple parameters should be checked: the mass and the geometry of the object on the conveyor (when talking about paper waste there can be the simple light paper, or it can the thick heavy paper, and the geometry can be a plain sheet or any possible shape), the exact coordinates of the object on the conveyor, the orientation of the object (there is a huge difference when the surface is parallel or normal to the jet).

The useful energy transfer from the air flow to the object would be counted as Impulse, due to the fact that the air jet shot out of the nozzle is a short time action. The system controller can process the data gained from the recognition module including the assumable mass of the object (depending on physical properties and geometry). In this case the outlet amount of air can be actuated proportionally to the presumed mass of the object.
In this case we have no constants, but the required relation of outlet air and the presumed mass of the object (the paper on the conveyor).

Also we do not have to be considering friction force of the object to the conveyor surface, as it gets marginal, when the air jet is shot, due to the fact that air gets under the object, as well as on other sides of it. There is now particular friction between the object and the surface of conveyor, which make the model even easier.

The effective impulse transfer from an air jet to the object in case of on critical pressure drop (difference between pressure on side of the flow to the pressure on other side of the object is lower than $P1/P2 \leq 0{,}524$) is 0,74. Which means that

$$I_{obj} = 0{,}74 \bullet I_{air} \quad \Rightarrow \quad m_{air} \bullet v_{air} = 0{,}74 \bullet m_{obj} \bullet v_{obj} \,. \qquad (5.7)$$

Given formula is valid only if the object is situated next to the nozzle, but as soon, as objects are moving away from the nozzle, then using the formula would not provide the adequate answer. Therefore author uses the Mathlab simulation to get adequate results on the behavior of paper sheets. As a simulation object there is chosen 300 g/m2 paper piece with sizes 0,1 to 0,1 meters.

The air speed would be around 20 m/s, so this number is taken for the simulation.

```
V = 25;
a = 45;
Vx = V * cos(a);
Vy = V * sin(a);
[t, x] = ode45(@flights, [0, 1.5], [0, Vx, 0, Vy]);
plot(x(:, 1), x(:, 3));
title('With Drag coef.');
xlabel('X m');
ylabel('Y m');
grid on
ylim([0, 5])
end
function xprime = flights(t, x)
C_d = 1.00;
p = 1.25;
A = 0.1;
m = 3;
D = ((1 / 2) * C_d * p * A);
xprime = zeros(2, 1);
xprime(1) = x(2);
xprime(2) = - (D / m) * x(2) ^ 2;
xprime(3) = x(4);
xprime(4) = - 32.2 - (D / m) * x(4) ^ 2;
end
```

Figure 24. Mathlab algorithm

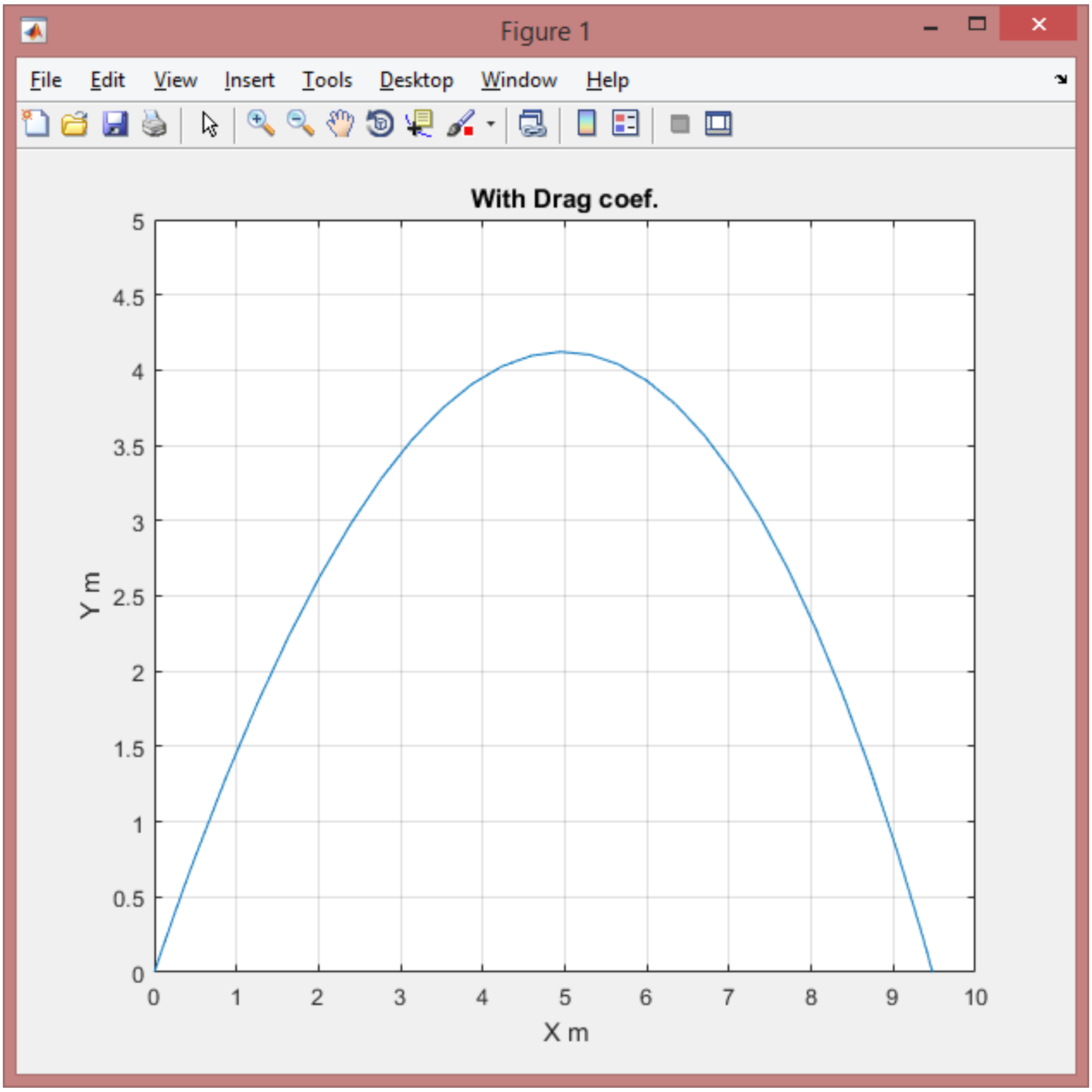

Figure 25. Object trajectory simulation.

So the parameters for the high-velocity air flow solution would be:

Working pressure at least 6,5 Bar;

Nozzle pipe diameter – 1,8 mm;

Main pipeline diameter - at least 10 mm.

6.2 Cost calculation for high-velocity airflow solution

Initial expenses to start the line would consist of next main articles:

- Pneumatic line – Usually the pneumatic line is built in the facility before the main equipment is installed. Therefore the prices may be significantly different of those named here. The prices taken in this paper are produced by the local resellers over a phone call.

  As discussed before the pneumatic line consists of basic components: compressor, piping, air reservoir, air filters and driers, condensate removers and air cooler. The whole set for the effective volume of 22-24 m3/h would cost around 4500 EUR. Final price depends upon special agreement.

- Nozzle block – Non controllable nozzles, 100 pcs. 880 EUR net.
- 9 Valve stacks, with 12 valves each and with electric actuators – 630•9=5670 EUR net
- Controller – 120 EUR

Which gives 11170 EUR initial expenses besides conveyor and material recognition module.

Exploitation expenses:

- Electricity – 3,5 KW power compressor consumption would be roughly 30,5 MWh, and would make 1143 EUR per year at price 0,0373 EUR/KWh (march 2017, Eesti Energia)
- Pneumatic line maintenance – To be maintained once a month. One maintenance duration – about 2 hours, at 35 EUR/hour rate, which gives total 35•2•12=840 EUR per year net.

Based upon previous one can see, that the exploitation cost for high-velocity air flow solution stays within 2000 EUR per year, which is way more cost-effective than other variants.

7. CONVEYOR

Selection of the type conveying machine - depends on the properties of transported goods, specified performance and conveying circuit track sizes. Conveyors consist of traction and carrying bodies with support and guide elements, a leading (driving) and slave drums, tension device, loading and unloading devices and frames. Drive the most frequently carried out by an electric motor through a reduction gearbox. If necessary, the drive has a built-in braking device. Conveyors are equipped with standard or normalized units and parts. Calculation of the conveyor is to determine key parameters: selection and calculation of the working body; determining the power and the type of engine.

7.1 Conveyor productivity

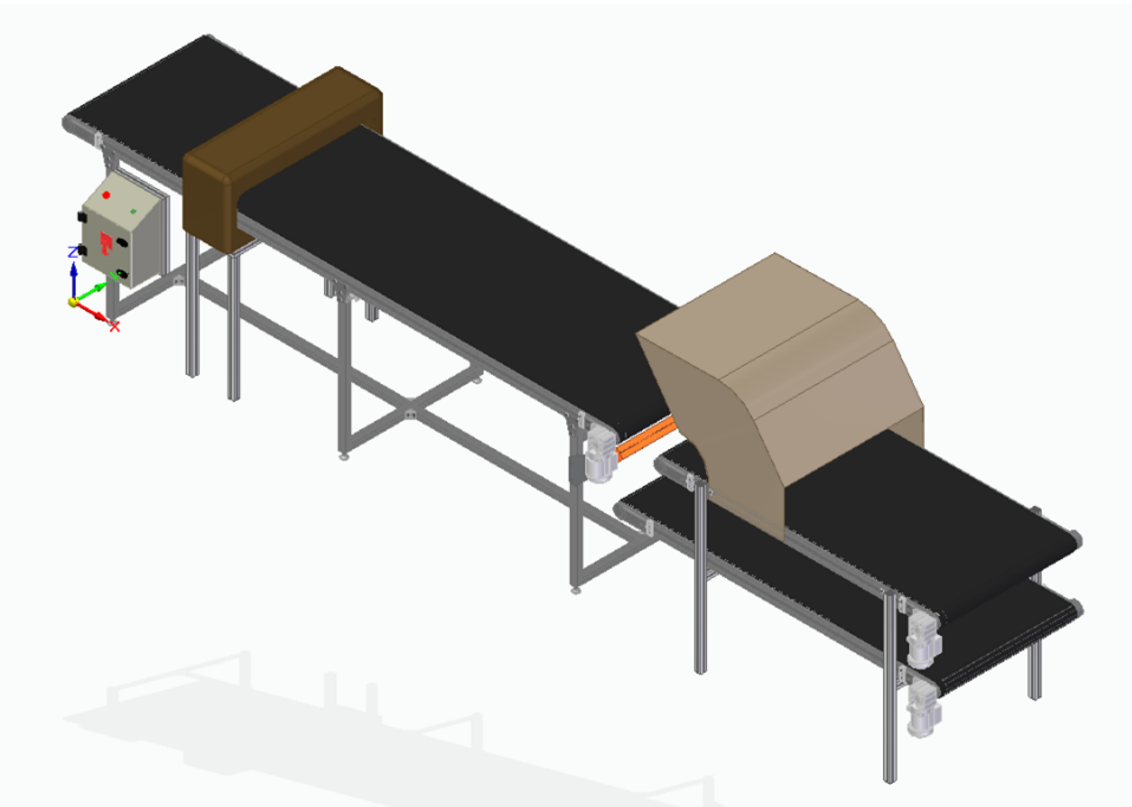

Figure 26. Conveyor line assembly. 3D model.

The productivity declared as a 2 ton per hour. Consider that the paper on the conveyor tape is already mechanically evenly distributed. The waste is spread on the conveyor tape. The common density of the paper (ρ) is in the range on 60 to 300 $\frac{\mathrm{g}}{\mathrm{m}^2}$ or, the average density (ρ_A) is about 180 $\frac{g}{m^2}$. The area of the sorted paper (S) is limited by 100 x 100 mm^2. The thickness or caliper (l) is taken from the lineboard average meaning which is defined as 0,000293 m, assuming that the paper on the conveyor line can be folded it is neccessary to use a coefficient f_1 in calculus, which is set as 3. Denoting mass as m and volume as V, we get

$$V = m/\rho_A = S\ x\ l \tag{6.1}$$

Mass of a single measure unit is

$$m_1 = S \cdot \rho_A \cdot f = 0{,}01 \cdot 180 \cdot 3 = 5{,}4\ \mathrm{g}\,.$$

Volume of a single measure unit is

$$V_1 = 0{,}01\ x\ 0{,}000293 = 0{,}00000293\ \mathrm{m}^3$$

Density is equal to

$$5{,}4[\mathrm{g}]\ /\ 0{,}00000293\ [\mathrm{m3}] = 1843\frac{\mathrm{kg}}{\mathrm{m}^3}.$$

Total volume per hour is

$$V = \frac{2000}{1843} = 1{,}09\ \mathrm{m}^3$$

Analyzing data and video recorders from the waste recycle facilities it is obvious that waste covers about 70% of the conveyor tape. Coefficient in this case is $f_2 = 0{,}7$

Since productivity is declared as 2 tons per hour, then covered area on the tape is calculated by

$$S_T = \frac{V}{l \cdot f_1 \cdot f_2}\ . \tag{6.2}$$

$$S_T = 1{,}09\ /\ (0{,}000293 \cdot 3 \cdot 0{,}7) = 146\ \mathrm{m}^2$$

Next parameters of the conveyor should be determined are the velocity (v) and the width (b) of the tape. Dependence of the speed and width can be expressed as:

$$v = \frac{S}{3600b}\ \left[\frac{m}{s}\right]. \tag{6.3}$$

The dependence of the speed and width is shown on the figure 1. The reasonable width of the conveyor could be taken $b = 1\,m$. With this width the speed will be equal $V = 0.5\ \mathrm{m/s} = 1.8\ \mathrm{km/h}$.

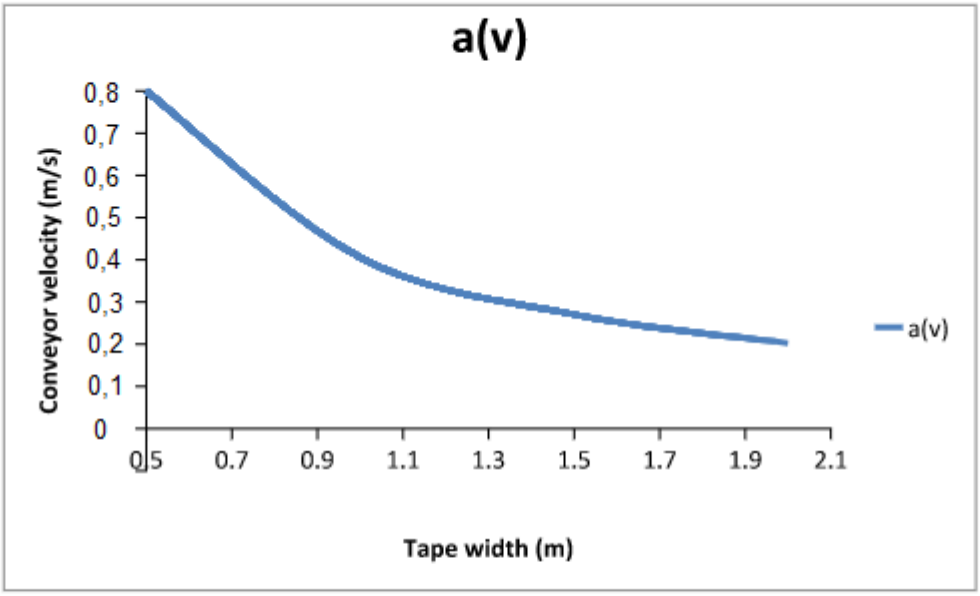

Figure 27. Tape width and velocity dependence

Figure 28. Sorting conveyor [8]

7.2 Conveyor traction force determination

Conveyors traction force is calculated by formula 6.3:

$$W_0 = \left(k \cdot L\left(g + g_c\right) + gH\right) f_3 + R_0\,, \tag{6.3}$$

where k is a resistance coefficient

$L = 4 \cdot \cos 0 = 4\ m$ - conveyor belt projection to horizontal plane

g – load force

g_c - load force from conveyors moving parts

f_3 - coefficient

h_t – conveying height

R_0 - unloader resistance force

$R_0 = 0$ due the fact it is missing in the scheme

Belt resistance coefficient is taken from the Table 1, $f_3 = 0.022$, assuming that the conveyor works in a heated room with a small amount of dust formed and normal humidity, and that the rollers are straight with bearings.

Table 6.1 Conveyor rollers

Type of roller support	Working conditions	Rollers	
		straight	groove
1	2	3	4
bearings	Dry and dustless	0,018	0,02
	Normal humidity, heated room, little amount of dust	0,022	0,025
	Unheated room or outside the room, big amount of adhesive dust, increased air humidity	0,035	0,04
	Very hard working conditions	0,04	0,06
bearings	Average conditions	0,06	0,065

Weight load per unit length is determined by the formula 6.4.

$$\mathrm{g} = 1000 \cdot A \cdot p_i\,. \tag{6.4}$$

where A – cross section of the waste on the conveyor, m^2.

For straight rollers with 0 degrees incline:

$$A = 0.05 \cdot B^2 = 0.05 \cdot l^2 = 0.05 \cdot 10^{-3}\ i^2\,,$$

from where

$$g = 1000 \cdot 50 \cdot 10^{-3} \cdot 1{,}5 = 75 \text{ kg.}$$

Load from the moving parts of the conveyor is calculated by formula 6.5:

$$g_c = 2$$

$$g_c = 2 \cdot g_b + \frac{m_r}{l_u} + \frac{m_r}{l_o}; \qquad (6.5)$$

where: g_b – load from the belt, kg/m;

m_r –mass of the rolling parts, kg;

l_u –step between the working rollers, m;

l_o –step between free rollers, m;

$g_b = 0{,}011(\delta_{0i} + \delta_1 + \delta_2) \cdot B$, N/m, or

$g_b = \frac{0{,}011}{9{,}81}(\delta_{0i} + \delta_1 + \delta_2) \cdot B$, kg/m,

where: *B* – belt width, mm; *i*- number of layers (*i*= 3); δ_1 и δ_2 - layer thickness; $\delta_0 = 1{,}2$ mm (for fiber with durability of 55N/mm – layer thickness);

From where:

$g_b = \frac{0{,}011}{9{,}81}(1{,}2 \cdot 3 + 3 + 1) \cdot 1000 = 8{,}57$ kg/m;

Mass of rolling parts is taken from table 2. With belt/ tape width of 1000mm and roller diameter equal to 65mm the mass of the rolling part will be m_r = 21,5 kg.

Table 6.2 Belt width

Belt width, mm	400	500	650	800	1000	1200	1400
Roller diameter, mm	50	50	50	65	65	65	82
Mass of rolling parts, kg straight groove	 6,0 10	 7,5 11,5	 10,5 12,5	 19 22	 21,5 25	 26 29	 40 50

From the table 3, due to the paper density of ($\rho_Í$ <2 tons/ m^3) and tape width (B = 1000 mm), we take the dimension between the working rollers as:

l_u = 1200 mm = 1,2 m.

Table 6.3 Gaps between rollers

Material density, t/ m^3	Maximum gap between rollers taking into account tape width, mm			
	400–500	650–800	1000–1200	1200–1600
Up to 1	1500	1400	1300	1200
2	1400	1300	1200	1100
3,15	1300	1200	1100	1000

The gap between spare / free rollers:

l_o=2·l_u=2·1,2 m = 2,4 m;

2m<l_o<3,5 m.

From where we get: $g_c = 2 \cdot 8{,}57 + \frac{10}{1{,}2} + \frac{10}{2{,}4} = 27{,}85$ kg/m.

Coefficient $m = m_1 \cdot m_2 \cdot m_3 \cdot m_4 \cdot m_5$, which are defined from the table6,5

Table 6.5 Conveyor variables

Coefficient	Conveyor variables	Meaning
1	2	3
m_1	Conveyor length 0-15 m 15-30 m 30-150 m More than 150 м	1,5-1,2 2,1 - 1,2 1,1 - 1,05 1,05
m_2	Straight conveyor / negative convex With positive convex: In head part In the middle part In the tail part	1 1,06 1,04 1,02
m_3	Head drive	1
	Drive situated in the middle or tail	1,05–1,08
m_4	Tail tightening station Middle tightening, having 7 drums	1 1-0,02

m_5	With unloading through head drum	1
	With motorized unloading cart in case of single drum	1,3

With conveyor length of 4m m_1= 1,2.

Conveyor is straight m_2 = 1.

Conveyor has a head drive m_3 = 1.

Tightening station - tail (1 drum) m_4= 1.

Unloading accomplished through head drum m_5= 1.

$m = 1,2 \cdot 1 \cdot 1 \cdot 1 \cdot 1 = 1,2$.

In result calculating conveyor traction force:

$W_0 = [0,022 \cdot 4 \cdot (75 + 27,85) + 3,75 \cdot 0] \cdot 1,2 + 0 = 10,86$ kg.

7.3 Defining drive and tightening drum dimensions

$$D = a \cdot i \text{ ; } d = 0,8 \cdot D.$$

where: D and d - diameters in mm;

D – drive drum diameter;

d – tightening drum diameter;

i — gasket or layer number which should be proven by formula 6.6:

$$i \geq \frac{S_{max} \cdot n_0}{K_\rho \cdot B} \quad (6.6)$$

a– coefficient;

S_{max} – maximum static tape tension, kg;

n_0 – tape nominal margin of safety;

K_ρ – gasket threshold strength, kg / cm

B– tape width, cm.

From the table 4 for the belt type Y taking coefficient:

a =30

Table 6.6 Belt types

Belt type	a
X Y W WH WL	30-35 30-35 35-40 70-80 40-50

From the table 5 with gasket number (/ = 3) nominal safety margin is n_0 = 9.

Table 6.7 Safety margins

Gasket number	1-4	5–9	9–11
Nominal safety margin	9	10	10,5

The maximum strength at break is taken from table 6 for the belt type Y = 55 kg / cm.

Table 6.8 Belt strength limits

Belt type	Strength limit per 1 cm width of the tape in one gasket, kg / cm
X Y	 55-65
W	67
WH	109
WL	75

Maximum static tape tension is calculated by formula 6.7:

$$S_{max} = K_S \cdot W_0 , \qquad (6.7)$$

where K_S - is a function from the friction coefficient between drum and a tape μ

and from the corner of gripping area with the drum. Let the surface of the drum lined with rubber and covered with dry dust. Then, according to the table 7 taking μ = 0,3. With gripping area angle between drum and tape equal 180°

then K_S =2,65.

Table 6.9 Surface materials

Drum surface material	Density	Coefficient
Steel	Very wet wet dry	0,1 0,2 0,3
Wood, rubber	very dry wet dry	0,15 0,25 0,4

Coefficient μ	K_s gripping angle		
	180°	200°	225°
0,15	1,5	1,42	1,35
0,25	1,85	1,73	1,61
0,30	2,65	2,46	2,26
0,4	2,86	2,27	2,1

From where $S_{max} = 2{,}65 \cdot 10{,}86 = 28{,}78$ kg.

$$i = \frac{S_{max} \cdot n_0}{K_\rho \cdot B} = \frac{28{,}78 \cdot 9}{55 \cdot 100} \approx 0{,}4 < 3$$

Calculation shows that, *i* = 3 suits the safety needs.

Drum diameters:

$D = 30 \cdot 3 = 90$ mm $\qquad$ $d = 0{,}8 \cdot 90 = 72$ mm.

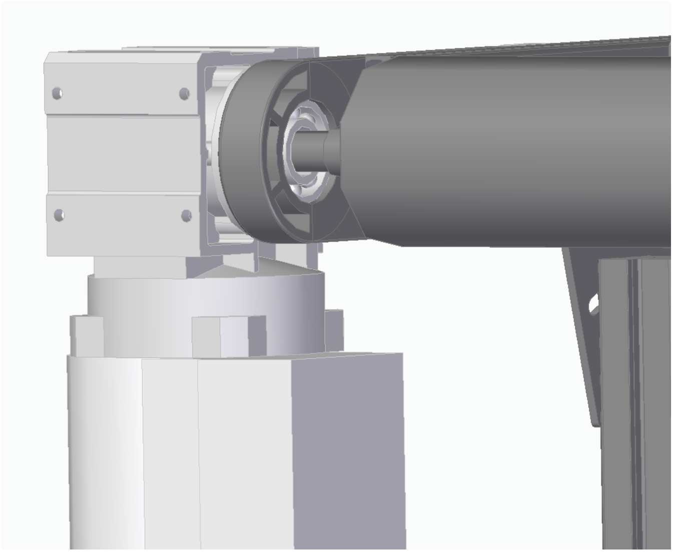

Figure 29. Tractive drum and motor reducer.

7.4 Defining motor power

Motor power required to operate the conveyor in a given state is calculated according to the formula 6.8:

$$P = \frac{K \cdot P_0}{\eta}, \text{ kW} \qquad (6.8)$$

where: K = 1,1–1,4 - coefficient taking into account the working conditions of the conveyor;

In average conditions K = 1,25;

η–drive efficiency; η = 0,6- 0,85;

Taking η = 0,85.

Power on drive shaft, kw, calculated by formula 6.9:

$$P_0 = \frac{W_0 \cdot \eta}{102 \cdot \eta_d}, \qquad (6.9)$$

where $\eta_d = \dfrac{1}{1 + \omega_d (2K_S - 1)}$

ω_d = 0,04 – drum resistance coefficient.

Then $\eta_d = \dfrac{1}{1 + 0{,}04\ (2 \cdot 2{,}65\ - 1)} = 0{,}85$ - drum efficiency.

Power on drive shaft: $P_0 = \frac{10{,}86}{102 \cdot 0{,}85} = 0{,}13$ kW

Desired motor power: $P = \frac{1{,}25 \cdot 0{,}13}{0{,}85} = 0{,}2$ kW

7.5 Selecting and calculating a gear motor

When choosing a specific model of the geared motor, the following specifications are taken into account:

- Type of reducer;
- power;
- Output speed;
- Gear ratio;
- The design of the input and output shafts;
- Type of installation;
- additional functions.

Structurally, the gearboxes are divided into the following types:

- Worm single-stage with cross-linked input / output shaft (angle 90 degrees).
- Worm two-stage with perpendicular or parallel arrangement of the axes of the input / output shaft. Accordingly, the axes can be located in different horizontal and vertical planes.
- Cylindrical horizontal with a parallel arrangement of input / output shafts. The axes are in the same horizontal plane.
- Cylindrical coaxial at any angle. The axes of the shafts are in the same plane.
- In the conical-cylindrical gearbox, the axes of the input / output shaft intersect at an angle of 90 degrees.

The location of the output shaft in space is of decisive importance for a number of industrial applications. The design of worm gearboxes allows to use them at any position of the output shaft.

The use of cylindrical and conical models is often possible in the horizontal plane. With the mass-dimensional characteristics identical with worm gearboxes, operation of cylindrical units is economically more expedient due to an increase in the transmitted load by 1.5-2 times and high efficiency.

For our case the reducer is used in horizontal plane, which makes special shape unimportant, and efficiency would be preferred. Unless before making the final choice one needs to calculate the gear ratio.

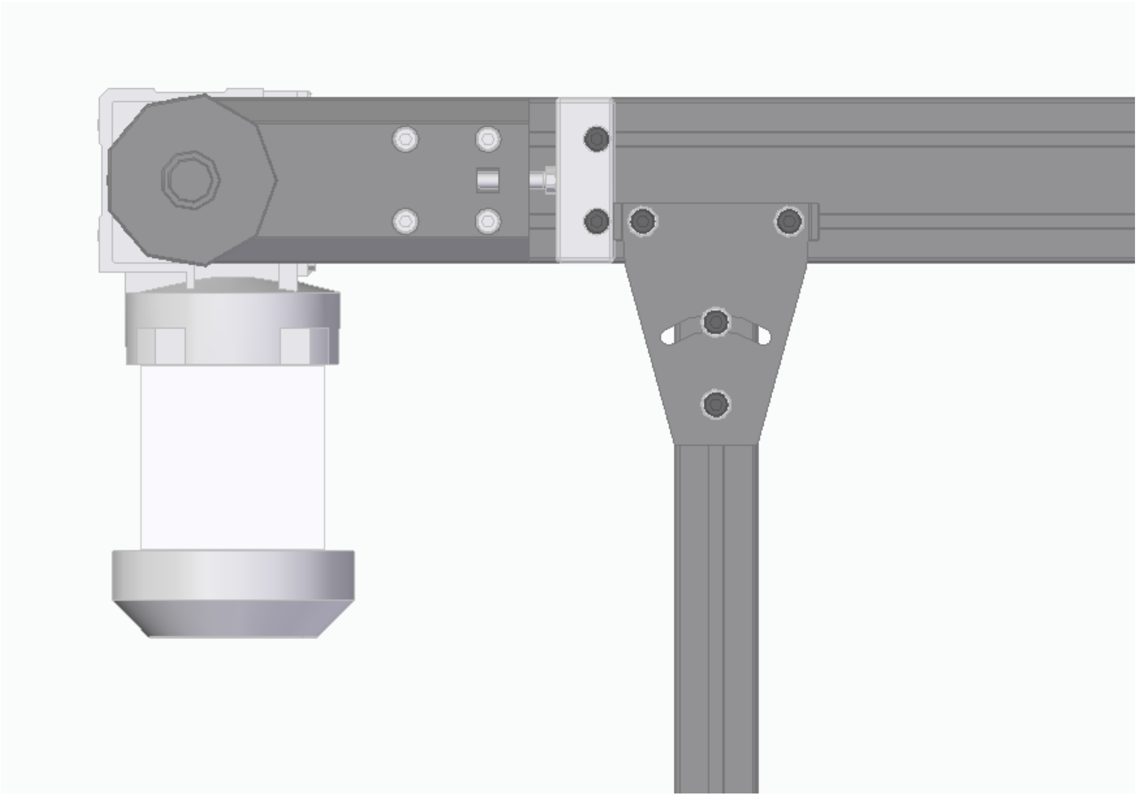

Figure 30. Possible orientation of the motor.

The gear ratio is calculated using the formula 6.10:

$$I = N_1 / N_2 . \qquad (6.10)$$

Where

N1 - shaft rotation speed (rpm) at the input;

N2 - shaft speed (rpm) at the output.

As soon as conveyor speed is 0,5 m/s and traction shaft diameter 80 mm, then traction shaft rotation speed should be 0,5•60/(0,080*П) = 119,4 rpm. The electrical motor shaft rotation speed is 1500 rpm. Therefore:

I = 1500/119,4 = 12,56

The value obtained in the calculations is rounded to the value specified in the technical specifications of a particular type of gearboxes.

Table 6.10 Gearbox types and ratios

Gearbox type	Gear ratios
Worm single-stage	8-80
Worm-type two-stage	25-10000
Cylindrical single-stage	2-6,3
Cylindrical two-stage	8-50
Cylindrical three-stage	31,5-200
Conical-cylindrical single-stage	6.3-28
Conical-cylindrical two-stage	28-180

From the above mentioned one can see that suitable type of gearbox can be Worm single-stage, Cylindrical two-stage, Conical-cylindrical single-stage. For our purpose the preferable is the one with better efficiency.

The torque on the output shaft [M_2] is the torque on the output shaft. The nominal power [Pn], the safety factor [S], the estimated operating time (10 thousand hours), the efficiency of the gearbox are taken into account.

Nominal torque [Mn_2] is the maximum torque for safe transmission. Its value is calculated taking into account the safety factor - 1 and the operation time - 10 thousand hours.

The maximum torque (M_2max) is the limiting torque maintained by the gearbox under constant or varying loads, operation with frequent starts / stops. This value can be treated as an instantaneous peak load in the operating mode of the equipment.

The required torque [Mr_2] is the torque that meets the customer's criteria. Its value is less than or equal to the rated torque.

Rated torque [Mc_2] is the value required to select the gearbox. The calculated value is calculated using the following formula 6.11 [11]:

$$Mc_2 = Mr_2 \cdot Sf \leq Mn_2 \tag{6.11}$$

Where:

- Mr_2 - the required torque;
- Sf - service factor (operational factor);
- Mn_2 is the rated torque.

The service factor (Sf) is calculated by the experimental method. The calculation takes the type of load, the daily duration of work, the number of starts / stops per hour of operation of the geared motor. The operational coefficient can be determined using the data in next Table "Parameters for calculating the operating ratio".

Table 6.11 Exploitation coefficients

Type of load	Number of starts in an hour	Exploitation time during a day			
		0-2	2-8	9-16	17-24
Smooth load, static exploitation regime, medium mass acceleration	0-10	0,75	1	1,25	1,5
	10-50	1	1,25	1,5	1,75
	80-100	1,25	1,5	1,75	2
	100-200	1,5	1,75	2	2,2

For our case it would be the lowest start number during an hour, and exploitation time 24 h a day, which means Sf is 1,5.

Correctly calculated power of the drive helps to overcome the mechanical frictional resistance that occurs with rectilinear and rotational movements. The elementary formula for calculating the power [P] is the calculation of the ratio of force to speed.

In the case of rotational motions, the power is calculated as the ratio of the torque to the number of revolutions per minute:

$P = (M \cdot N) / 9550$.

Where
M - the twisting moment;
N is the number of revolutions per minute.

The output power [P2] is calculated by the formula 6.12:

$$P2 = P \cdot Sf . \qquad (6.12)$$

Where
P - power;
Sf is the service factor (exploitation ratio).

The value of the input power must always be higher than the value of the output power, which is justified by the loss in meshing: $P1 > P2$

The required power for tractive shaft on the conveyor is 0,13 KW according to calculation brought in chapter 1.4.

According to the technical offer the most suitable and cost effective solution for our case would be the Bonfiflioli C - Helical Gear motor Type C 05 2. (Figure 31)

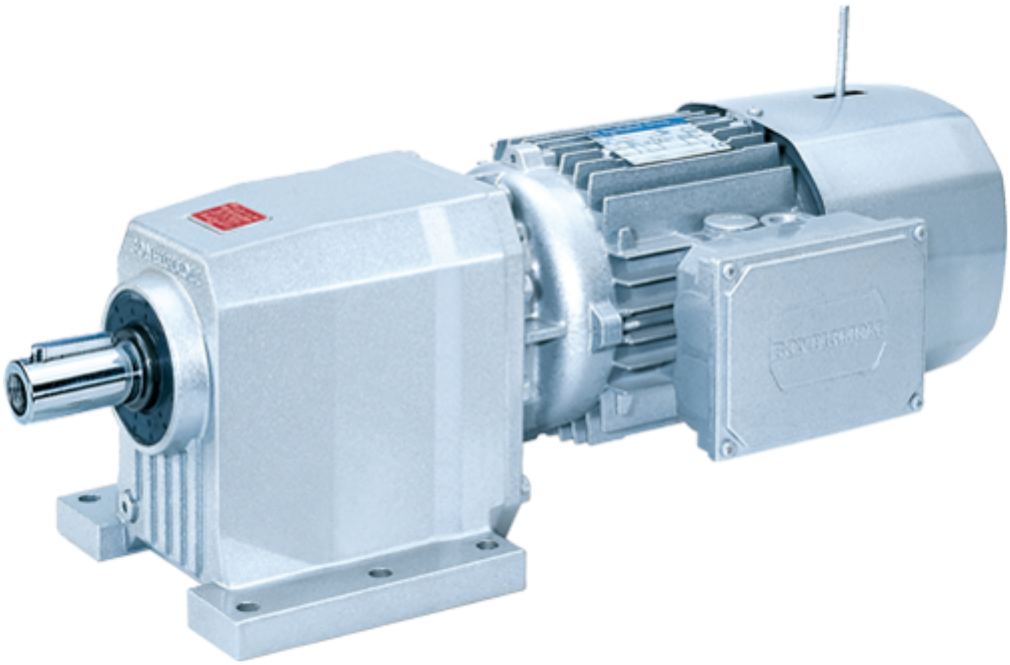

Figure 31. Bonfiglioli Helical Gear motor Type C05.

According to the specification its dynamic efficiency of mechanical gear

$$\eta_d = \frac{P_2}{P_1} \cdot 100 \qquad [\%]$$

Is 95%, as for single stage mechanical gear.

8. MATERIAL RECOGNITION MODULE

To get the final overview of the initial expenses and check the availability of material recognition module solutions author inquired for a ready-to-use solution from multiple companies over the world. The companies who gave response to the inquiries were:

- Bibus Menos Sp. Z o.o.(Poland) –

Offered price: 3550 EUR

Price contains:

- Set of recognition sensors
- Power supply block
- Frames
- Microprocessor
- Software
- Signal convertor
- Wiring diagrams
- Warranty 1 year

- Titoma (Taiwan)

Offered price: 4500-5500 USD

Price contains:

- Optical recognition sensors
- Frame
- Microprocessor
- Software

- Concurrent Design Inc

Offered price 12000 USD

Price contains:

- Inductive sensor
- Optical sensor
- Infra-red sensor
- Microprocessor
- Software
- Signal convertor
- Wifi signal output

9. SAFETY SYSTEMS

In Estonia the safety requirements for machines are settled by the Equipment Safety Act [9], which applies the regulations of Directive 2006/42/EC that amended Directive 95/16/EC. For the type of equipment, that is described in current thesis it has following requirements:

- Personnel working with any kind of equipment powered by electricity, and that uses compressed air over 0,5 Bar compression, must have competency to work with the specified equipment.
- The user of the equipment must ensure that there is no danger to human life and health, property or the environment. The user must take the necessary measures to prevent, identify, control and eliminate the risks of accident or negative consequences.

Therefore from author’s point of view it is necessary to install the safety barriers around the work zone of the conveyor line, to avoid unintended pass to the conveyor mechanism or the separation module. Also in case of unintended entrance to the working area occurs the safety system that would shut down the conveyor line and the separation module.

Multiple variants for that could be used:

1. “Security guiderails” (figure 32)

Figure 32. Security guiderails

Prices begin with 15 EUR/meter. Disadvantages: pieces of paper blown away from the conveyor can escape the machine work zone, therefore can be dangerous for the operators. Also does not stop any dust arising to the air form the separation module.

2. Transparent plastic or glass shields (figure 33)

Figure 33. Transparent plastic shields

Available at a median price of 75 EUR/meter. Advantages: closes the working area totally, no dust and no pieces of paper would pass out form the area. Provides protection against loud sound.

3. “Cage” (figure 34)

Figure 34. Cage

Available at price beginning with 45 EUR/meter. Prevents pieces of paper from exiting the working area, but do not provide protection against dust and loud sounds.

The automatic shut-down can be made using the usual motion sensors that would be scanning the borders of the working area. For additional safety emergency switches are placed in visible places along the conveyor, so that any operator or other worker could power off the plant in case of emergency.

CONCLUSION

Current thesis is written in 2017 spring. The main objective of thesis was to create a project for automatic paper waste separation system. Waste management is a highly demanded economic activity in today's society. Governments are taking multiple action to keep the environment and recycle as much materials as possible. Paper recycling is therefore even more important due to the fact, that it is being very widely used in all kind of packages, prints, etc.

The separation of paper can be made in many different ways. In today's European countries the bigger part of separation activities lie on the consumers and entrepreneur's, who separate their waste and put it into different containers. In fact, still some other materials are mixed with the paper, so the processing of it is not possible before the separation.

The author's idea is to separate paper according to its color, to keep the properties of paper for further processing. To achieve the objective author makes a wide background analysis of the existing systems and patents. The author studies a lot of different technical possibilities of the project implementation. As key aspects, the author considers working principles, economic indicators, the cost of implementation, initial investments in the project.

The paper consists of 8 chapters. First five chapters analyze the different possible solutions for the project including human-operated segregation, simple automated single line segregation system, high-end mechanical solution, high-end servo-electric manipulator solution, high-velocity air flow solution.

Based on the analysis and the economical calculations author finds, that the most cost-effective is high-velocity air flow solution. Its exploitation stays within 2000 EUR per year, and the initial investment for the solution is around 11170 EUR of expenses besides conveyor and material recognition module, which is significantly lower than any other proposed variant.

In the sixth chapter author designs a conveyor for the system, make the engineering calculations, and selects the main components for the conveyor. The seventh chapter gives an overview of prices for material recognition module. As soon as there are few companies with competency to build a material recognition module, the overview is small, and contains only the information provided by the companies. Therefore in case if project would be brought to realization, then it is always possible to find another companies with more competitive offers.

In the eighth chapter author brings out the required measures that have to be taken to meet the legal aspects of equipment building and exploitation.

As a result of current thesis author makes next conclusions:

1) High-velocity air flow is the most cost effective paper waste separation method.
2) Human operated separation is the less cost effective method, and should be used as few as possible to keep the waste management business profitable.
3) Mechanical and servo-electrical manipulator solutions are too complicated for use on the waste segregation facility, therefore are not really suitable.

Besides that current thesis contains ready-to-use technical information for conveyor solution and for high-velocity air flow separation module.

From authors point of view the objective of the thesis is achieved. For realization of current project additional studies show be made in the field of possibilities of waste preparation for automated segregation. Also at the moment the cost of conveyor remains unknown due to the fact, that it is a very big volume of work for a technologist to give a price offer for it.

Author would also like to point out the fact, that although in theory the solution seem to be the best, in practice other problems may occur, that could not be foreseen at this point of the project.

LÜHIKOKKUVÕTTE

Käesolev lõputöö on kirjutatud 2017 aasta kevadsemestril. Töö põhiülesanne oli projekteerida automatiseeritud paberjäätmete sorteerimissüsteem. Jäätmekäitlus on tänapäeval oluline majandusharu. Riiklikul tasandil reguleeritakse jäätmekäitlust ja püütakse võimalikult palju materjale saata taaskasutusse. Paberi taaskasutus on sealjuures eriti oluline, kuna väga palju paberit kasutatakse pakendites, trükistes jne.

Paber sorteerimine saab toimuda mitmel võimalikul viisil. Tänapäeva Euroopa riikides suurim koormus jäätmete sorteerimises laskub inimeste ja ettevõtjatele, kes panevad jäätmeid vastava markeeringuga konteineritesse. Sellest hoolimata sattub ebasoovitud materjali ka paberi konteineritesse, ning seda ei saa otse taaskasutusse saata ilma sorteerimata.

Autori idee seisnes selles, et sorteerimine võiks toimuda paberi värvi järgi, et säilitada paberi visuaalsed omadused ümbertöötluseks. Eesmärgu saavutamiseks autor uurib olemasolevaid patente ja süsteeme. Sammuti autor uurib erinevaid võimalike tehnilisi lahendusi projekti teostamiseks. Võtmeaspektideks autor võtab tööpõhimõtet, majanduslike näitajaid, ekspluatatsiooni hinda, alginvesteeringut projekti.

Töö koosneb kaheksast peatükkist. Esimesed viis peatükki analüüsivad erinevaid tehnilisi lahendusi sorteerimisjaamale: inimeste poolt opereeritud, lihtsa automatiseerimisega ühe konveierliiniga, kõrgtehnoloogiline mehaaniline lahendus, servo-elektriliste manipulaatoritega lahendus, suruõhu lahendus.

Võttes aluseks tehtud analüüsi ja majanduslike arvutusi autor leiab, et kõige kuluefektiivsem lahendus on suruõhu lahendus. Selle ekspluatatsioonikulud jäävad umbes 2000 Eur piiridesse aastas, ja selle sorteerimismooduli alginvesteering (lisaks konveierliinile ja materjali tuvastusmoodulile) on vaid 5620 EUR.

Kuuendas peatükkis autor arendab konveieri nimetatud süsteemile, teeb tehnilisi arvutusi ja valib konveieri põhikomponente. Seitsmes peatükk annab kiire ülevaate materjali tuvastusmoodulite hindadest. Kuna firmasid, mis on võimelised valmistama materjali tuvastusmooduli on suhteliselt vähe, siis ka ülevaade on väike ja sisaldab vaid informatsiooni, mida firmad olid nõus jagama. Sellegi poolest autor leiab, et kui antud projekt hakatakse realiseerima, siis on võimalik leida konkurentseid pakkumisi paremate tingimustega.

Kaheksas peatükk tutvustab meetmeid, mida tuleb rakendada selleks, et täita masina ja seadmete ehituse ja käitamisega seotud õiguslike aspekte.

Lõputöö tulemusena autor teeb järgnevaid järeldusi:

1) Kõige efektiivsem meetod paberi sorteerimiseks on suruõhuga sorteerimine.
2) Inimeste poolt sorteerimine on kõige kulukam meetod, ning seda tuleks kasutada võimalikult vähe, et jäätmekäitlus äri tooks tulu.
3) Mehaaniline ja servo-elektriliste manipulaatoritega lahendused on liiga keerukad töötamaks jäätmekäitluses, mistõttu on ebapraktilised.

Lisaks eeltoodule lõputöö käigus on tekitatud kasutusvalmis tehnilist informatsiooni konveieri ja suruõhu sorteerimismooduli kohta.

Autori seisukohalt lõputöö eesmärk on saavutatud. Projekti realiseerimiseks oleks vaja täiendavalt uurida jäätmete ettevalmistust sorteerimiseks. Sammuti hetke seisuga on teadmata konveieri valmistamise hind, kuna selle teatamiseks peavad valmistaja ettevõtte tehnoloogid tegema omapoolseid arvutusi ja tegema hinnapakkumise.

Sammuti autor sooviks pöörata tähelepanu asjaolule, et kuigi teoorias võib see tunduda parim lahendus, siis praktikas võib selle juurutamisega olla seotud hulgaliselt probleeme, mida ei olnud võimalik mõistlikult eeldada käesolevas projekti faasis.

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APPENDICES