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Specialization:	Transport Engineering and Logistics
Report number:	2014.TEL.7833
Title:	**A study towards yield optimization for the Expanded Tobacco II process of Philip Morris Holland B.V.**
Author:	P. Tieleman

Title (in Dutch)	Een studie naar yield-optimalisatie voor het Expanded Tobacco II proces van Philip Morris Holland B.V.

Assignment:	Master thesis
Confidential:	Yes (until March 05, 2019)
Initiator (university):	Prof. dr. ir. G. Lodewijks
Initiator (company):	R. Haverkort (Philip Morris Holland B.V., Bergen op Zoom)
Supervisor:	Dr. ir. H.P.M. Veeke
Date:	March 05, 2014

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Supervisor (Company):	R. Haverkort	Specialization:	PEL
Professor (TUD):	Prof. dr. ir. G. Lodewijks	Report number:	2014.TEL.7833
		Confidential:	Yes until March 05, 2019

Subject: **A study towards yield optimization for the Expanded Tobacco II process of Philip Morris Holland B.V.**

Context

The main component of a cigarette is tobacco. Tobacco for cigarette production needs to comply with several requirements. In order to meet these requirements within the department Primary of Philip Morris Holland B.V., part of Philip Morris International, there are several tobacco manufacturing processes to cut the tobacco leaves and add moisture, sauce, semi-finished products and flavors. Philip Morris Holland B.V. has a historical background of frequently expanding the production capacity. During that period there was less focus towards waste reduction. Currently, market demands are decreasing whereby the demand for improving process efficiencies increases. The process generating the largest waste fraction within the Primary department is the Expanded Tobacco II process. The goal of this process is to stretch the tobacco cells in order to create a permanent volume increase of the tobacco. The input material of the process is preprocessed tobacco, i.e., cut rag tobacco. This cut rag tobacco gets impregnated with liquid CO_2 after which the impregnated tobacco is quickly heated to create a high internal cell pressure. This internal cell pressure forces the tobacco cells to stretch. Finally the temperature of the then expanded tobacco is reduced and moisture is added to meet the final product requirements. At several areas of the process waste, i.e., tobacco fines, is separated from the main tobacco flow. Within Philip Morris Holland B.V. no prior research has been made towards optimizing the tobacco yield within the Expanded Tobacco II process.

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Problem definition

Within the Primary department, part of Philip Morris Holland B.V., the tobacco manufacturing process that is generating the largest waste fraction is the Expanded Tobacco II process. Since tobacco is an expensive material, reducing waste is desired. Waste consist of tobacco dust, i.e., small size particles. These fines could not be added back to the final product since its particle size is not conform final product requirements. Currently the root causes of the several waste flows are not known. The aim of this study is to determine relevant areas for improvement and to quantify possible optimizations.

Assignment

Analyze the current Expanded Tobacco II process to identify possible optimizations concerning yield of the infeed tobacco. Investigate the root causes of the several waste flows and identify possible optimizations, taking into account the requirements of the final product quality.

Execution

1. Analyze the current processes according to the Delft Systems Approach
2. Determine the relevant areas for improvement and corresponding problems
3. Quantify possible process optimizations
4. Formulate the definite problem statement
5. Develop a control model for managing sufficient tobacco yield and waste control
6. Research and test possible process improvements towards increase of tobacco yield
7. Study relevant literature

The professor,

Prof. dr. ir. G. Lodewijks

The TU supervisor,

Dr. ir. H.P.M. Veeke

Abstract

In the tobacco industry, Philip Morris Holland B.V., part of Philip Morris International, is a cigarette manufacturing company. Within its Primary department tobacco leaves are pretreated in such a way to meet the requirements for cigarette production, which is done in the Secondary department. Tobacco pretreatment processes are: cutting, adding moisture, sauces, semi-finished products and flavors. One of the semi-finished products is expanded tobacco. The aim of a expanded tobacco production process is to stretch the tobacco cells in order to create a permanent volume increase. Tobacco expansion within Philip Morris Holland B.V. is accomplished by means of the Dry Ice Expanded Tobacco technology. In several process steps tobacco cells get impregnated with liquid CO_2, which together with the intercellular moisture reacts whereby CO_2-hydrate forms. After a impregnation cycle has been completed, the tobacco cells are quickly heated to a temperature of 300ºC. Due to the temperature increase, the CO_2-hydrate inside the tobacco cells disintegrates and causes enough gas, and as a result inner pressure, to stretch the cells to the desired volume. The hot expanded tobacco gets cooled down and finally moisture is added to meet the final product requirements. During the several process steps multiple tobacco waste flows, which consist of tobacco fines (dust), are separated from the main tobacco material flow. Since tobacco in general is an expensive material Philip Morris Holland B.V. has the demand for waste reduction.

Waste flows consist of small size tobacco particles. Within Philip Morris Holland B.V. tobacco is classified generally in three size classes: fine, intermediate and coarse size particles. Fine particles are not desired to be part of the final product flow. For this reason the tobacco waste flows cannot directly be minimized or added back. The root causes of the fraction of tobacco fines ending up as being several waste flows were not known. To determine relevant areas for improvement, the process has been evaluated by means of the Delft Systems Approach. At first the input and output flows were analyzed. Based on their particle size distributions, within the expanded tobacco process degradation, i.e., particle breakage, occurs. To locate root causes of tobacco degradation, at several specific chosen positions within the process tobacco samples have been collected. Those samples have been characterized by sieving analysis to obtain their particle size distributions. Based on the results of the sieving analysis, main causes of degradation are cause due to the clump breaker and the cold box conveying. The clump breaker crushes the impregnated (frozen) tobacco, whereby the harmonic mean particle size reduces by 35%. Inside the cold box the crushed impregnated tobacco is transported towards the expansion tower, where the tobacco gets heated for the actual expansion. During the conveyed transport in the cold box the harmonic mean particle size reduces by 3.3%. Since in the expansion tower tobacco expands in volume, with sieving analysis possible degradation could not directly be quantified.

Within the process there are multiple separate waste collection positions which are supposed to contain only tobacco fines. Each of the flows has been evaluated towards quantity and particle size distribution. Based on this analysis, each of the flows still contains a fraction of intermediate and

coarse size tobacco particles. When reducing tobacco degradation those particles would still end up as being waste, therefore possibilities to optimize waste flows should be studied.
In order to implement a sufficient control model towards tobacco yield and waste control, the system must be able to properly measure specific process parameters. At the current measurement devices deviations have been quantified. A monitoring dashboard has been created to enhance focus towards yield optimization by waste control. Yield monitoring has been improved by implementing a batch closure forecasting script which reduces the standard deviation over dry area yield results by 81%. Hereby actual deviations and possible problems are much quicker observable.
A mathematical model had been developed to calculate the relation between tobacco degradation and waste flow quantity and quality amounts. Results of the model are that the maximum yearly improvable final product tobacco quantities due to degradation would equal respectively for the crusher, cold box and expansion tower: 139×10^3kg, 3.09×10^3kg and 13.0×10^3kg. For the crushing process tests have been performed to quantify the influence of crushing rotational speed towards degradation. Also other crushing techniques, i.e., a vibratory screen crusher and a jaw crusher, have been evaluated. No significant improvements have been found to reduce degradation due to crushing. The root causes of tobacco degradation during the cold box conveying are traced back to the multiple transition points. Installing transfer chutes will reduce the amount of degradation. Degradation due to pneumatic conveying of tobacco inside the expansion tower can be reduced by replacing sharp radius bends by large radius bends.
When optimizing waste flows, most profitable are positions TP026, TP027 and TP028 which contain respectively 88.5%, 12.6% and 3.62% intermediate and coarse size particles. TP026 waste is toasted tobacco due to process startups and stops. It can be reduced by increasing the processing of batches of equal blend type in series. Positive tests have been performed to continuously sieve out larger size particles from the TP027 flow since directly minimizing is hampered due to taste related issues. The root cause of TP037 waste containing larger size particles is due to ineffectivity of the tangential separator, the device separating the expanded tobacco from the air flow after the expansion tower. By narrowing the tangential separator inlet the separating effectivity can be improved.

For improving control, it is advised to apply the batch closure forecasting script and to improve the effectivity of the measurement devices. It is recommended to test the proposed countermeasures towards tobacco degradation. Improving the crusher, cold box and expansion tower could yearly save up to respectively €625K, €14K and €59K. For optimizing the crusher it is recommended to further research the possibilities to reduce degradation during this process step. Enhanced focus on scheduling batches of equal blend type in series will reduce the fraction of TP027. It is advised to research the effect towards final product tobacco taste when TP026 tobacco is added back scattered over a full batch, profits are yearly up to €52K. By improving the tangential separator the total waste fraction can be reduced resulting in a yearly saving up to €23K. It is recommended to sieve out the intermediate and coarse size particles and adding them back by using the regular add-back route. Those savings would equal yearly up to €56K.

Abstract (Dutch)

Binnen de tabaksindustrie is Philip Morris Holland B.V., onderdeel van Philip Morris International, een prominente producent van sigarettenproducten. Binnen de afdeling Primary worden tabaksbladeren voorbewerkt om tabak te maken die geschikt is voor sigarettenproductie, wat op de afdeling Secondary wordt gedaan. Het voorbewerkingtraject bestaat uit het snijden van de tabaksbladeren, toevoegen van vocht, sauzen, halffabricaten en smaakstoffen. Één van de halffabricaten is geëxpandeerde tabak. Het doel van tabaksexpansie is het oprekken van de tabakcellen om zo een permanente volumevergroting te realiseren. Tabaksexpansie wordt binnen Philip Morris Holland B.V. bewerkstelligd middels de Dry Ice Expanded Tobacco technologie. Binnen diverse processtappen wordt tabak geïmpregneerd met vloeibare CO_2, wat samen met intercellulair vocht reageert tot CO_2-hydraat. Wanneer na een volledige impregnatiecyclus de tabak eensklaps wordt verhit naar een temperatuur van 300ºC ontbindt het CO_2-hydraat en wordt er een zodanige hoeveelheid intercellulair gas gevormd wat een hoge interne druk tot stand brengt die de tabakscellen uit doet rekken. Vervolgens wordt de warme geëxpandeerde tabak afgekoeld en wordt vocht toegevoegd om aan de producteisen te voldoen. Gedurende diverse processtappen komen afvalstromen tot stand. Dit houdt in fijne tabaksdelen die vanwege hun deeltjesgrootte niet meer geschikt zijn om terug te voeren naar de uiteindelijke productstroom. Daar tabak een dure grondstof is heeft Philip Morris Holland B.V. de focus liggen op procesoptimalisatie door afvalreductie.

Afvalstromen bestaan uit tabaksdelen van kleine grootte. Binnen Philip Morris Holland B.V. wordt de grootte van tabaksdelen in drie groepen geclassificeerd: fijn, middel en grof. Kleine delen zijn niet gewenst binnen de uiteindelijke productstroom. Daar de oorzaak achter de verscheidene afvalstromen niet bekend was is het proces geëvalueerd volgens methodieken uit de Delftse Systeemkunde. Dit om probleemgebieden te kunnen identificeren en kwantificeren. Om een kwantitatief oordeel te vellen zijn op specifiek bepaalde posities binnen het productieproces samples genomen welke middels zeefmetingen naar verdeling van deeltjesgrootte zijn geanalyseerd. Uit de resultaten bleek dat er tabaksdegradatie, i.e., opbreken van tabaksdelen, plaatsvindt. De processtappen die significant bijdragen aan degradatie zijn het crushen van geïmpregneerde, bevroren tabak middels de 'clump breaker' en transport van de geïmpregneerde tabak naar de expansietoren, waar de tabak verhit wordt. Door het crushen van de tabak reduceert de harmonisch gemiddelde grootte met 35%. Door transport bedraagt de reductie van grootte 3.3%. Daar in de expansietoren de tabak daadwerkelijk in grootte toeneemt, is middels zeefanalyse het effect van degradatie niet direct te kwantificeren.

Binnen het proces zijn diverse afvalstromen die verondersteld worden te bestaan uit slechts fijne tabaksdelen. Elk van de afvalstromen is geanalyseerd naar kwantiteit en kwaliteit. Kwaliteit in de zin van zeefanalyse. Uit deze analyse bleek dat elk van de afvalstromen naast fijne delen, ook een fractie middel en grove delen bevat. Wanneer procesmatige degradatie gereduceerd zou worden zouden deze delen nog steeds als afval afgevoerd worden, waardoor de mogelijkheden tot het optimaliseren van de afvalstromen onderzocht dienen te worden.

Voor het tot stand brengen van een toereikende controleomgeving dient het systeem in staat te zijn de benodigde parameters op een juiste wijze te meten. Uit onderzoek blijkt dat de huidige manier van meten afwijkingen teweeg brengt wat afbreuk doet aan de kwaliteit van controlemogelijkheden. Om afvalstromen in relatie tot tabaksopbrengst kwalitatief te kunnen monitoren is een dashboard ontwikkeld. Er was een hoge mate van spreiding over individuele resultaten van tabaksopbrengst. Met behulp van een script wat het batch-afsluitmoment voorspelt kan de standaardafwijking over de resultaten van tabaksopbrengsten met 81% worden gereduceerd. Hierdoor kunnen daadwerkelijke problemen sneller worden geïdentificeerd.

Er is een rekenkundig model ontwikkeld om de relatie tussen degradatie enerzijds, en kwaliteit en kwantiteit van afvalstromen anderzijds, te berekenen. Met behulp van dit model is aangetoond dat wanneer degradatie wordt gereduceerd er afval wordt bespaard. Respectievelijk bedraagt dit voor de crusher, cold box en expansietoren 139×10^3kg, 3.09×10^3kg and 13.0×10^3kg tabak. Ter reductie van degradatie door de crusher zijn diverse testen verricht. Zo is de invloed van rotatiesnelheid op degradatie onderzocht en zijn twee andere technieken, i.e., een trilzeef crusher en een kaakbreker, bestudeerd. Hierbij zijn geen significante verbeteringen ter vermindering van degradatie waargenomen. De oorzaken van degradatie in de cold box zijn herleid naar diverse valpunten bij bandovergangen. Het plaatsen van glijplaten zal hier degradatie reduceren. Degradatie in de expansietoren is terug te dringen door voor pneumatisch transport lange radius bochten in plaats van scherpe radius bochten te plaatsen.

Binnen de afvalstromen is het optimaliseren van stromen TP026, TP027 en TP037 het meest interessant. Deze stromen bevatten respectievelijk 88.5%, 12.6% en 3.62% delen van bruikbare grootte. TP026 afval bestaat uit getoaste tabak vanwege starts en stops in het proces. Het kan gereduceerd worden door batches van gelijke samenstelling opeenvolgend te produceren. Testen met positief resultaat zijn verricht naar het continu uitzeven van de bruikbare delen van de TP027 stroom, daar direct minimaliseren vanwege smaakgerelateerde eisen belemmerd wordt. De oorzaak van grotere tabaksdelen in TP037 is herleid naar een ineffectieve werking van de tangentiële separator, het apparaat wat tabak na de expansietoren van de luchtstroom scheidt. Het vernauwen van de invoeropening zal de separatie-effectiviteit vergroten.

Ter verbetering van controle binnen het systeem is het aan te raden batches af te sluiten middels het voorspellingsscript en de effectiviteit van meetinstrumenten te vergroten. Het is aanbevolen de implementatie van oplossingen voor verdere verlaging van degradatie te onderzoeken. Door het verbeteren van de crusher, cold box en expansietoren kan jaarlijks respectievelijk €625K, €14K en €59K bespaard worden. Juiste focus tijdens planning kan bijdragen aan reductie van TP026 afval. Het is aan te raden te onderzoeken wat de effecten zijn op smaak door TP026 afval verspreid over een batch toe te voegen, daar er jaarlijks €52K mee bespaard kan worden. Door de tangentiële separator te verbeteren kan er jaarlijks tot €23K bespaard worden. Het is aanbevolen TP027 afval continu uit te zeven, en de middel en grote delen terug te voeren middels de reguliere add-back route. Hiermee kan jaarlijks tot €56K bespaard worden.

List of Abbreviations

Abbreviation	Description
ASTM	American Society for Testing and Materials
CCV	Corrected Cylindrical Volume
CO_2	Carbon dioxide
Cut rag tobacco	Cut, pretreated tobacco (input of the ET process)
CV	Cylindrical Volume
DAY	Dry Area Yield
DIET	Dry Ice Expanded Tobacco
ET	Expanded Tobacco
ET1	Expanded Tobacco I process
ET2	Expanded Tobacco II process
GCO_2	Gaseous carbon dioxide
HARS	Humid Air Reordering System
LCO_2	Liquid carbon dioxide
NET	New Expanded Tobacco
OV	Oven Volatilities
PMH	Philip Morris Holland B.V.
PMI	Philip Morris International
QA	Quality Assurance
QSMP	Quality System Management Portal

Contents

1 Introduction

The aims of this chapter are to:

- *Introduce the material tobacco and its use in the Expanded Tobacco process.*
- *Describe the historical background of Philip Morris International.*
- *Describe the historical background and current characteristics of Philip Morris Holland B.V.*

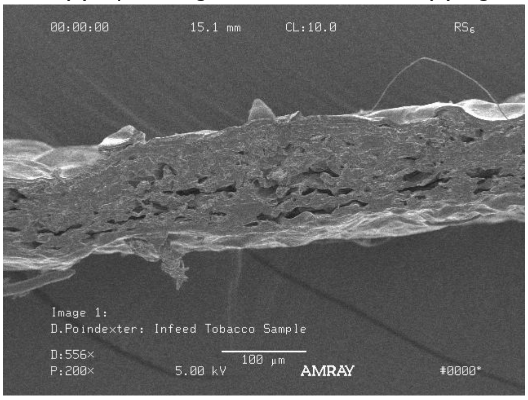
1.1 Tobacco

For cigarettes, a substantial component is tobacco. Tobacco is a product processed from the leaves of tobacco plants. Before tobacco can be used for cigarette production, it first needs to be prepared in several process steps to meet multiple requirements. Within the Philip Morris Holland B.V. factory, part of Philip Morris International, there are several different tobacco manufacturing processes. One of these processes is the expanded tobacco (ET) process. The aim of this process is to stretch the cells in dried tobacco leaves for creating a permanent volume increase.

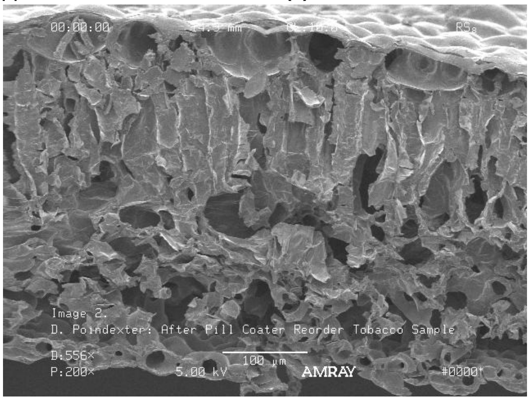
(a) A pile of cigarettes

(b) Cigarette upper sides

(c) Cut tobacco



(d) Dried tobacco cross section



(e) Expanded tobacco cross section

Figure 1.1: Multiple cigarette and tobacco examples

Processing at optimal effectivity related to source material usage, usable process output quantity equals input quantity. In practice there is a deviation in weight between process in- and output. The deviation could be a result either of input tobacco containing fines, or creation of fine, i.e., tobacco particle degradation, during the process which leave the system. In order to design possible optimization options, the root cause of waste flows needs to be found. For this an analysis of the production process is required.

1.2 Philip Morris International

The company Philip Morris was established in 1847 when Mr. Philip Morris opened a small shop in London, where he sold imported cigars. He later went on to sell handmade cigarettes as well. After 25 years, Philip Morris decided to expand his horizons and started exporting to the US. When machines were developed in the US to take over this production, the company established its registered office in America in 1902, under the name Philip Morris Corporation. The small shop expanded into a global company. Until 2008, the company was part of the Altria Group. From March 2008, Philip Morris International (PMI) separated from the Altria Group, while Philip Morris USA remained as an Altria Group division. PMI has been an independent company ever since.

The company covers the entire world, except the USA. The PMI headquarters is located in New York, the Operations Center is in Lausanne and the Research & Development center is in Neuchâtel. There are 56 factories in 35 countries, spread all over the world except the USA. Worldwide PMI has more than 78,000 employees.

PMI is the global market leader in the area of cigarettes. In 2011 its market share in the cigarettes market was 16.0%. The main competitors are British American Tobacco and Japan Tobacco International which had a market share of respectively 12.4% and 9.4% in 2011. That year, 7 of the PMI brands were in the global top 15 with PMI's brand Marlboro at number 1. Total revenues in 2011 were 76.3 billion dollars, which consists of 60% excise taxes, 23% operating costs and 17% operating income. That leaves 13.3 billion dollars, from which taxes must be deducted. Important markets are the European Union and Asia, with parts in total revenue equal to respectively 30% and 34%.

1.3 Philip Morris Holland B.V.

Philip Morris Holland B.V. (PMH) is part of PMI. The factory is located in Bergen op Zoom and it is the largest PMI factory. PMH has a Marketing & Sales department located in Berchem, Belgium. It all started in 1969 by taking over the Mignot & De Block factory in Eindhoven. One year later, the ITTC factory in Bergen op Zoom had also been takeover. In 1977 the decision was taken to concentrate production at Bergen op Zoom.

Figure 1.2: Aerial view of the PMH factory

A new factory was built next to the existing one. Over the years the factory underwent several major changes which provided the possibility to increase productions as shown in figure 1.3. The developed number of cigarettes, the total amount of cigarettes produced, is also shown in figure 1.3. The production volumes in 2011 totaled 85.4 billion cigarettes. Besides production of cigarettes, PMH also produces tobacco for other affiliates. The markets for which MPH produces have changed over time. The PMI Operations Center in Lausanne controls which factories are producing what volume for which markets.

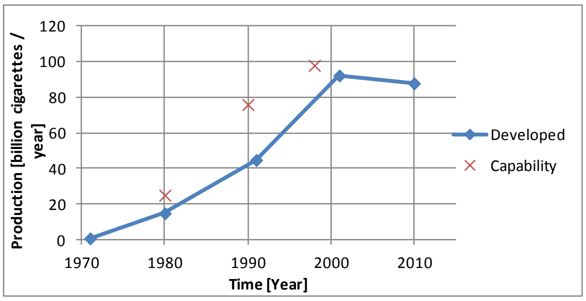


Figure 1.3: Historical capacity and production development

The biggest markets PMI produced for in 2011 are Japan (41.5%), Italy (19%), France (14.3%), Benelux (14.3%) and Spain (3.9%). In Bergen op Zoom, the factory has 1,400 employees.

PMH's production process consists of two main processes. First the process Primary, in which raw tobacco is processed into a mixture of cut tobacco's called cut filler. With different compositions of tobacco types and flavors the composition of cut filler changes. Different kinds of compositions are called blends. Secondly the process Secondary, in which the cigarettes are produced and packaged.

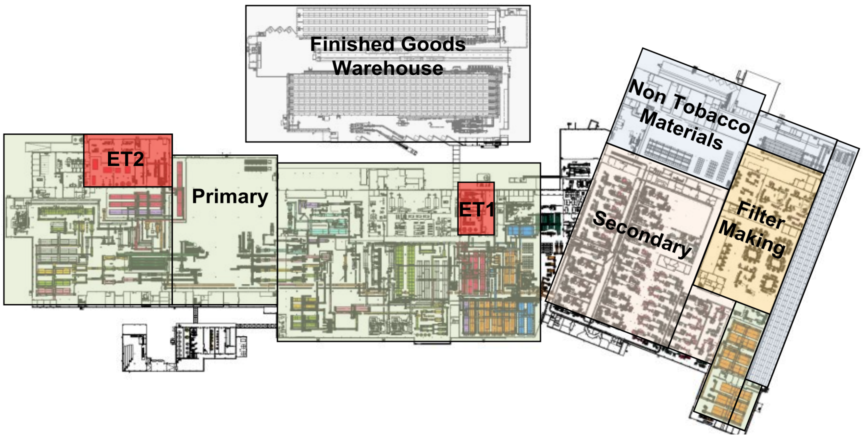


Figure 1.4: PMH departments overview

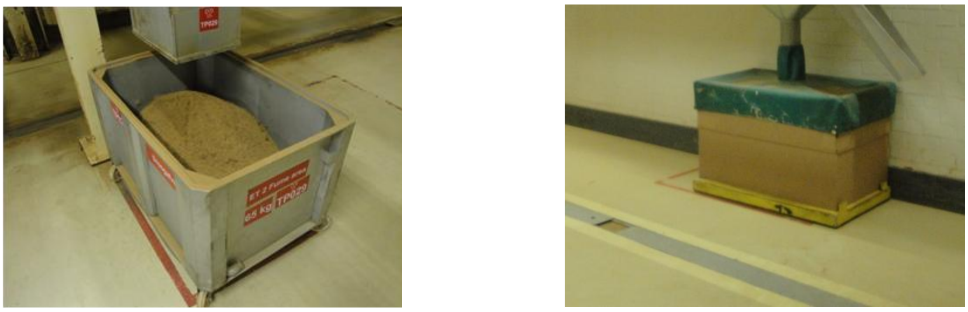
Within Primary, boxes filled with raw tobacco are transported on a daily basis from the tobacco warehouses, where it is stored and allowed to age. The warehouse contains a working stock of two days. There are four types of tobacco, Virginia, Orient, Burley and Homogenized. Each type of tobacco is processed by a separate sub-process. For every single production order boxes are brought together, unpacked and brought into the production process. The tobacco is loosened and the tobacco from the various boxes is mixed and cut. Moisture level and temperature are adjusted to the correct value, and sauces are added. The four types of tobacco are now mixed and processed further, including cutting the tobacco. Finally a number of semi-finished products are added, expanded tobacco, stems and ripper shorts.

Expanded tobacco (ET) is tobacco that has been put through a process that can be compared to making popcorn, the tobacco is expanded. Stems are the reusable stems of large tobacco leaves which are removed and crushed in de country of origin. Ripper shorts consist of tobacco obtained from the result of mistakes during the packaging process. Adding a last flavor is the final stage in creating the cut filler.

Within Secondary the actual cigarette production takes place. Filters are being manufactured and together with cigarette paper, tipping paper and cut filler from Primary, cigarettes can be put together. This is done by high tech machines capable of producing up to 18,000 cigarettes per minute. The cigarettes are then packaged in a packet, bundle and box. Finally the boxes are put onto pallets for storage in a warehouse. From there further distribution takes place by train, lorry, boat and sometimes even by plane.

1.4 First Impressions

As stated before, at several positions in the production process waste, i.e., tobacco dust, is being collected. This waste is stored in aluminum or cardboard boxes. Photos of examples are given below.



(a) Aluminum waste box (b) Cardboard waste box

Figure 1.5: Waste boxes

When having first talks with several employees, e.g., process operators, about possible root causes of tobacco dust their shared opinion is that the main cause would be tobacco degradation. Based on their opinions the largest contributors towards degradation would be (1) the process step in which a frozen clump of tobacco gets crushed, and (2) the process step in which tobacco gets cooled down and transported by a series of vibratory conveyors. Photos of both process steps are given below.

(a) Crushing process step (b) Vibratory conveyors

Figure 1.6: Expected degradation causing process steps

2 Expanded Tobacco

The aims of this chapter are to:

- *Introduce the concept of expanded tobacco.*
- *Describe the operation of a DIET plant.*
- *Describe the main challenges associated with source material usage.*

Tobacco entering the production plant has been dried for an amount of time. By drying, the tobacco volume decreases. The Expanded Tobacco (ET) process aims to increase the tobacco volume at a given firmness necessary for filling a cigarette, without an increase in dry weight. This is an interesting product transformation from the point of view of source material usage and transportation costs.

In the 1950s and 60s blend components were studied to increase rod firmness with no increase in rod weight. The first patent for a continuous expanded tobacco process was established in the early 70s. The main idea is to impregnate the tobacco cells with a certain substance, where by heating the tobacco the substance creates pressure inside the tobacco cells. This inner pressure stretches the tobacco cells. PM developed a process that used ammonium carbonate for impregnating the tobacco. During the mid-70s an expansion process was developed that used liquid CO_2. This process is called the DIET (Dry Ice Expanded Tobacco) process. Large scale production started in 1979. In the 70s and 80s several patents were established on the use of supercritical impregnating fluids. Through the early 90s, PM developed the NET (New Expanded Tobacco) process. In this process, the infeed tobacco gets impregnated by liquid CO_2. By expanding, the tar and nicotine level per volume decreases. This makes expanded tobacco applicable for light cigarettes.

The general steps for expanding tobacco cells by means of the DIET process are illustrated in figure 2.1. In this figure, (a) represents a tobacco cell to be expanded. The first step is to impregnate the tobacco cell with liquid CO_2 (b).

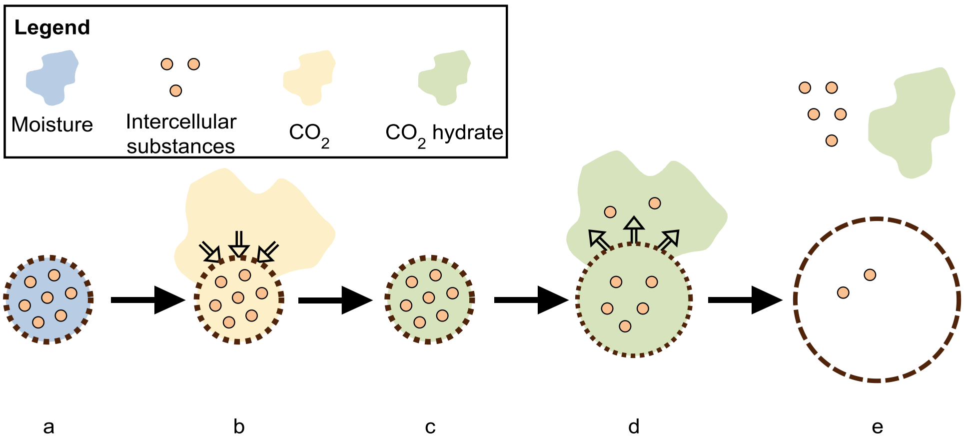


Figure 2.1: Tobacco cell impregnation and expansion

The intercellular moisture reacts with the CO_2 whereby CO_2-hydrate ($CO_2 \cdot nH_2O$) is formed (c). By heating the tobacco cell, the CO_2-hydrate turns into gas which creates an intercellular pressure. Due to this pressure the cell wall stretches and simultaneously the CO_2-hydrate and intercellular substances leave the cell (d). At the end, the tobacco cell has a stretched cell wall, i.e., volume increase, and less intercellular substances (e).

PMH has two DIET plants for expanding tobacco, Expanded Tobacco 1 (ET1) and Expanded Tobacco 2 (ET2). The ET1 and ET2 processes produce respectively ⅓ and ⅔ of the total volume. Both of the processes are fed with a blend prepared by the 'Expanded Tobacco line' (ET-line). Within this ET-line, boxes filled with a certain type of tobacco that are assigned to a specific order are removed from the warehouse. Each of these boxes contains a block of dried tobacco. In a number of steps the blocks are pulled apart, moistened, cut, sauced and mixed together for creating a homogeneous product. This is called cut rag tobacco. Depending on the ratio between different tobacco types, multiple blends can be created. For instance, blend B_1 contains 100% Virginia tobacco, while blend B_2 contains 90% Virginia tobacco and 10% Burley tobacco. A blend of cut rag tobacco produced at the ET-line is stored in a silo, from where it is fed to an ET process.

The process is running five 24-hours per week in a three-shift system. The first shift runs from Sunday 23:30 to Monday 7:30, the second shift 7:30 to 15:30 and the third shift from 15:30 to 23:30. Figure 2.2 shows the organizational structure of the process.

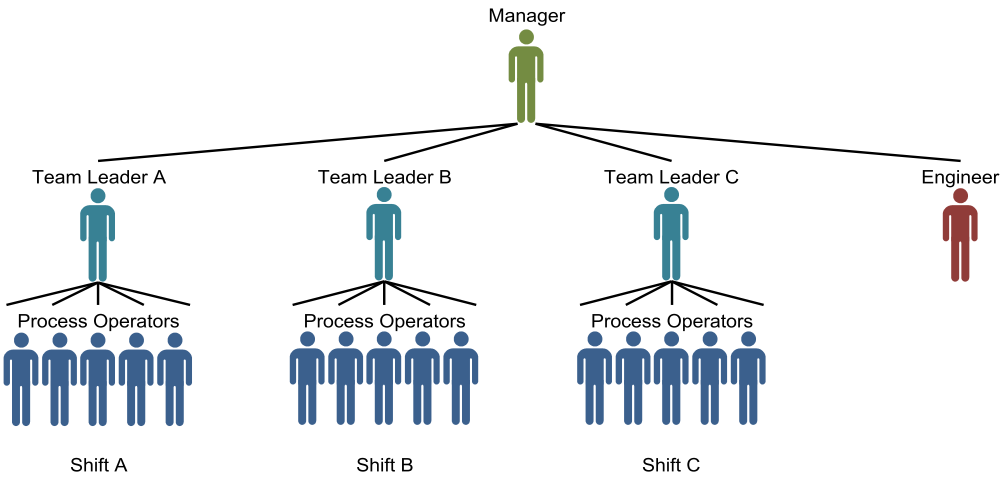


Figure 2.2: Expanded Tobacco organizational structure

The Manager is accountable for the process as a whole. Under his leadership, he manages an Engineer and thee Team Leaders, one for each shift. The Engineer is responsible for the management of technical problems and improvement projects. Every Team Leader is responsible for managing a group of Process Operators. Process Operators are accountable for performing the requirements of the process.

For expanding the tobacco by means of the DIET process at given conditions, the process consists of multiple process steps. Figure 2.3 shows a visual representation of the diverse process steps of PMH's ET2 process.

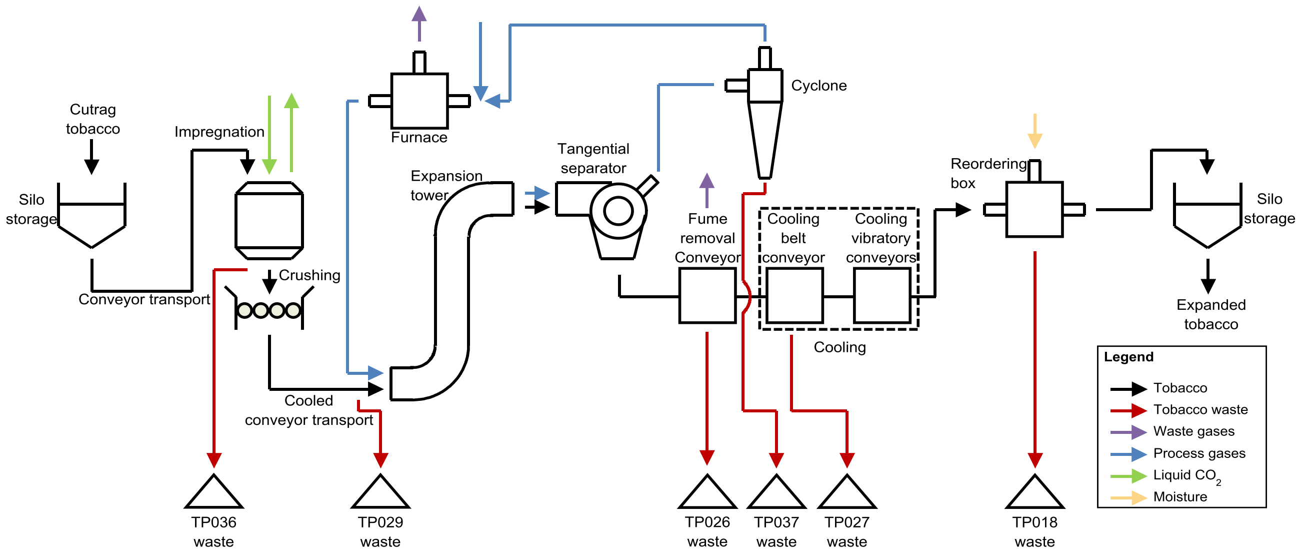


Figure 2.3: Visualization of the ET2 process steps and material flows

As visual in the figure, during processing several tobacco waste flows are separated from the main tobacco flow. These waste flows consist of tobacco dust, i.e., fine tobacco particles which are not desired to be part of the final product flow. If those fines are no part of the feed flow, then in case of optimal processing related to source material the waste flow fractions would equal zero. During 2012 the dry area yield, i.e., the effectivity of tobacco usage equaled 95.6% at the ET1 process and 94.9% at the ET2 process.

3 Problem Analysis

The aims of this chapter are to:

- *Introduce the concept of the Delft Systems Approach.*
- *Describe the multiple analysis strata.*
- *Explain the sampling methodology used.*
- *Formulate the research questions stated after analysis.*

3.1 The Delft Systems Approach

The Delft Systems Approach aims to contribute to a quick but thorough understanding of operational problems. Its founder is Prof. Jan in 't Veld. It has a certain systematic way of thinking about problems, provides a better understanding and insight, and is a tool that can lead to a higher level of abstraction regarding specific situations. The approach makes a logical systematic combination of quantitative and qualitative modeling. In 2007 Veeke, Ottjes and Lodewijks extended the theory with a by in 't Veld approved view of behavior modeling. [1]

3.2 The Expanded Tobacco Process: a Black Box Approach

To get better insight in the functions that are performed within the process it is modeled as a black box, a system without known properties. Only the input and output flows of the system are known. The black box model for the ET2 process is shown in figure 3.1. The model contains multiple in- and outputs.

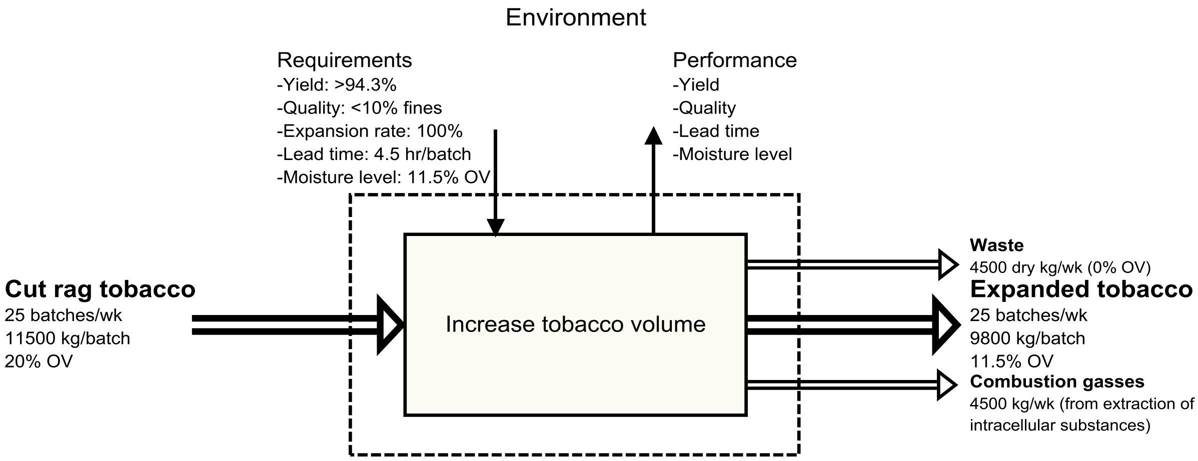
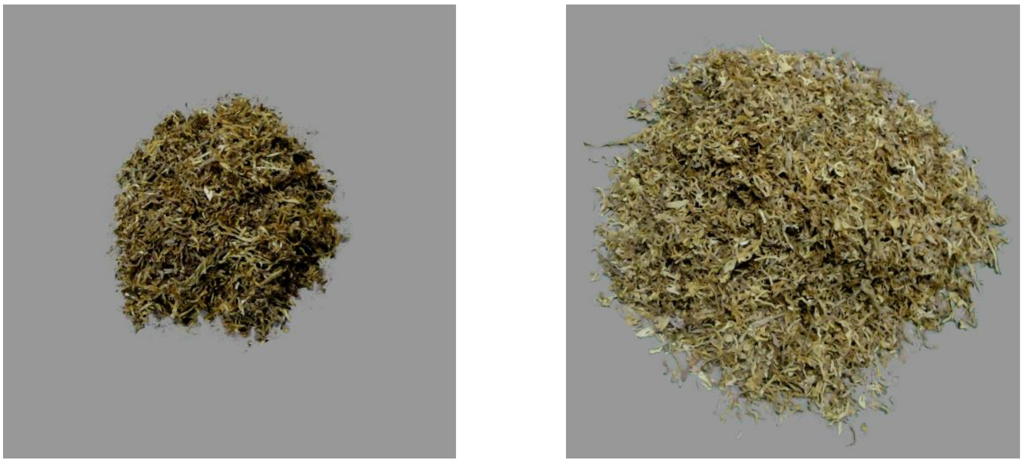


Figure 3.1: Expanded tobacco black box model

Cut rag tobacco enters the system as a material input flow. Expanded tobacco, tobacco waste, and combustion gasses leave the system. Pictures of cut rag tobacco and expanded tobacco are shown in figure 3.2. As can be seen, due to the transformation process the tobacco expands in volume. Within the model the environment imposes requirements and receives the performance of the system.



(a) Input material: cut rag tobacco (b) Output material: expanded tobacco

Figure 3.2: Expanded tobacco process input and output material

From the input and output flows, the transformation inside the black box can be derived and can be described as 'expand tobacco'. In order to execute this function an order flow, a resource flow and support material flow is required. Incoming processing orders are processed and this provides tasks for the 'expand tobacco' function. This means in practice that based on an internal scheduling scheme, the system starts the process to expand a certain batch of cut rag tobacco. In order to make execution possible, several resources such as employees and pallet trucks are required. These three aspects are modeled in a PROcess PERformance model, also called PROPER-model, shown in figure 3.3. A PROPER-model shows different aspect flows, their interrelations and the function control of a system. [1, p101-102]

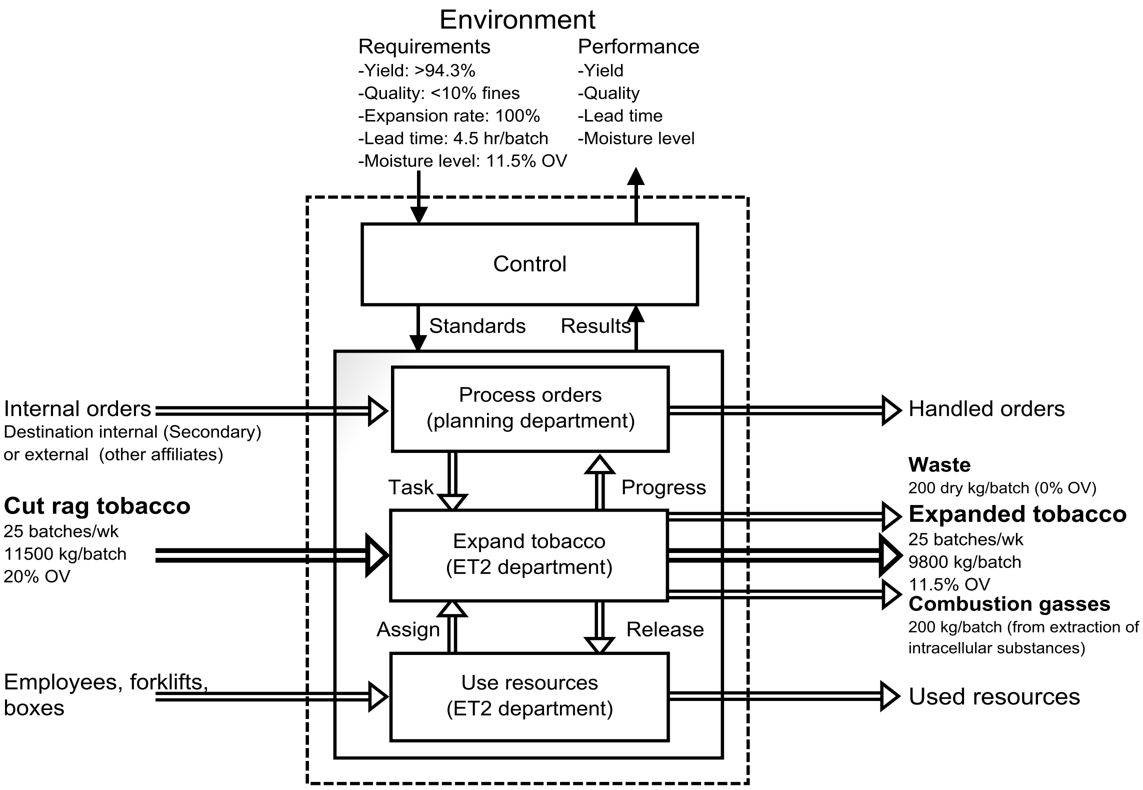


Figure 3.3: Expanded tobacco PROPER model

When a task is derived from an order, the subsystem 'expand tobacco' receives a task from the subsystem 'process orders' and it receives the required resources from the subsystem 'use resources'. When a certain batch of cut rag tobacco is expanded, the expanded tobacco leaves the system, which is represented by the arrow at the right of the model. Both handled orders and used resources also leave the system. The performance of the system as a whole is monitored and controlled by a controlling function. This so called 'function control' measures results from the system and requirements from the environment. Based on this information it provides standards to the system. Performance of the system as a whole is presented to the environment.

In chapter 2 problems concerning the dry area yield of the ET2 process are described. Dry area yield is a performance indicator of the system as a whole. In this chapter, the functions which influence dry area yield are analyzed in order to find improvement opportunities. First, the 'expand cut rag tobacco' function will be further analyzed.

3.3 The Expanded Tobacco Process: a High-Level Steady State Approach

Within the 'expand tobacco' subsystem of the PROPER-model in figure 3.3 the actual tobacco expansion which determines the dry area yield takes place. For further analyzing, this subsystem itself can be divided into several subsystems. Figure 3.4 shows a more detailed model of the subsystem 'expand tobacco'. According to the guidelines of the Delft Systems Approach the subsystem is modeled as a steady state model. [1, p62-65] The dashed lines separate the material flow from its function control and process control.

3.3.1 Steady state of the tobacco material flow

According to the Delft System Approach, a system is in a steady state when it displays behavior that is completely determined and repeatable in time, whereby the behavior in one interval is similar to the behavior in another interval. [1, p21] The ET2 process expands batches of tobacco in a repetitive way, so as shown in figure 3.4 the tobacco expanding flow is in a steady state. First the input and output flows and intermediate subsystems are explained. Second the process control and function control are explained.

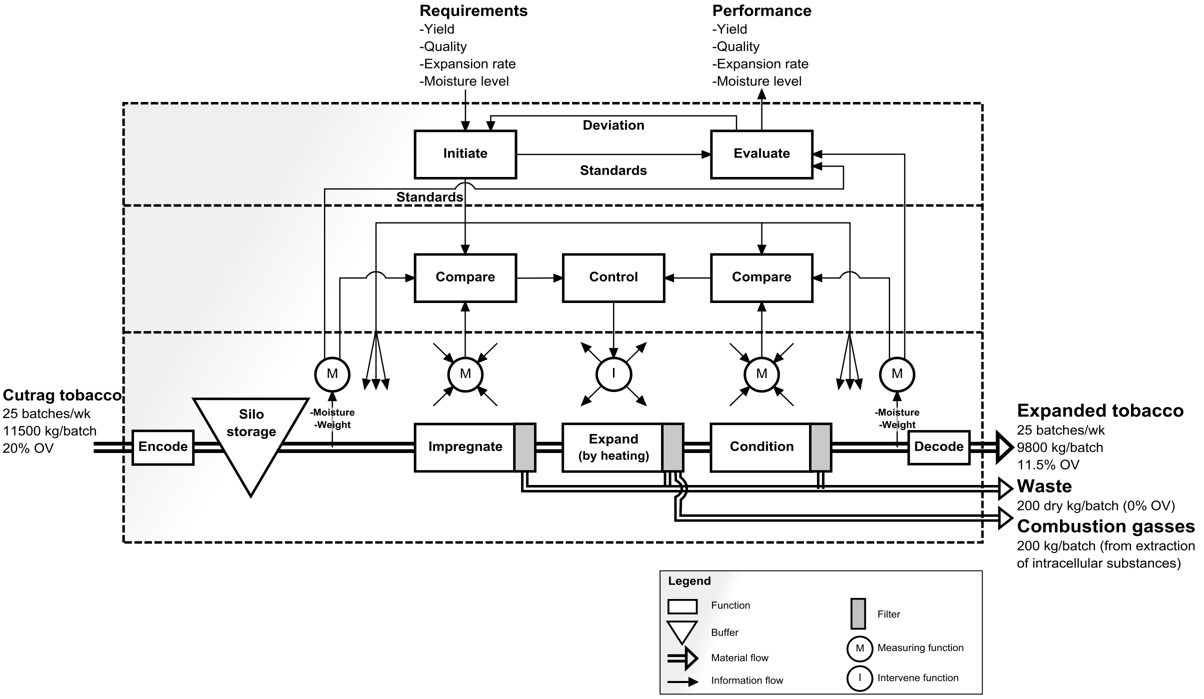


Figure 3.4: Expanded Tobacco high-level steady state model

3.3.1.1 Tobacco material flow

As an input of the model, a flow of cut rag tobacco and process supporting materials is entering the system. The cut rag tobacco flow consists of 11,500kg 20% OV (Oven Volatilities) cut rag tobacco batches of a certain blend composition. This quantity of weight results in a tobacco volume that equals storage volume of one input silo. Batches of cut rag are delivered during the workweek, five days a week in a three-shift system. The incoming batches enter a buffer, which is achieved by silo storage. Figure 3.4 shows cut rag tobacco entering a silo, ready to undergo the expanding process.

3.3.1.1.1 Silo storage

Within the store buffer, incoming cut rag tobacco batches are stored for an amount of time. The output of the buffer contains an equal amount of dry tobacco, but the moisture level may have been changed by moisture exchange with the environment. Tobacco leaving the silo storage for entering the impregnate function should have a moisture level of ~20% OV.

3.3.1.1.2 Impregnate function

In the impregnate function cut rag tobacco together with liquid carbon dioxide (LCO_2) is transformed into impregnated tobacco. Together with the intercellular moisture the LCO_2 reacts into carbon dioxide hydrate ($CO_2{\cdot}nH_2O$). The output flow of the impregnate function is a flow of impregnated tobacco, ready to be expanded in the expansion function.

3.3.1.1.3 Expand function

During the expand function, impregnated cut rag tobacco is through heating transformed into hot (~100°C) expanded tobacco at ~3.5% OV. The tobacco volume increase is achieved by stretching the tobacco cells with intercellular pressure created by quickly turning the CO_2-hydrate into gas.

3.3.1.1.4 Condition function

In the condition function the hot expanded tobacco is transformed to conditioned expanded tobacco. Meaning that undesired fumes are removed, temperature is reduced to ~30°C and moisture level is increased to a value of ~11.5%.

3.3.1.2 Control of the system

3.3.1.2.1 Process control

To control the process there is a process control system. Data from several measuring points along the material flow is compared to standards, from which a deviation is determined. Depending on this deviation the process can be controlled by interventions at several locations.

3.3.1.2.2 Function control

For controlling the process and its process control, the system contains function control. Output of the process is monitored and is compared to requirements from the environment. In order to meet these requirements, standards can be adjusted. Performance of the system is presented to the environment.

Related to tobacco quantity and quality the used performance indicators are listed below. The frequency of measuring and monitoring can differ per indicator.

Performance indicator	Monitoring frequency	Monitored by
Dry Area Yield	Shift level (single batch figures)	Supervisor(s) and Process Operators
	Daily	Supervisor(s) and Manager
	Weekly	Supervisor(s) and ET Manager
	Monthly	ET Manager
	Yearly (average)	General management
Tobacco waste	Weekly	Supervisor(s) and ET Manager
	Monthly	ET Manager
	Yearly	General Management
Particle size distribution	Monthly	Process Engineer
Cylindrical volume and expansion rate	Monthly	Process Engineer

Table 3.1: Relevant performance indicators

These relevant process performance indicators will be clarified and explained in the following subsections.

3.3.1.2.2.1 Dry Area Yield

At the input side of the expanded tobacco process the tobacco is weighted by a weighing belt, and the amount of oven volatilities (OV) is determined by a moisture meter. Both measurements are also carried out at the output side of the process. With those four measurement results, the performance indicator Dry Area Yield (DAY) is calculated:

$$Dry\ Area\ Yield = 100\frac{Final\ tobacco\ weight\left(\frac{100 - OV_{final}}{100}\right)}{Cutrag\ tobacco\ weight\left(\frac{100 - OV_{cutrag}}{100}\right)} \tag{3.1}$$

Calculating the DAY is done for each single batch. An example of the dry area yield DAY per batch is shown in the figure below, from week 11 2013.

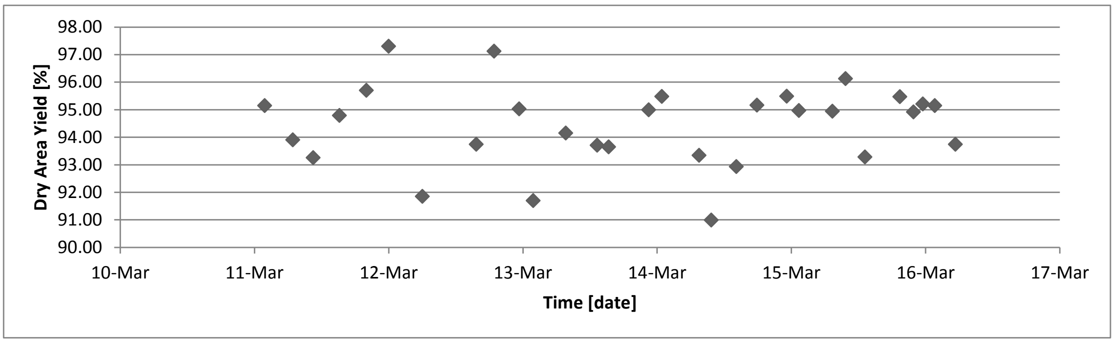


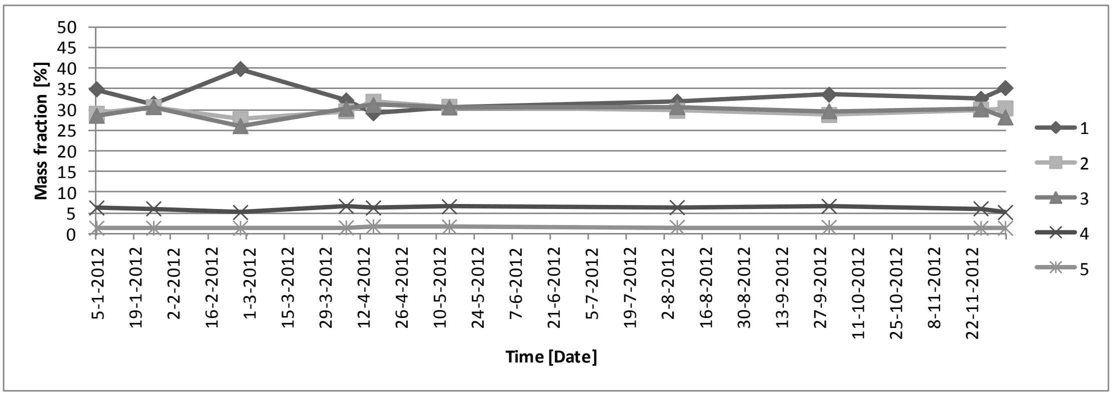
Figure 3.5: DAY results week 11 2013

During this example week the average DAY equals 94.5% at a remarkable high dispersion, the standard deviation equals 1.5%. Minimum and maximum DAY numbers during this week are respectively 91.0 and 97.3. During the year 2012 the ET2 DAY is on average 94.9%. DAY is monitored on a daily basis.

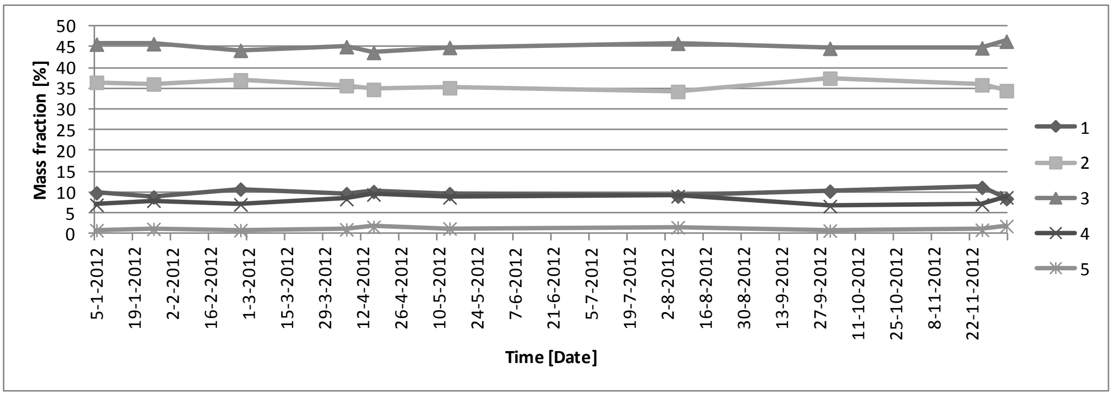
3.3.1.2.2.2 Particle size distribution

For creating cigarettes with a given firmness, the tobacco needs to have a certain particle size distribution (e.g. if a cigarette is filled with a too large fraction of small tobacco particles the firmness will not equal the requirements by being too low and chances increase that the tobacco falls out of the cigarette). Output depends on input, therefore also the particle size distribution of the infeed tobacco is interesting.

On a monthly basis at both sides of the process samples are collected for analysis to determine the particle size distribution. Sieve analysis data of the year 2012 from both input and output side is shown in figure 3.6.



(a) Input side: cut rag tobacco



(b) Output side: expanded tobacco

Figure 3.6: Sieve analysis results 2012

The size distributions are divided into five size fractions, where size fraction 1 contains the largest size particles and size fraction 5 the smallest size particles.

Size class	Mass fractions [%]	
	Process input	Process output
1	33.1	9.8
2	29.8	35.8
3	29.5	45.1
4	6.1	8.1
5	1.4	1.2

Table 3.2: Average mass fraction per size class 2012

Table 3.2 shows the average mass fractions per size class for the year 2012. Particle size distribution analysis results are not evaluated on a fixed moment in time.

3.3.1.2.2.3 Cylindrical volume and expansion rate

The goal of the process aims to be increasing tobacco in volume. To monitor the actual expansion rate, on a monthly base samples are collected at the input and output side for analysis. From these measurements the expansion rate can be calculated by use of the following formula:

$$Expansion\ rate = 100\frac{Output\ CCV - Input\ CCV}{Input\ CCV} \tag{3.2}$$

Where CCV stands for the Corrected Cylindrical Volume of the tobacco (cm^3/g). CCV values and corresponding expansion rates for the year 2012 are shown in figure 3.7.

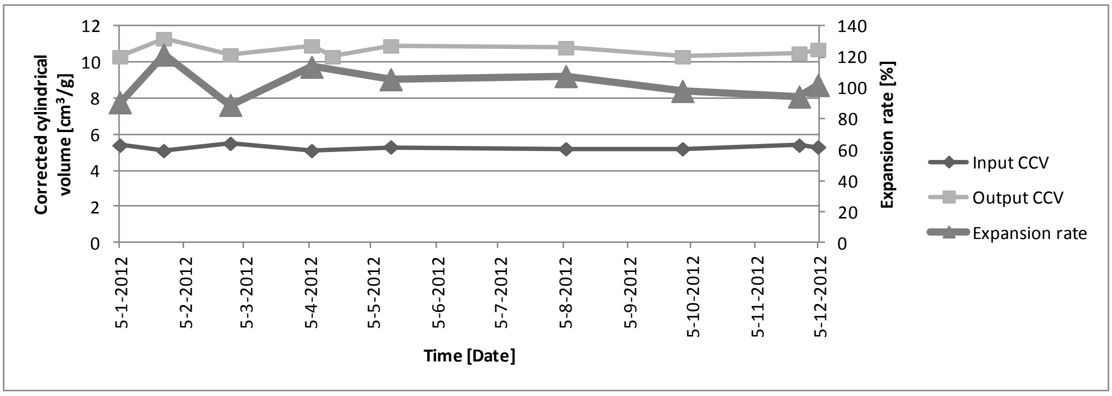


Figure 3.7: CCV and expansion rate results 2012

The input and output CCV values during the year 2012 are on average respectively 5.28cm^3/g and 10.64cm^3/g, making the average 2012 expansion rate 102%. CCV values and corresponding expansion rates are not evaluated on a fixed moment in time.

3.4 The Expanded Tobacco Process: a Low-Level Steady State Approach

The impregnate, expand and condition functions from figure 3.4 contain processes that physically transform the tobacco. Also during these functions, in several different steps the measuring towards dry area yield takes place. Furthermore during these functions, tobacco waste flows are separated from the main tobacco flow. In this section the three functions from the model in figure 3.4 will be analyzed further by modeling the steady state model in more detail.

This model is visualized in figure 3.8. Each of the transformation and control functions are explained and described in this section.

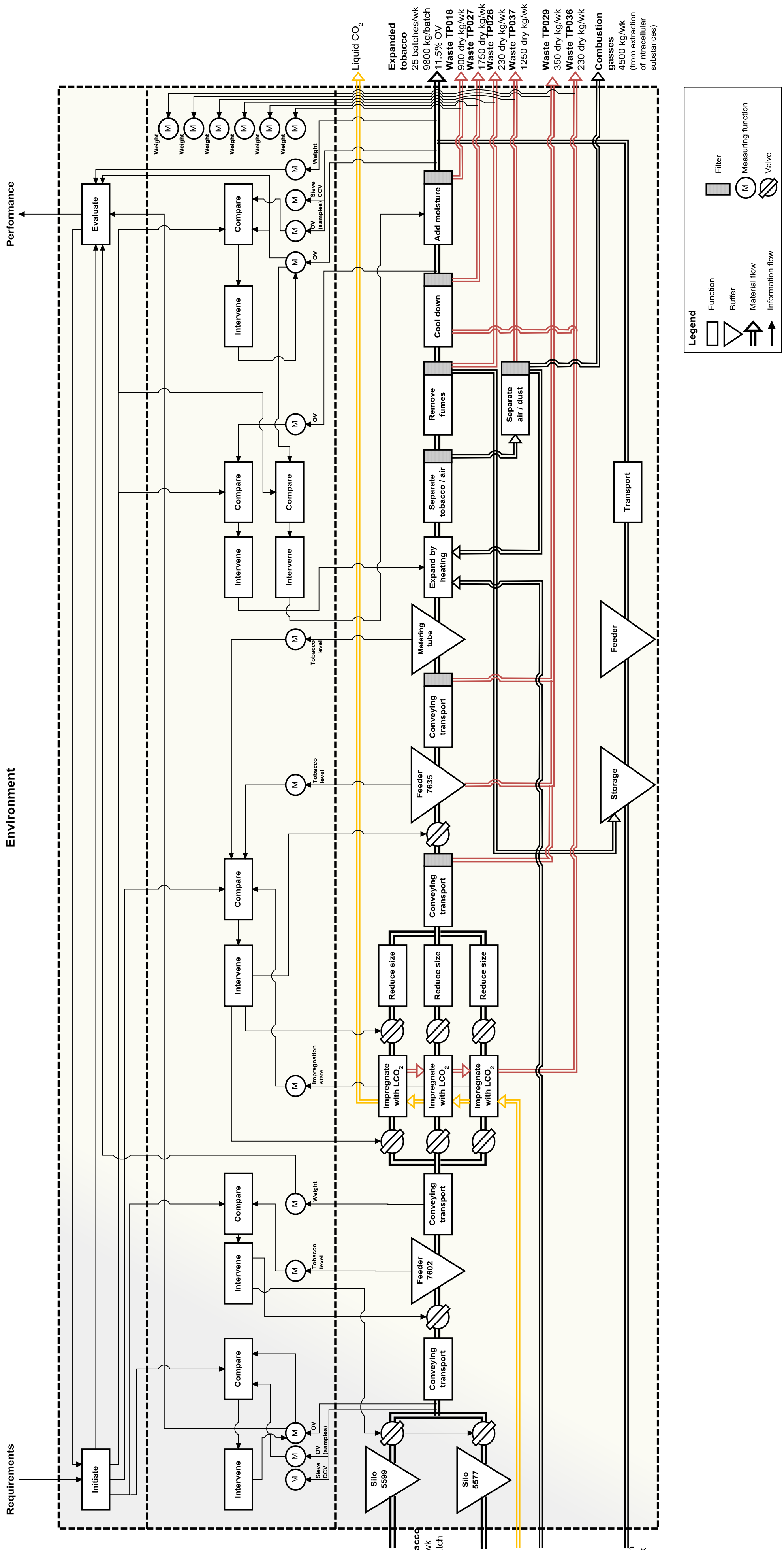


Figure 3.8:
Expanded Tobacco low-level steady state model

3.4.1 Material flow functions

In this section for clarification first in a short introduction the general overview of process steps is described. After this in a more detailed way the functions within the system are explained.

3.4.1.1 Introduction

In the model the material flows are shown by the use of double line arrows. A batch of cut rag tobacco enters the system, on the left side of the model and is stored in a silo. By use of a feeder and weighing belt sub batches are created to be impregnated. Impregnating is done with liquid CO_2 in one of three parallel impregnator vessels. When the impregnating function is completed its output is frozen, impregnated tobacco (-79°C). This frozen tobacco gets crushed and transported into a feeder.
From out this feeder the crushed tobacco is transported into a buffer, after which it gets heated by an air flow with a temperature of 360°C in the expansion tower. The output flow of the expansion tower is a hot expanded tobacco / air flow. Hot expanded tobacco at low humidity (105°C, 3.5% OV) is separated from the air flow.
Undesired fumes are removed by a fume removal conveyor from the expanded tobacco in the next step. After fume removal, the expanded tobacco gets cooled down (38°C) and checked for hot bodies which will be separated. This is done by a cooling conveyor and a series of vibratory conveyors and conveyor belts.
With an air flow at high humidity inside the reordering box the cooled expanded tobacco gets increased in moisture level (12% OV). The output is conditioned expanded tobacco, which after a final moisture level determination and weight determination leaves the system.
There is a separate input flow of expanded tobacco, being an input of the model. This expanded tobacco is part of a safety stock in case of for instance incidents or maintenance activities.

3.4.1.2 Detailed function descriptions

A batch of cut rag tobacco enters the system, on the left side of the model and is stored in one of the two silos (#5577 or #5599). A silo is emptied by the control of flow switches inside a feeder, which is a tobacco buffer to allow a constant flow afterwards. Silo emptying stops when the tobacco level inside the feeder reaches an upper bound, and continues when the tobacco level reaches a lower bound. Before entering the feeder the moisture level of the tobacco is measured.

(a) Cut rag silo side view (b) Cut rag silo top view (c) Cut rag feeder

Figure 3.9: Cut rag process equipment

After passing the feeder sub batches of 320kg are created by the control of a weighing belt in order to be impregnated.

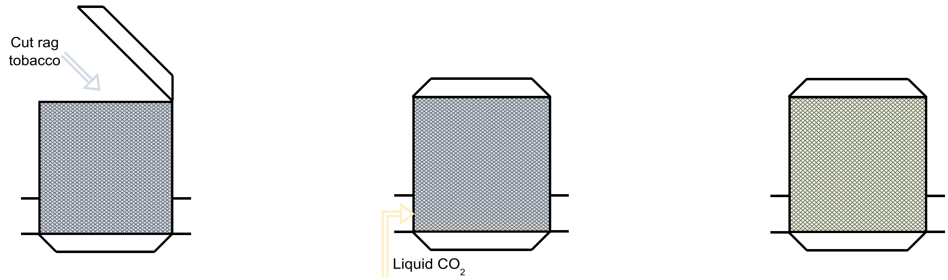
3.4.1.2.1 Cut rag tobacco impregnation

The goal of impregnating is to create a crystalline substance inside the tobacco cells, so that heating will cause a large amount of gas that stretches the cells to almost 'green leaf' state. After emptying a cut rag storage silo, a continuous flow of tobacco can be achieved.

(a) Conveying transport (b) Impregnator vessel top side (c) Impregnator vessel bottom side

Figure 3.10: Impregnation process equipment

The tobacco impregnation is a batch process, because the vessel in which the tobacco gets impregnated can only be filled with a limited amount of tobacco. Therefore preceding the impregnation vessel batches of appropriate size are laid out. Impregnating takes place at a high pressure, 30 bar. This is necessary to ensure liquid CO_2. Impregnated CO_2 molecules react with H_2O molecules already present in the tobacco cells.



(a) Cut rag tobacco filling (b) Closure and CO_2 addition (c) Impregnation

(d) Draining redundant CO_2 (e) Opening and expanded tobacco release

Figure 3.11: Impregnation vessel impregnating steps

The product of this reaction is CO_2-hydrate. After a fixed time of exposure the remaining CO_2 gets drained out. Depressurization beneath the CO_2 triple point at 4.2 bar causes the liquid CO_2 partly to vaporize while the remaining liquid turns into solid, dry ice. At atmospheric conditions the CO_2-hydrate is stable at temperatures below -45°. During depressurization (solid) dry ice was formed onto the tobacco fibers. This dry ice has a temperature of about -79°C, allowing the CO_2-hydrate to stay stable during transportation towards the expansion tower. Dry ice itself does not aid the expansion process, like the name Dry Ice Expanded Tobacco would suggest. For creating a maximum amount of CO_2-

hydrate and thus a maximum expansion level, cut rag moisture level, temperature, pressure and heat transfer values need to be monitored and controlled.

The dry ice causes all the tobacco fibers to stick together. This results in formation of a massive frozen tobacco clump inside the impregnation vessel. For further processing and transportation, the clump of frozen tobacco needs to be crushed. This is done by the 'clump breaker', a crusher with multiple horizontal rotating axes to which pins are attached. After crushing, the impregnated tobacco arrives at a conveyor in the so called 'cold box'. This cold box ensures low temperature conveying transport for stable CO_2-hydrate. The conveyer ends above a feeder, allowing continuous tobacco flow afterwards.

Figure 3.12: Frozen tobacco crusher: clump breaker

Both the cold box and the feeder are isolated to ensure temperatures below -45°C. During startups, stops and blend changes, a cooling installation into the cold box is turned on. Fans blow cold air onto the bottom of the isolated conveyor belt. This minimizes movement of the air above the belt, to prevent CO_2 evaporation.

(a) Cold box outside (b) Inner cold box transition (c) Metering tube

Figure 3.13: Cold box process equipment

Controlled by microwave level switches, the feeder transports the tobacco into a metering tube. From the metering tube transport towards a weighting plate takes place by a supply belt conveyor. To ensure continuous pressure onto this belt, the conveyors before the metering tube are controlled in order to achieve constant flow.

After passing the weighting plate, the impregnated tobacco ends up in the input lock of the expansion tower. The speed of the supply belt conveyor is controlled by a feedback control signal from the weighting plate.

3.4.1.2.2 Impregnated tobacco heating

The goal of heating is to heat the impregnated tobacco in such a short amount of time that disintegration of CO_2-hydrate inside the tobacco cells causes enough gas and thus inner pressure to stretch the cells to the desired volume. Stretching tobacco cells could be compared to inflating a porous balloon. The inner generated amount of gas must be high enough that even though there is loss of pressure by the cell pores, it creates enough pressure to stretch the tobacco cells.

(a) Expansion tower tobacco inlet

(b) Tangential separator

Figure 3.14: Expansion tower equipment

The heating takes place by a system of tubes and equipment in which process gas circulates. After leaving the input lock, process gas with a speed of 40m/s transports the impregnated tobacco into the expansion tower. The input lock is covered by gaseous CO_2, so no ambient air can enter the process gas loop. Too much air inside the expansion tower will easily cause the hot tobacco to catch fire. Temperature inside the expansion tower will reach 370°C, while the tobacco combusts at 300°C.

The expansion tower is a S-shaped tube with a height of 5.3m. In this tower the tobacco enters the lower turn, and leaves the higher turn. High temperature will force the tobacco to expand. From here the expanded tobacco goes into a tangential separator, in which by centrifugal forces the tobacco and process gasses will be separated.

The process gas flows through a dust cyclone separator. This separator separates charred tobacco particles form the process gas. By gravity and volume expansion in the dust cyclone separator the particles will drop down. Clean process gas gets recycled by reheating in a gas fired furnace.

Tobacco separated by the tangential separator ends up in an output lock, from where it reaches the fume removal conveyor. After heating in the expansion tower the expanded tobacco is very dry, hot and gives off irritating fumes. These fumes must be removed, because they would cause change in tobacco taste when condensed back onto the tobacco during cooling. The fume removal conveyor is a mesh belt conveyor in which from below a fan blows air onto the tobacco so that the fumes will be discharged. Solids in the fumes get separated by a pre-washer, and the remaining vapor gets cleaned in a scrubber. Clean vapor is fed to the outside air.

3.4.1.2.3 Cooling hot expanded tobacco

The goal of cooling is to lower the tobacco temperature, in order to meet the requirements for the remaining process steps. Before the cooling process starts, there is a dump valve. This dump valve allows off-spec tobacco to leave the system. Control of the valve can be done either by hand or by a system control action. For system control there is a spark detection system placed under the output lock, above the mesh belt fume removal conveyor and in the tubes leading towards the pre-washer.

(a) Fume removal conveyor (b) Cooling conveyor (c) Vibratory conveyors

Figure 3.15: Cooling process equipment

After passing the dump valve, the hot expanded tobacco enters the cooling conveyor. This cooling conveyor is a mesh belt conveyor where a by pressure differences between above and under the belt controlled closed loop fan system blows cooled air onto the tobacco. The air circulates over a heat exchanger cooled by cooling water. Remaining fumes, if still present, are not allowed to condensate due to risk of change in taste. Therefore continuously a part of the air gets extracted towards the pre-washer and scrubber.

At the end of the cooling conveyor there is a transition chute from which flow towards a series of vibratory conveyors is possible. In this transition chute spark detection systems are placed. In case of detection, a dump valve opens and the expansion process stops. The fume removal conveyor and the cooling conveyor will then be emptied at the two dump valves.

Two infrared cameras are also placed in the transition chute, for detection of product with a too high temperature. These particles are called 'hot bodies' and in case of detection can be thrown out without interrupting the expansion process.

The vibratory conveyors further cool down the tobacco in order to meet the requirements for reordering. Above one vibratory conveyor the tobacco temperature is monitored in order to control the cooling water flow in the cooling conveyor. A moisture meter measures tobacco moisture level.

3.4.1.2.4 Reordering expanded tobacco

The goal of reordering, i.e., moistening, is to recondition the dry and brittle tobacco obtained from the expansion tower. In order to achieve the desired moisture level, 12% OV, the tobacco is transported through a Humid Air Reordering System (HARS). This system consists of a conditioning part and an air treatment part.

For conditioning the tobacco is exposed at a humid atmosphere for about an hour. During this conditioning, the tobacco is located onto a vertical spirally rolled-up mesh belt with a length equal to about 550m. The tobacco flows through the spiral from bottom to top, while humid air flows in reverse direction. Water vapor condensates onto the tobacco, and will be absorbed.

(a) Reordering box outside

(b) Reordering box outlet conveyor

Figure 3.16: Reordering process equipment

The air flow within the HARS gets contaminated by the tobacco and therefore air treatment is required. This is done by refreshment of the air; a part gets extracted through a dust collector, while fresh air enters the HARS. The main air flow is led through an internal dust collector and thereafter cooled. Two fans blow the clean cooled air through three steam injection lances to adjust the desired humidity. Inside the tubes where contaminated air leaves the HARS, a spark detection system is installed. Fire detection inside the HARS is done by a system that monitors scattering and attenuation of a laser beam. In case of detection a fire extinguishing system will be activated.

After staying inside for roughly an hour, the tobacco exits the HARS to be weighted and transported towards a silo for storage.

3.4.1.3 Qualification of the tobacco flow

The aim of this section is to evaluate the multiple process steps by quantifying their possible contribution towards tobacco degradation. This is done by taking samples at several transition points within the process and determine the particle size distributions of those samples.

3.4.1.3.1 Sample requirements

The object of sampling is to gain knowledge of the characteristics of the whole from measurements impracticable to apply to the whole, bias at any of the reduction stages adversely affects the final analysis. With samples withdrawn from a population characteristics of that population are estimated within established confidence limits. Problems arise due to inhomogeneity of the population. If the bulk material is homogeneous, or can be mixed prior to sampling in order to generate a homogenous powder, sampling problems do not arise. [2, p4] The definition of homogeneity requires specification of the sample size between which variability is sufficiently small to be neglected.

3.4.1.3.2 Sample positions

For characterizing the system, ideally samples should be collected before and after each process step. In practice some process steps are not reachable for sample collecting or their contribution towards tobacco degradation is expected to be negligible, e.g., during belt conveyor transport.

Based on characteristics of process steps and tobacco characteristics during those steps, a distribution is made to predict the possible level of impact towards tobacco particle breakage. This is done in order to determine the required sample positions. An overview is given in table 3.3.

#	Description	Tobacco speed	Additional forces	Moisture level	Drop height	Sum
1	Belt conveyors	0	0	0	+	**+**
2	Feeder 7602	0	+	0	0	**0**
3	Belt conveyors	0	0	0	0	**0**
4	Impregnator	0	0	0	+	**+**
5	Clump breaker	0	++++	0	0	**++++**
6	Cold box conveyors	0	0	0	++	**++**
7	Feeder 7635	0	+	0	0	**+**
8	Metering tube	0	0	0	0	**0**
9	Expansion tower	++	0	+	0	**+++**
10	Fume removal conveyor	0	0	+	0	**+**
11	Cooling conveyor	0	0	+	0	**+**
12	Vibratory conveyors	0	++	+	+	**++++**
13	Reordering box	0	0	+	0	**+**
14	Belt conveyors	0	0	0	0	**0**

Table 3.3: Process equipment characteristics

With the results of table 3.3 and the fact that some positions are not accessible for the desired way of sample collecting, the following sample collection positions have been defined:

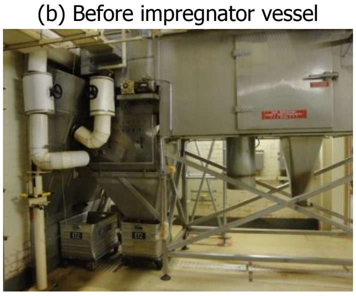
1. After cut rag silo
2. Before impregnator vessel
3. After clump breaker
4. Before metering tube
5. After fume removal conveyor
6. Before reordering box
7. After reordering box

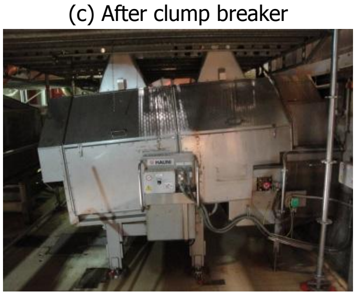

(a) After cut rag silo


(b) Before impregnator vessel


(c) After clump breaker


(d) Before metering tube


(e) After fume removal conveyor


(f) Before reordering box


(g) After reordering box

Figure 3.17: Sample collection positions

3.4.1.3.3 Sampling technique

The two basic principles of sampling are: (1) The to be sampled particles should always be sampled when in motion. (2) The whole of the stream of flowing particles should be taken for many short increments of time in preference to part of the stream being taken for the whole of the time. [2, p6]

When collecting particles from a falling stream, care should be taken to offset the effects of segregation. Segregation is defined to be "the separation of material by particle size". As a belt carries material along the conveyor, a slight bouncing motion is created by the belt rolling over its idlers. This is due to the slight sag in the belt between each idler. This motion causes the finer particles to settle to the bottom of the material cross section of the belt, and the coarser particles to stay on the top of the material cross section.

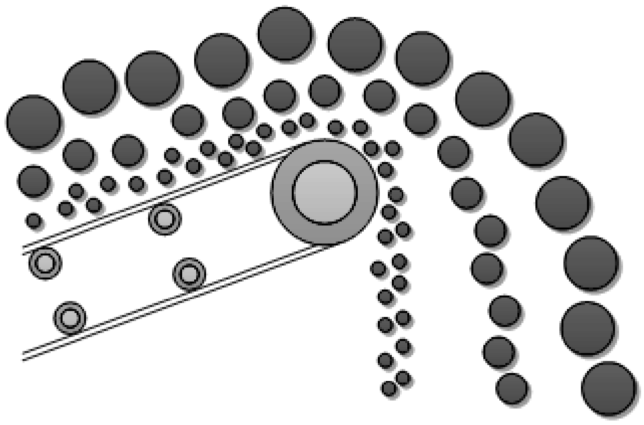


Figure 3.18: Belt conveyor transition point segregation example

Once the material reaches the conveyor discharge pulley, it is already somewhat segregated with the coarser particles on top and the finer particles on the bottom. As the material begins to travel around the curvature of the discharge pulley, the top particles flow at a greater velocity than the bottom particles. This difference in velocity then causes the coarser particles to travel farther from the conveyor before landing and finer particles to drop closer to the conveyor. Furthermore, the fine material has a greater tendency to cling to the belt and has not to be discharged until the belt has continued around the discharge pulley. This causes even more fines to be pulled back. [3, p6] Visualization of this segregation is shown in 3.18.

3.4.1.3.4 Sample size

It is imperative that a sample is representative of the tobacco quality characteristics at its sample point. Samples must be collected in a container bigger than the sample volume, in order to keep the tobacco quality properties intact. The sample must not be compressed to fit the container size. In case of overfilling the container, it must be emptied and a new sample must be collected. For each sample at least 200g of tobacco must be collected. This amount is sufficient for one sieve test. [4, p8]

3.4.1.3.5 Required number of samples

With any measured property there is an uncertainty associated which can be estimated using the confidence interval. Giving a random set of n samples with its calculated mean x_m,, standard deviation σ and the multiplier M that is determined by the chosen confidence level, the true mean will lie in the interval [5, p38]:

$$\mu = x_m \pm \frac{M\sigma}{\sqrt{na}} \tag{3.3}$$

For not knowing the population standard deviation, it must be estimated by using a sample standard deviation s. When replacing σ for s in equation 3.3, this will not result in the desired confidence interval unless the number of samples is infinitely large. Using s, sample number dependent multipliers are chosen from the t-distribution and the denominator in equation 3.3 is replaced by $\sqrt{n-1}$. Assuming a normal distribution of variance, the number of samples required to calculate the true mean $\pm A$ at a chosen confidence interval is given by [2, p39]:

$$n = \left(\frac{ts}{A}\right)^2 \tag{3.4}$$

where $A = |\mu - x_n|$ defines the maximal allowable interval for μ and t is the t-distribution value dependent on the confidence level and the number of samples related to s.

With sieving analysis results from historical samples taken at process input and output side the required number of samples per position can be estimated. Sieving results are within PMI divided in three size classes:

1. Coarse particles: mass fraction of particles >12 mesh
2. Intermediate particles: mass fraction of particles ≤12 mesh and >35 mesh
3. Fine particles: mass fraction of particles ≤35 mesh

Results from historical sieving analysis at the input and output position are shown in table 3.4.

	Position				
	Exit cut rag silo		Exit reordering box		
Size class	Mean mass fraction [%]	Standard deviation [%]	Mean mass fraction [%]	Standard deviation [%]	**Percentage change [%]**
1	65.3	1.07	47.9	0.5	**26.6**
2	28.4	0.84	43.6	0.34	**53.5**
3	6.4	0.36	8.5	0.32	**32.8**

Table 3.4: Historical sample sieving analysis results

With a number of m sampling positions and assuming an equal percentage of change between each subsequent sample position, the required value of A for obtaining significant dissimilar measurement results can be calculated with the following formula.

$$A = \frac{Smallest\ percentual\ change}{2(m-1)} \tag{3.5}$$

For the chosen number of sample positions this would return a value of A equal to 2.22%.

For each of the three size classes used to characterize the sieving results, the required number of samples at a chosen confidence interval can be calculated. In applied practice, confidence intervals are typically stated at the 95% confidence level. [6. p43-45] Table 3.5 shows the number of samples per sampling position required for a 95% confidence interval at several values of A (using the Student t distribution as given in Appendix B).

	Number of samples required per sampling point [#]							
	Exit cut rag silo				Exit reordering box			
A [%]	1	3	5	7	1	3	5	7
Coarse particles	21	3	1	1	9	1	1	1
Intermediate particles	68	8	3	1	108	12	5	3
Fine particles	244	28	10	5	110	13	5	3

Table 3.5: Required number of samples for multiple values of interval boundary A

Increasing the number of samples increases the required sample collection time. Within four hours it is possible for one person to take five samples at each of the determined seven sampling points. Every sample must be conditioned for 24 or 48 hours, depending on moisture level. At the Quality Assurance laboratory there is only a limited amount of space available for samples to be conditioned, which puts a limit on the number of samples. During one week, there is space for 35 samples in the conditioning room. The actual sieving work takes ~15 minutes per sample.

A [%]	1	3	5	7
Number of samples per sampling point [#]	245	30	10	5
Required working time [hours]	643	77	26	13
Required time period due to conditioning [weeks]	49	6	2	1

Table 3.6: Required working time for multiple values of interval boundary A

Based on the results shown in table 3.5 and 3.6 the number of samples to be taken from each of the seven sampling points is determined to be 10.

3.4.1.3.6 Sample storage and transport

Tobacco quality properties can change due to factors such as: shocks, vibration, ambient humidity and temperature variations, etc. [7, p6] For this reason the number of transfers and tobacco handling from collecting to testing should be minimized.

Figure 3.19: Sample storage container

In order to minimize shocks and vibrations during transport the collected samples are put in a closed container (as shown in figure 3.19) and are loaded onto a trolley. For minimizing ambient and humidity variations the samples must be placed in a conditioned room as quick as possible after sample collection.

3.4.1.3.7 Sample conditioning

It has been determined that providing a sample at or close to its equilibrium OV, the error that results that the sieve fraction determination is statistically insignificant. [8, p7] Before performing an actual sieving analysis, a sample first needs to reach equilibrium conditions. To reach equilibrium conditions the sample is placed in a conditioned room at a humidity level of 60% ± 3% and a temperature of 22ºC ± 1ºC for a fixed amount of time.

(a) Sample conditioning storage tray (b) Conditioning area

Figure 3.20: Sample conditioning

At the PMH Quality Assurance laboratory there is an air-conditioned room without forced air for conditioning samples. Using this conditioning variant time to reach equilibrium is equal to ≥ 24 hours for samples with a moisture level ≤ 15% OV. Conditioning time for samples > 15% OV equals ≥ 48 hours. [8, p7]

3.4.1.3.8 Sieving equipment and procedure

In order to carry out a sieve test the following equipment is required [9, p5]:

1. A weight balance with an accuracy ± 0.1g
2. A PMI laboratory sieve tester (350rpm ± 5rpm, 19mm eccentric, 5 round 30cm Ø screens, screen characteristics listed in table 3.7)

(a) Weight balance (b) Sieving screens (c) Laboratory sieve tester

Figure 3.21: Sieving equipment

Sieve number (1 = top)	Aperture [mm]	ASTM mesh size
1	12.5	-
2	3.35	6
3	1.70	12
4	0.85	20
5	0.50	35
Pan		

Table 3.7: Sieve screen characteristics

For this thesis, by using the above mentioned equipment and the procedure below, the different mass fractions at the several sample points are obtained.

Procedure:

1. Spread out the equilibrated sample over a flat surface
2. Weigh out the required quantity of tobacco
    a. Cut rag tobacco : 150g ± 5g
    b. Expanded tobacco : 100g ± 5g
3. Spread out the tobacco uniformly over the upper screen of the sieving machine
4. Set the sieving time to 5 minutes
5. Remove the upper screen, any tobacco remaining on this screen must be added to the next screen, the upper screen is only used to loosen the tobacco
6. Remove the new top screen and empty its content into the empty container
7. Weigh the screen loaded with tobacco and record the result to the nearest 0.1g
8. Repeat from point 6. onwards for each screen and the pan

The formula applied for each fraction f from screen i is given below:

$$f_i = \frac{100(W_i - W_{mi})}{W_t} \tag{3.6}$$

where W_i is the weight of sieve screen i (g), W_{mi} the total weight of sieve screen i loaded with tobacco (g) and W_t the total sieved tobacco weight (g).

3.4.1.3.9 Sieving analysis results

For this analysis a total amount of 70 samples is collected, conditioned and sieved in order to quantify the particle size distribution at the precious determined positions. To compare the sieving analysis results, the mass fractions are plot together. Figure 3.22 shows an example of a sieved sample.

(a) Particle size p>3.35mm ∧ p≤12.5mm

(b) Particle size p>1.70mm ∧ p≤3.35mm

(c) Particle size p>0.85mm ∧ p≤1.70mm

(d) Particle size p>0.50mm ∧ p≤0.85mm

(e) Particle size p≤0.50mm

Figure 3.22: Sieving results example

The next figures show the summarized results of the sieving analysis performed on each sample from the determined seven positions.

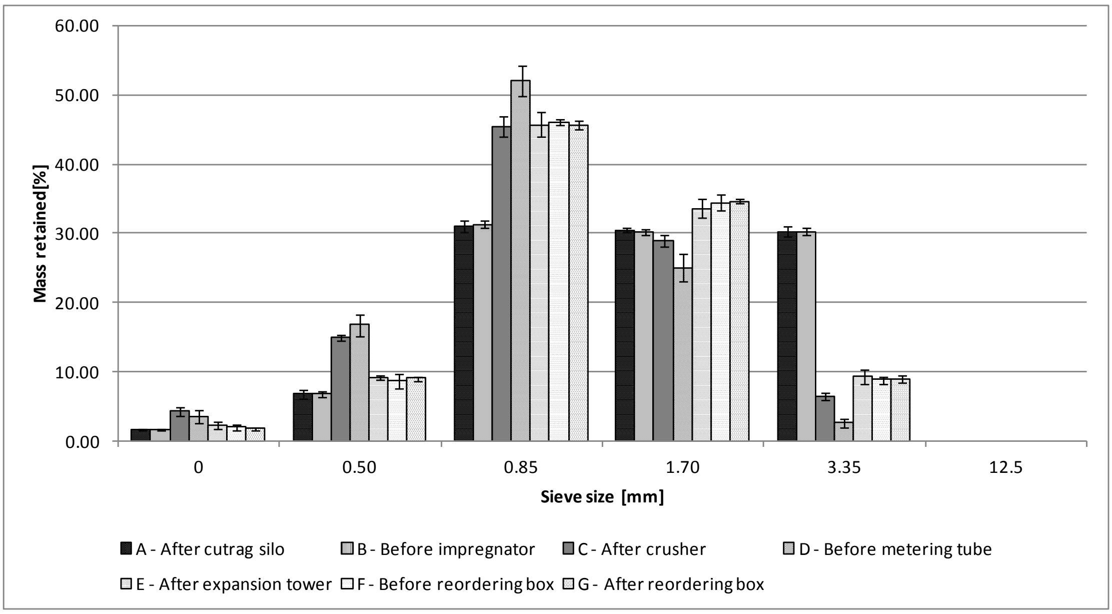


Figure 3.23: Particle size distribution at each characterization position

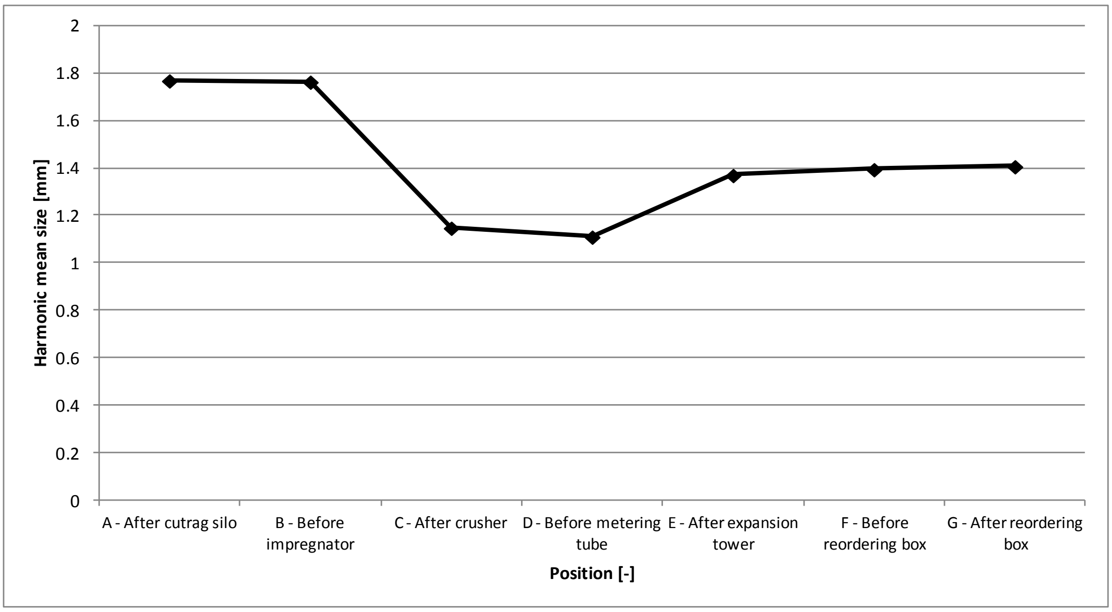


Figure 3.24: Harmonic mean size at each characterization position

Figure 3.23 shows the tobacco behavior towards size distribution at the different positions. Figure 3.24 shows the change in harmonic mean size of the particle size distribution after each sample position. The harmonic mean size x_h of a particle size distribution was defined by the equation:

$$\frac{1}{x_h} = \sum_n \frac{w_n}{d_n} \quad (3.7)$$

where w_n is the fraction of material retained between sieves of mean size d_n [10, p22].

As expected, the process steps between cut rag silo and impregnator vessel have no significant impact towards tobacco breakage. After that, the crushing process step i.e. clump breaker breaks down the largest size class by -79% while increasing the smallest size class by 162%. Due to crushing, particles from the larger size classes get broken down resulting in higher mass fractions from the smaller particle size classes.

Also during the cooled transport and pre expansion tower buffer, in the cold box, tobacco particles from the large size classes break down. The measured decrease in smallest size class particles can be explained due to the fact that during this process step a fraction of those particles are separated from the main flow.

After the fume removal conveyor the tobacco has been expanded in the expansion tower, resulting in increasing mass fractions from the largest particles size classes. However with this analysis the possible degradation caused during transport in the expansion tower could not be quantified.

Remarkable is the fact that after passing the series of vibrating conveyors, the tobacco particle size distribution approximately does not change. The unchanged distribution after the reordering box is in line with expectations. Decrease in smallest size class mass fractions at the last two positions can be explained by separation of small particles from the main flow.

3.4.1.4 Quantification and qualification of tobacco waste flows

In order to quantify the tobacco waste flows, waste registration data on a weekly base has been collected, calculated back to a dry weight fraction of the weekly feed volume. Results of this calculation for figures of production year 2012 are shown in table 3.8. For clarification figure 3.25 is added to visualize the several waste positions.

Waste collection position	**TP018**	**TP026**	**TP027**	**TP029**	**TP036**	**TP037**
Mass fraction [%]	0.391	0.100	0.759	0.154	0.098	0.545

Table 3.8: Year 2012 waste flow fractions

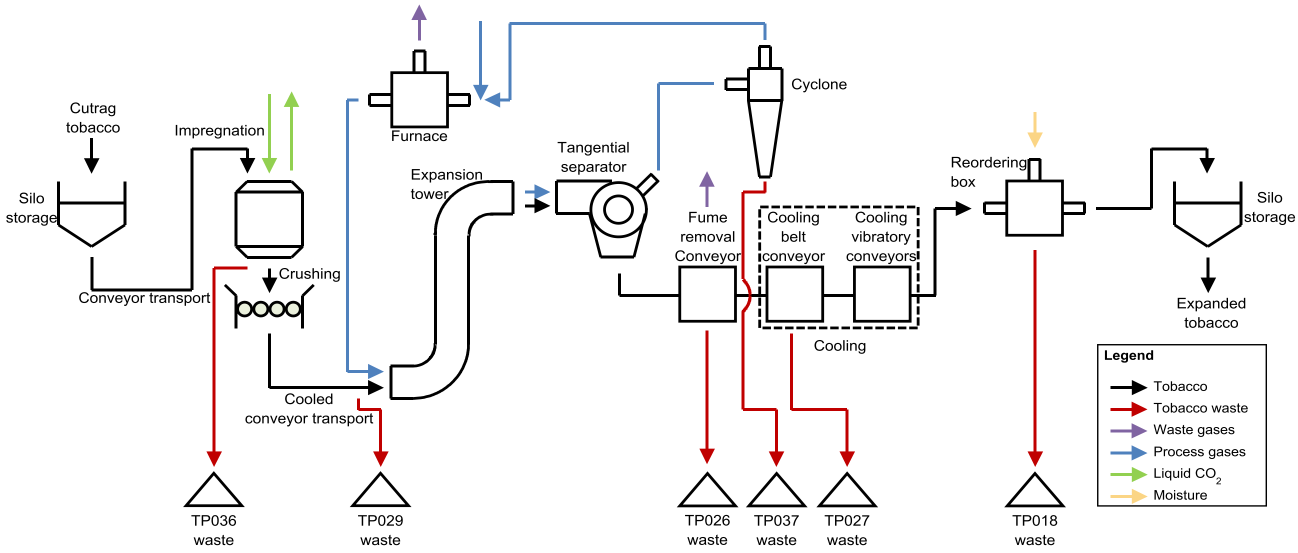


Figure 3.25: Visualization of the ET2 process steps and material flows

Qualitative data concerning the multiple waste flows was not available. Waste from the different flows is called dust, without knowing the composition towards particle size distribution. A first optical observation indicates that several boxes filled with waste from the multiple flows contain relatively large size particles.

(a) TP027 waste collection (b) TP029 waste collection

Figure 3.26: Waste collection areas

In order to substantiate this observation, samples have been collected from the several waste positions for quantification. These samples are analyzed towards their particle size distributions, which are presented in the graph in figure 3.27.

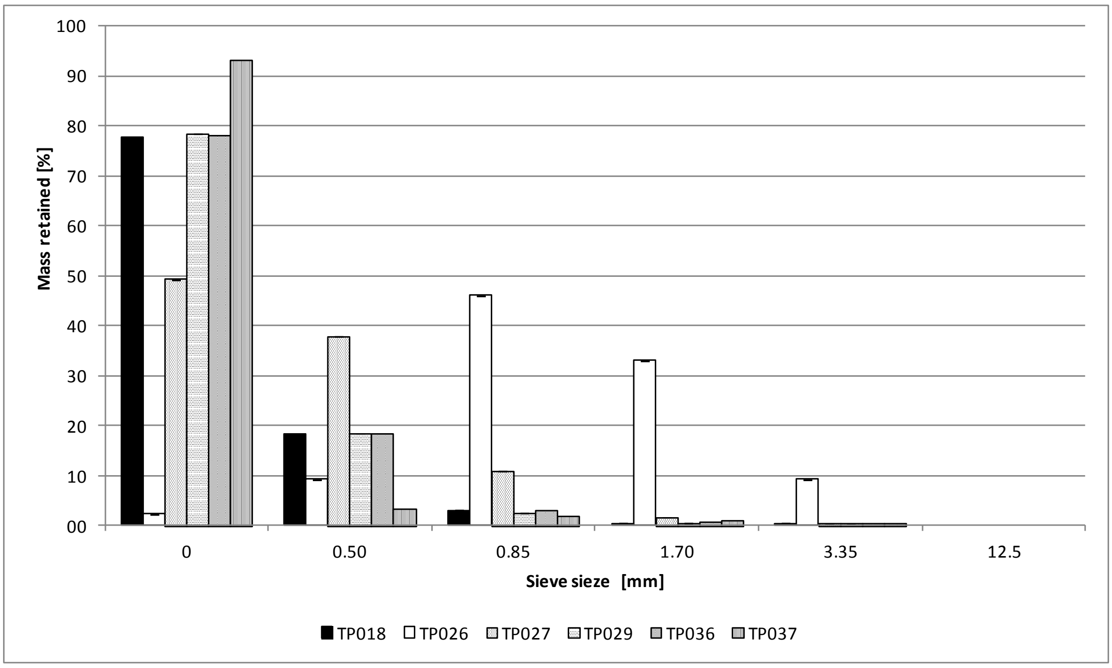
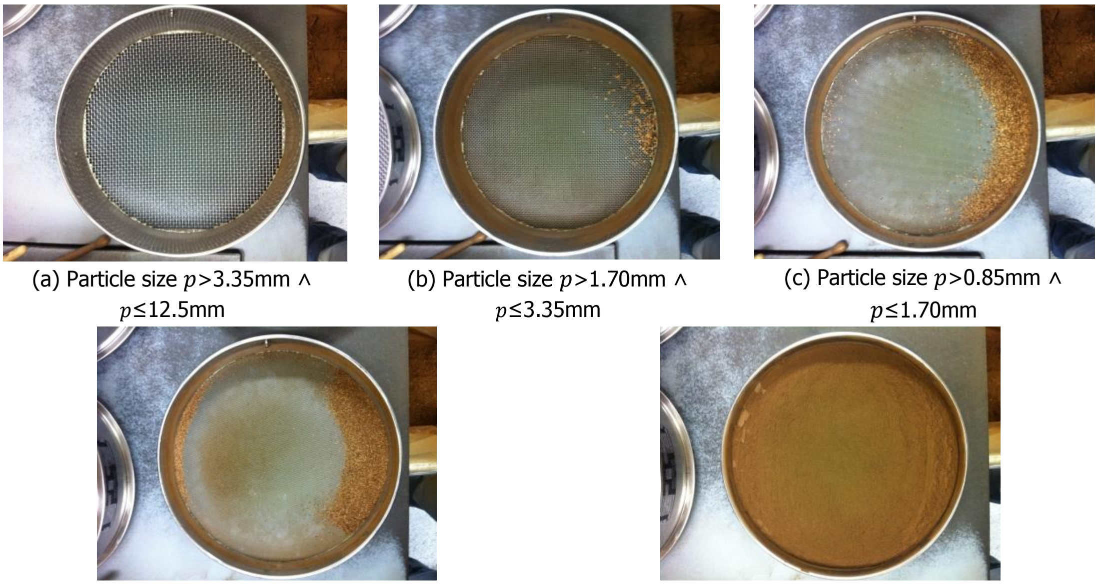


Figure 3.27: Waste flows sieving analysis results



(a) Particle size p>3.35mm ∧ p≤12.5mm (b) Particle size p>1.70mm ∧ p≤3.35mm (c) Particle size p>0.85mm ∧ p≤1.70mm

(d) Particle size p>0.50mm ∧ p≤0.85mm (e) Particle size p≤0.50mm

Figure 3.28: TP037 sieving results

Results from this analysis support the observation that waste from multiple collecting positions is still containing tobacco particles from the coarse and intermediate size classes. In the best scenario only the smallest particles, tobacco fines, would end up being collected as waste. If this is not possible, winning back coarse and intermediate size particles could possibly still be profitable.

When knowing the particle size distribution and dry weight fraction of each waste flow, the financial losses due to wasting coarse and intermediate size particles could be calculated. Table 3.9 shows the quantities of loss in amount and value.

	Quantity [kg/yr]	**Value [€/yr]**
TP018	2.00×10^3	**9K**
TP026	11.5×10^3	**52K**
TP027	12.4×10^3	**56K**
TP029	0.679×10^3	**3K**
TP036	0.516×10^3	**2K**
TP037	2.56×10^3	**12K**

Table 3.9: Losses due to coarse and intermediate particles in waste flows

3.4.1.5 Process control

To control the process there is a process control system. Data from several measuring points along the material flow is compared to standards, from which a deviation is determined. Depending on this deviation the process can be controlled by interventions at several locations.
For example the expansion tower temperature is controlled by use of feedback control. After the expansion tower tobacco OV is measured, on which the expansion tower temperature is controlled in such a way that the tobacco OV after tower stays equal to ~3.5%.

3.4.1.6 Function control

For controlling the process and its process control, the system contains function control. Output of the process is monitored and compared requirements from the environment. In order to meet requirements, standards can be adjusted. Performance of the system is presented to the environment.

Several measurements from the material flow are an input of the function control. In order to be able to perform effective control, measurement devices must be reliable. To check for reliability, in this section relevant measurement devices are verified.

3.4.1.6.1 Moisture meters

To check the effectivity of the moisture meters, measuring results from each moisture meter is compared towards sample results on a weekly basis. If necessary a corrective factor is updated manually.

3.4.1.6.2 Weighing belts

In order to validate the proper functioning of both weighing belts, tests are performed and evaluated on a semiannual basis. According to PMI standards this should be done at least after every 1000 production hours. A pre-weighed amount of tobacco is weighed for a number of runs to check for deviations. To ensure proper functioning of the weighing belts during this research, the test has been carried out. The cut rag weighing belt measured according to standards, while the final weighing belt showed small deviations. After mechanical repair and a new test, the weighing belt was measuring according to standards.

When the correct measuring of both weighing belts according to standards was validated, tests had been performed to check if the correct amount of measured quantity of weight was registered into the system. For this test during one production week the total counted number of kilograms from the weighing belt cabinet was compared to the registered amount of kilograms. Based on the results of multiple tests, the cut rag weighing belt and final weighing belt write respectively 0.30% and 0.04% too much into the system.

3.4.1.6.3 Position of measurement devices

For determining the dry tobacco weight at the input and output side of the process there is a weighing belt - moisture meter combination at each side. Both moisture meters used to calculate the performance indicator dry area yield are not positioned above their pertaining weighing belt, there is a certain distance in between. Due to moisture exchange with the environment during this distance, it could be the case that the subtracted amount of measured moisture is too high or too low.

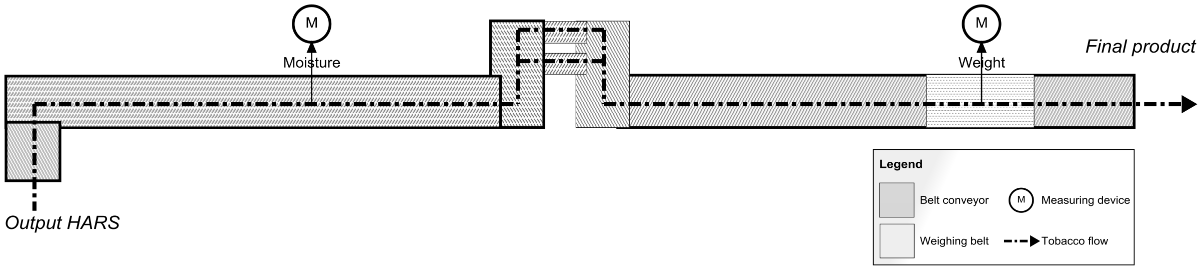
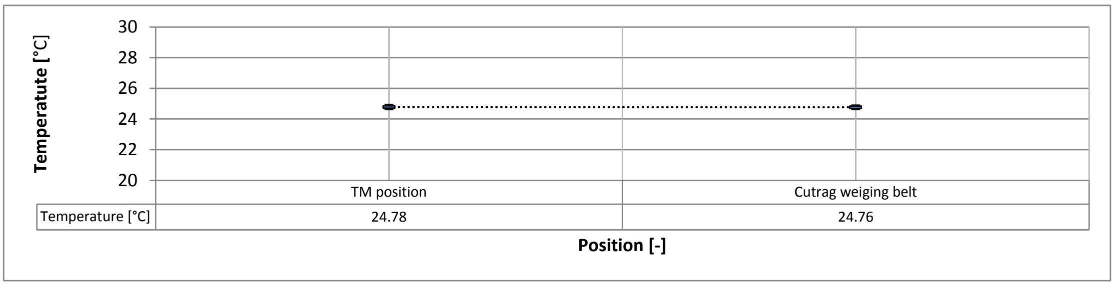
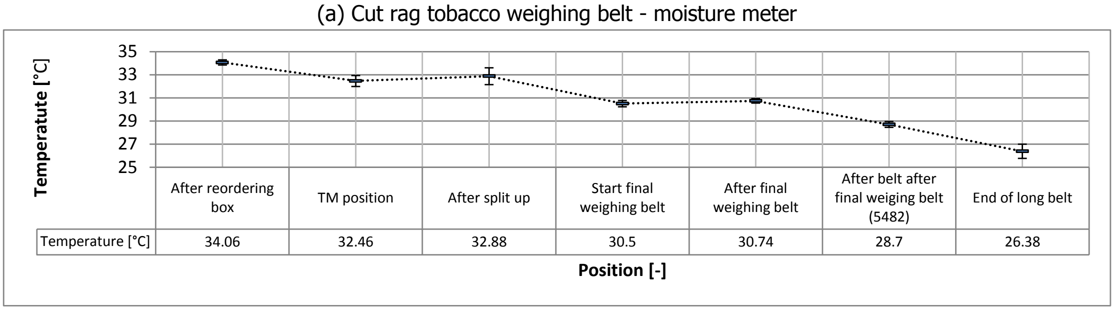


Figure 3.29: Final weighing belt - moisture meter top layout view

Figure 3.29 shows a top view of the layout of the weighing belt and moisture meter to visualize that there is a distance in between. To get a first quantified indication of change in product characteristics due to transportation and height drops temperature measurements are performed at multiple positions.



(a) Cut rag tobacco weighing belt - moisture meter



(b) Expanded tobacco weighing belt - moisture meter

Figure 3.30: Temperature measurement results weighing belt - moisture meter

Figure 3.30a and 3.30b show the measurement results from respectively the cut rag and final weighing belt - moisture meter. Cut rag tobacco temperature is stable, while prior to the final weighing belt tobacco temperature decreases.

To see if this decrease in temperature influences the moisture level between the moisture meter and final weighing belt position samples have been taken to analyze their moisture level. For this test a total number of 30 samples has been collected at both positions. After weighing each sample before and after oven heating according to the PMI moisture determination procedure, the difference in moisture level can be calculated with the formula given below: [11]

$$OV_{\Delta} = \frac{\sum_{i=1}^{n} OV_{A,i}}{n} - \frac{\sum_{i=1}^{n} OV_{B,i}}{n} \quad (3.8)$$

where $OV_{A,i}$ and $OV_{B,i}$ are moisture levels from sample i at respectively position A and B and n is the total number of samples. The calculated difference based on the collected samples equals 0.28%. This implies that when calculating the final dry tobacco weight, in the current situation the deducted amount is always too high. By the deducted amount being too high, the dry area yield is too low.

4 Problem statement after analysis

This section is dedicated to the identification of problems concerning PMH's ET2 process. Problems with respect to the performance on certain by PMH defined important indicators. These performance indicators were: (1) tobacco quality and (2) tobacco dry area yield.

With these performance indicators in mind, the process had been analyzed according to the Delft Systems Approach in order to clarify problem areas. While zooming in on the process, it became clear that different sort of problems could be identified with respect to the performance. Identified problems for are listed below.

1. The relation between the multiple waste flows and dry area yield is unknown
2. No evaluating takes place concerning quality and quantity of the multiple tobacco waste flows
3. No evaluating takes place concerning tobacco quality
4. No standards are defined concerning output particle size distribution
5. There is a large deviation in dry area yield between batches resulting in an unstable situation
6. The effectivity of the dry area yield related measurement devices is not optimal
7. No relation is known between tobacco degradation and waste fractions
8. Tobacco quality decreases by the clump breaker
9. During transport in the cold box tobacco particles get broken down
10. Cyclone dust contains larger size tobacco particles
11. Waste from the cooling conveyor contains larger size tobacco particles

These problems can be attributed to (1) control of the system, function and process control, and (2) effectivity of the process steps from the material flow which transform the cut rag tobacco into expanded tobacco. The research questions for each of these two areas that need to be answered are:

(1) Control of the system

1. What kind of control design and change in measurement devices would be required for effectively controlling tobacco quality and yield?
2. What is the relation between tobacco degradation during process steps and waste flows in quantity and quality?

(2) Effectivity of process steps in the material flow

1. Are there possibilities to reduce degradation of tobacco particles whereby waste will be reduced and final product quality will be improved?
2. How could the fraction of intermediate and coarse size tobacco particles ending up in multiple waste flows be reduced?

Answering these questions will result in insight in the parameters that are required for an objective view on the performance of PMH's ET2 process. When this objective view is developed, it is possible to define clear goals and implementation plans to increase the performance towards desirable levels.

5 Solutions to identified problems

The aims of this chapter are to:

- *Introduce a solution towards control improvement*
- *Present a study towards tobacco degradation improvements*
- *Present results of waste flow optimizations*

5.1 Design of a control model towards waste and tobacco quality

According to In 't Veld, controlling a system can only be done when the aspects that need to be controlled are defined. [31, p66] Specific requirements to each of these aspects must be clear. These requirements are defined based on the policy and organization of the primary transformation process. Based on the policy, standards for effectivity, productivity and flexibility are defined. Based on that, the aspects that need control can be identified.

In order to properly control a system, Veeke, Ottjes and Lodewijks distinguished four essential aspects: [1, p62]

1. There must be an objective; defining which output or which state the system should achieve
2. The system must be capable of realizing this objective
3. It must be possible to influence the systems behavior in one way or another
4. The relationship between the interference and the resulting behavior must be known

The term control is discerned into two different sorts of control: (1) function control and (2) process control. Function control concerns the combination of the translation of requirements into measurable standards and the evaluation of results expressed in terms of the original requirements. Function control does not react to disturbances, it assumes an ideal situation. Since in practice the ideal situation will generally not occur, process control is introduced to deal with disturbances. Within process control there are two sorts of control: (1) feed forward and (2) feedback. Feed forward is best described as cause determines intervention and feedback as result determines intervention.

Required inputs for proper tobacco yield and quality evaluation are (1) dry area yield numbers on batch level (2) individual waste flow quantities (3) individual waste flow quality data (4) process input and output tobacco quality data and (5) measurement equipment performance data.

Figure 5.1 shows the redesigned control model. With this new control model, the focus towards stabilizing and improving dry area yield and tobacco quality will be enhanced.

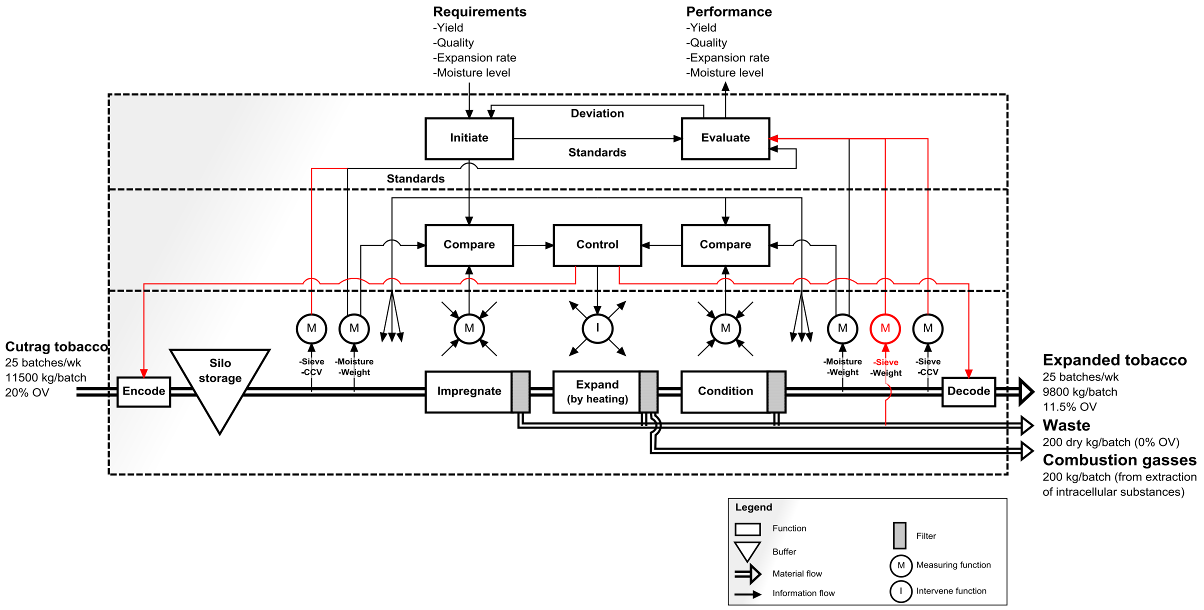


Figure 5.1: Steady-state model with redesigned control functions

In the current situation, waste flows are only measured quantitatively. No monitoring and control takes place. Since there is a direct relationship between waste on one hand and dry area yield on the other hand, quantitative waste measurements are important to evaluate. This could be done on a periodic basis up to weekly, since at the end of a five-day production week all the equipment is cleaned after which the total amount of collected waste from that production week is known.
Over time in case of no equipment adjustments waste flows should be constant towards quality and quantity. For those stable flows particle size distributions must be known so that in case of alterations, e.g., increase of a waste flow fraction, appropriate actions can be initiated.

When waste flows are increasing in quantity, whereby the dry area yield decreases, it could have several causes. One possible cause is that the input particle size distribution has changed over time. If the input tobacco contains a larger fraction fines than before, a higher amount of total waste will be the result. Therefore the input tobacco conditions towards particle size distribution are important to evaluate.
Also the particle size distribution from the output tobacco is of great importance. It reflects a quality parameter of the product supplied to the customer, i.e., Secondary and other PMI affiliates. By evaluating the output particle size distributions, customer complaints can be prevented.
Every month samples are collected at the input and output side of the process, and analyzed towards particle size distribution. This data could directly be used as a parameter for tobacco quality evaluation.

5.1.1 Solutions to problems with the current measurements

According to Veeke, Ottjes and Lodewijks a measuring point must be able to measure the necessary quantities. Also the accuracy and sensitivity of the measuring point, the measuring function plays a role. Usually, the less accurate the measurement, the worse the results of the control. [1, p69-70]

5.1.1.1 Determination of dry area yield on batch level

There is a large deviation in dry area yield between batches. This is explained by the fact that when producing several batches of equal blend type in sequence, processing is done in a continuous way instead of batch production. Then batch closure is done based on a fixed final weight quantity. Due to variations in input quantity and moisture levels a fixed number is not sufficient.

A solution to this would be to create physical separation between batches. However this results in an increasing amount of waste due to start up and close down effects from the expansion tower.

Another solution instead of ending a batch based on a fixed number, forecast the final quantity based on multiple batch characteristic parameters. This can be done by adjustment of the process control, calculating the predicted final quantity and making it available to the process operator. A script that is able to forecast the final weight quantity for a batch is given below:

```
For i = 1 to n do
      If Blend_Type = i then Final_Target_Weight = Avg_Dry_Area_Yield_i *
      (100 - Cut_Rag_OV) / (100 * (100 - Final_OV_Target))
Show  Final_Target_Weight
```

Where	`i`	=	index for the number of blends,
	`Blend_Type`	=	a unique number for each blend type,
	`Avg_Dry_Area_Yield_i`	=	a blend dependant average dry area yield number,
	`Cut_Rag_OV`	=	measured cut rag OV from the batch,
	`Final_OV_Target`	=	the target final OV for the batch.

For quantifying the effect of closing a batch by forecasting the final tobacco weight DAY numbers have been collected during a reference period and during testing. Figures are shown in the figure below.

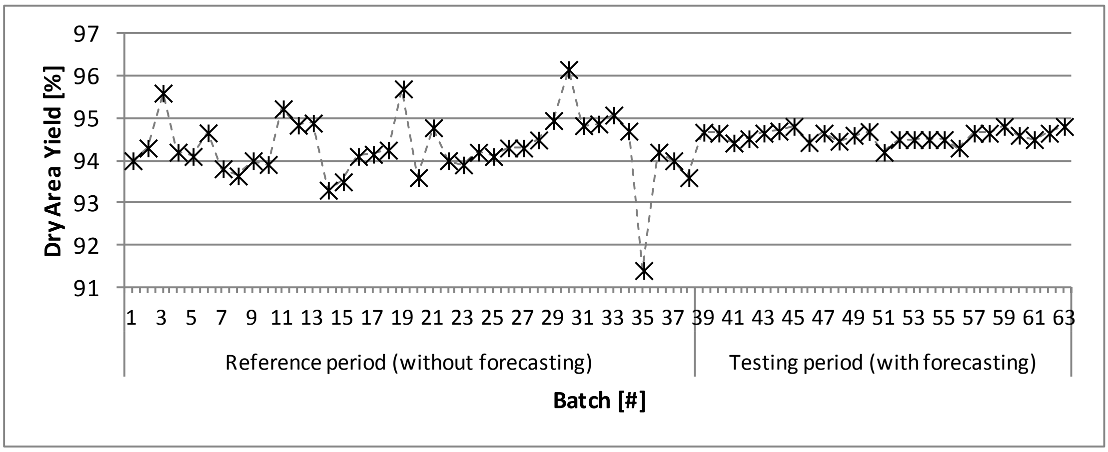


Figure 5.2: Dry area yield spread reduction test results

It is clearly visible that spread has been reduced by applying the forecasting script. In fact during the reference period standard deviation σ_{ref} equals 0.795%. During testing period standard deviation σ_{test} equals 0.151%. By applying the forecasting script the DAY spread is improved, since the standard deviation is reduced by 81%.

5.1.1.2 Weighing belts and moisture meters

Analysis showed that if the cut rag weighing belt measures a quantity of tobacco; there is a deviation between measured quantity and registered quantity. The deviation equals 0.30%, based on multiple measurements. The weighing belt cabinet, which transmits the measured quantity, is an outdated type using analog signals. Modern weighing belt cabinets are using digital signals.

The weighing belt cabinet is planned to be replaced by a new one. A simple solution in between is to correct for the deviation in software.

Tests have shown that between final moisture and weight determination the tobacco looses moisture. Due to this fact when calculating wet weight back to dry weight a too large amount of moisture is subtracted.

5.1.2 Monitoring dashboard

As mentioned in chapter 3, during the analysis phase of this thesis there was no qualitative or quantitative monitoring and control concerning waste flows. Each full waste container is weighed and its quantity is registered, linked to the waste collection position. Using this data, a waste flow monitoring dashboard has been created. An example sheet is shown in the figure below.

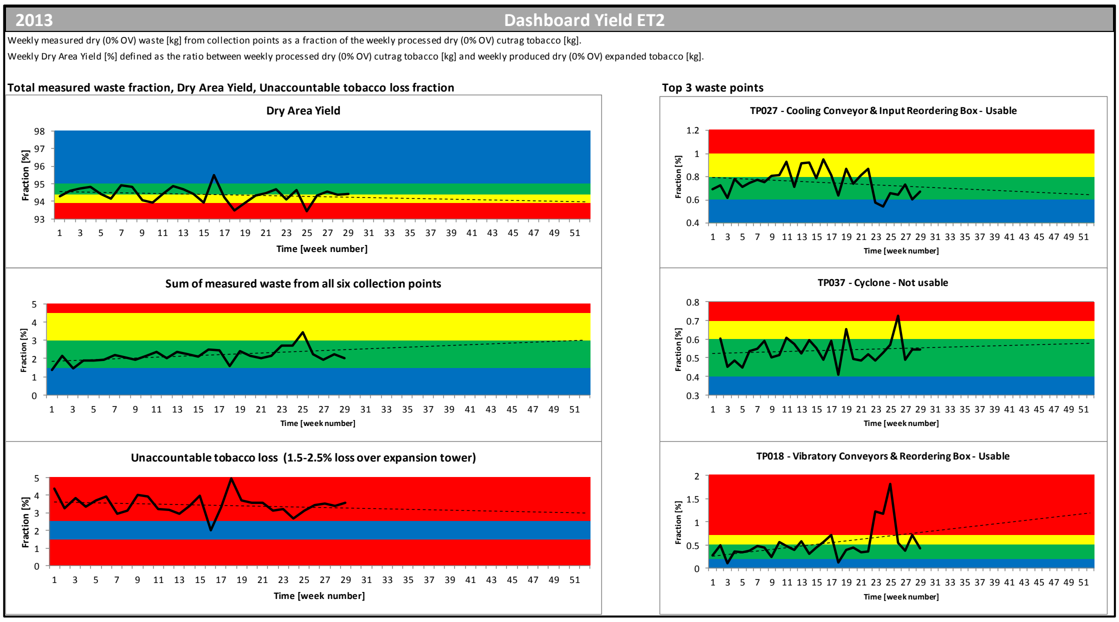


Figure 5.3: Monitoring dashboard for dry area yield and waste

With this dashboard the relation between dry area yield and waste on a weekly basis can be monitored. The dashboard is automatically collecting data from registration systems, minimizing the possibility of incorrect entries. Based on waste flow fraction levels and trends proper corrective actions could be initiated.

5.2 Mathematical model

The aims of this section are to:

- *Introduce a mathematical model for predicting tobacco degradation behavior.*
- *Describe possibilities for degradation reduction.*
- *Present opportunities for yield improvement by optimizing waste flows.*

Currently the relation between tobacco degradation caused during process steps and waste and final product flows in quantity and quality is not known. Within other industries the process of comminition had been observed and studied over the years. Statistical correlations of variables have been used to develop mathematical models describing unit and integrated operations. With a better understanding of processes and application of basic laws of physics, mathematical models have been developed to describe operations more fully. The developed models help to simulate the process. The basic idea of this section is to obtain a mathematical relation between feed and product size.

5.2.1 Calculations in the model

The next subsections describe the several calculations

5.2.1.1 Data inputs

Several data is used as an input for the model, data inputs are listed below:

- Measured particle size distributions before and after current process steps
- Measured particle size distributions from the multiple waste flows
- Tobacco passing percentage at separation point k from size class n
- Expansion tower expanding factor
- Expansion tower extracting loss fraction

5.2.1.2 Breakage model

The distribution of sizes produced from a single breakage step is known as the breakage function. It denotes the relative distribution of each size fraction after breakage. Several studies for example by Lynch, Broadbent and Callcot, Gaudin and Melloy, Kelsall and Reid, Klimpel and Austing, Austin et al. have been done in order to describe the breakage function. [12] [13] [14, p99] [15, p40] [16, p14-20] [17, p88]

Klimpel and Ausin's model encompasses most of others and is given below:

$$B(d_i) = 1 - \left[1 - \left(\frac{d_i}{d_j}\right)\right]^{n_1} \left[1 - \left(\frac{d_i}{d_j}\right)^2\right]^{n_2} \left[1 - \left(\frac{d_i}{d_j}\right)^3\right]^{n_3} \tag{5.1}$$

where d_j = the original size being broken,

d_i = size of the progeny fragment of breakage,

$n_1 - n_3$= constants depending on particle shape and flaw density within the particles,

$B(d_i)$ = the cumulative mass fraction finer than d_i where $d_j > d_i > 0$.

Broadbent and Callcott's model is easier for calculating the size distribution of particles after breakage. They introduced the idea of using breakage matrices to relate input and output particle size distributions, and presented empirical matrix equations of the form:

$$\mathbf{B} \cdot \vec{f} = \vec{o} \tag{5.2}$$

Where $\vec{f}$ and $\vec{o}$ are vectors describing respectively the feed and output particle size distributions and $\mathbf{B}$ is the breakage matrix which relates the feed and output. [18, p258-259] The relationship between d_j and d_i form elements of the breakage matrix and is expressed as:

$$B(d_i) = \frac{1 - e^{\frac{d_i}{d_j}}}{1 - e^1} \tag{5.3}$$

Based on their idea of using breakage matrices, another method to determine $\mathbf{B}$ for example used by Fistes and Chapelle et al. is to take a proper amount of sample of one size fraction for each of the size fractions, let the samples separately undergo the process and determine afterwards their size distribution by sieve analysis. [19, p322] [20, p21] [21, p528] Based on the matrix equation, elements b_{ij} of matrix $\mathbf{B}$ define the mass fractions of particles of size class j which end up in size class i as a result of breakage. A column of the matrix describes the fate of a given size class in the input size distribution, and its sum must therefore equal unity. By defining particle size of a particle after a breakage process stays the same or smaller, $\mathbf{B}$ is always written as a lower triangular matrix, e.g., for three particle size classes:

$$\mathbf{B} = \begin{bmatrix} b_{11} & 0 & 0 \\ b_{21} & b_{22} & 0 \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \tag{5.4}$$

Since there is no size distribution data from single size fraction tests performed on the PMH ET2 process available, breakage matrix calculation must be conducted otherwise. A number of n size classes returns into a $n \times n$ breakage matrix. If both feed and output mass fractions from all size classes are known, there is insufficient data available to backward calculate the parameters of the breakage matrix for $n > 2$. If n equals 2 the breakage matrix parameters can be calculated. Knowing this, if the particle size distribution of feed and output is characterized by a number of $n > 2$ size classes, the feed and output vectors can be divided into $n - 1$ two dimensional vector pairs. For each of the pairs the corresponding 2×2 breakage matrix parameters can be calculated.

If in a 3 size classes example $\vec{f} = \begin{bmatrix} a \\ b \\ c \end{bmatrix}$ and $\vec{o} = \begin{bmatrix} d \\ e \\ f \end{bmatrix}$, this would after dividing result in $\vec{f_1} = \begin{bmatrix} a \\ b + c \end{bmatrix}$, $\vec{f_2} = \begin{bmatrix} a + b \\ c \end{bmatrix}$, $\vec{o}_1 = \begin{bmatrix} d \\ e + f \end{bmatrix}$ and $\vec{o}_2 = \begin{bmatrix} d + e \\ f \end{bmatrix}$. Corresponding breakage matrices are: $\mathbf{B}_1 =$

$\begin{bmatrix} \frac{d}{a} & 0 \\ 1-\frac{d}{a} & 1 \end{bmatrix}$ and $\mathbf{B}_2 = \begin{bmatrix} \frac{d+e}{a+b} & 0 \\ 1-\frac{d+e}{a+b} & 1 \end{bmatrix}$. A general feed distribution $\vec{f}_{gen} = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}$ results in $\vec{f}_{gen\,1} = \begin{bmatrix} f_1 \\ f_2+f_3 \end{bmatrix}$ and $\vec{f}_{gen\,2} = \begin{bmatrix} f_1+f_2 \\ f_3 \end{bmatrix}$. So $\vec{o}_{gen\,1} = \mathbf{B}_1 \cdot \vec{f}_{gen\,1} = \begin{bmatrix} \frac{d}{a} f_1 \\ 1-\frac{d}{a} f_1 \end{bmatrix}$ and $\vec{o}_{gen\,2} = \mathbf{B}_2 \cdot \vec{f}_{gen\,2} = \begin{bmatrix} \frac{d+e}{a+b}(f_1+f_2) \\ 1-\frac{d+e}{a+b}(f_1+f_2) \end{bmatrix}$ whereby $\vec{o}_{gen} = \begin{bmatrix} \frac{d}{a} f_1 \\ \frac{d+e}{a+b}(f_1+f_2) - \frac{d}{a} f_1 \\ 1-\frac{d+e}{a+b}(f_1+f_2) \end{bmatrix}$.

In the model, for m size classes, a $m \times m$ breakage matrix $\mathbf{B}$ is defined and the calculation of its elements is given below:

$$b_{p,q} = \begin{cases} \sum_{s=1}^{m} \frac{i_s}{o_s} & , \quad for\ p = q\ and\ p,q \leq m \\ 0 & , \quad elsewhere \end{cases} \tag{5.5}$$

From which the retained output mass fraction after breakage at degradation process j from size class n can be calculated with the formula given below:

$$o_{j_n} = \left(100 - b_{n-1,n-1} \sum_{n-1} i_{j_n}\right) - \left(100 - b_{n,n} \sum_{n} i_{j_n}\right) \tag{5.6}$$

5.2.1.3 Expansion model

As a result of quickly turning intracellular CO_2-hydrate into gas, tobacco cells expand during their stay in the expansion tower. Caused by relatively high mass flow, low final moisture level and multiple bends in the expansion tower, the tobacco particles could break up. Therefore a model describing the characteristics of expanded tobacco must include both expansion and breakage effects. A method for modeling breakage effects has been shown, remaining the expansion phase to be modeled.

When a tobacco particle expands, its volume increases. Knowing the input volume and expanding factor, defined as the ratio of volume increase, the output volume can be calculated. Particles entering the expansion tower are never a fixed single size but consist of different sizes. Hereby the particles are also in different shapes making characterization of size complex. Mass of sample, M_p, containing a number of N particles of characteristic size d_p equals:

$$M_p = k\ N\ d_p^2\ \rho \tag{5.7}$$

where k is a shape related factor and ρ the density of the solid particles. [18, p45]

Since the frequency distribution is not known, having the size distribution and assuming particles of a known shape, the frequency distribution can be estimated. From sieving analysis the range of particle sizes is known. When dividing this range into a number of n fractions f_i, a part of the mass fraction from each single size class can be assigned to a fraction f_i by assuming linear size distribution in a size class. With a given shape and expanding factor, for each fraction f_i the expanded volume $V_{expanded}$ can be calculated. From the volume the new characteristic diameter can be calculated. Since each fraction f_i has a mass fraction, the particle size distribution after expanding is known.

The expansion behavior calculating sequence is given below.

- Determine by sieving analysis the maximal diameter d_{max}
- Create a range by dividing d_{max} into a number of j fractions f_i
- Sum the number of fractions f_i fitting in a size class n: l_n
- Calculate the mass per fraction for each of the fractions within a size class: $m_n = \frac{f_n}{l_n}$, where f_n is the mass fraction of the input feed in size class n
- Compute the expanded volume for each fraction f_i: $V_{exp,i} = d_i^3\, E$, where d_i is the characteristic diameter of fraction f_i and E the expanding factor
- Calculate the characteristic diameter after expansion for each fraction f_i: $d_0 = \sqrt[3]{V_{exp,i}}$
- Determine the mass fraction for each size fraction after expansion o_n, by summing up mass fractions with a characteristic diameter within the size class interval
- Set up the particle size distribution after expanding: $\vec{o} = \begin{bmatrix} o_1 \\ \vdots \\ o_n \end{bmatrix}$

Due to extracting intracellular substances during expansion, mass flow after expansion $\dot{o}$ must be corrected by use of an extracting rate R:

$$\dot{o}_{post-extraction} = \dot{o}_{pre-extraction}\,\frac{100 - R}{100} \tag{5.8}$$

The breakage and expansion model combined in series is used for modeling the behavior of the expansion process.

5.2.1.4 Separation model

The general form quoted for a mass balance is: 'The mass that enters a system must, by conservation of mass, either leave the system or accumulate within the system'. Mathematically the mass balance for a system is as follows: [22, p59–62]

$$Input = Output + Accumulation \tag{5.9}$$

When a process has one input flow with a mass flow $\dot{f}$ and size distribution $\vec{f}$, two output flows with mass flows $\dot{o}_1$, $\dot{o}_2$ and size distributions $\vec{o}_1$, $\vec{o}_2$ and the factors for mass from a size class in the input flow to retain in the first output flow, the relations between input and output flows are given on the next page by equations 5.10 - 5.13.

$$o_{1,i} = 100 \frac{f_i\, p_i}{\sum_{j=i}^{n} f_j\, p_j} \quad (5.10) \qquad o_{2,i} = 100 \frac{(1-f_i)\, p_i}{\sum_{j=i}^{n}(1-f_j)\, p_j} \quad (5.11)$$

$$\dot{o}_1 = \dot{f} \frac{\sum_{j=i}^{n} f_j\, p_j}{100} \quad (5.12) \qquad \dot{o}_2 = \dot{f} \frac{\sum_{j=i}^{n}(1-f_j)\, p_j}{100} \quad (5.13)$$

where $o_{k,i}$ = mass fraction from size class i belonging to output number k,

$o_{k,i}$ = output k mass flow,

$\dot{f}$ = input mass flow,

p_i = passing factor,

n = total number of size classes.

In the model, $o_{1,i}$ and $o_{2,i}$ represent respectively for the tobacco and waste flow the ith size class mass fraction after a given separation process.

Outputs of the model are:

- Particle size distribution after degradation process j

$$\vec{o}_{d_j} = \begin{bmatrix} o_{d_{j_1}} \\ o_{d_{j_2}} \\ \vdots \\ o_{d_{j_{m-1}}} \\ o_{d_{j_m}} \end{bmatrix}, \sum_m o_{d_{j_m}} = 100 \quad (5.14)$$

- Tobacco flow particle size distribution after separation process k

$$\vec{o}_{t_k} = \begin{bmatrix} o_{t_{k_1}} \\ o_{t_{k_2}} \\ \vdots \\ o_{t_{k_{m-1}}} \\ o_{t_{k_m}} \end{bmatrix}, \sum_m o_{i_m} = 100 \quad (5.15)$$

- Waste flow particle size distribution after separation process k

$$\vec{o}_{t_j} = \begin{bmatrix} o_{i_1} \\ o_{i_2} \\ \vdots \\ o_{i_{m-1}} \\ o_{i_m} \end{bmatrix}, \sum_m o_{i_m} = 100 \quad (5.16)$$

- Relative tobacco waste weight fraction after separation process step k, W_k
- Absolute tobacco waste weight fraction W_{total}

$$W_{total} = \sum_k W_k \quad (5.17)$$

- Harmonic mean size of a particle size distribution after process step:

$$x_h = \frac{1}{\sum_n \frac{w_n}{d_n}} \quad (5.18)$$

where w_n is the fraction of material retained between sieves of mean size d_n.

5.2.1.5 Assumptions in the model

The model as such is aimed to quantify the outputs of different sub processes in the ET2 process; however as most mathematical models it is merely a simplification of reality.

The following assumptions are made in the model:

- Particle shape of particles to be expanded is assumed to be cubical
- Expanding rate is equal in each dimension
- Waste separation is assumed to behave proportional to size class fraction sizes
- Size distribution in a given size class is assumed to be linear

5.2.1.6 Results and analysis

In this section the results are described and analyzed in a quantitative way. In accordance to the goals of this thesis multiple scenarios were tested in the model. Besides the current situation, generally 3 improvement situations are modeled:

1. Optimized crushing process
2. Optimized cold box transport
3. Optimized expansion tower transport

For quantifying combinations of these three scenarios also their combinations are modeled, making a total of eight modeled scenarios.

For all modeled scenario's, the corresponding waste figures compared towards the current situation are presented in figure 5.4. Waste numbers are compared to the current waste fraction, e.g., 50% waste means half the amount of waste the process is generating in the present situation.

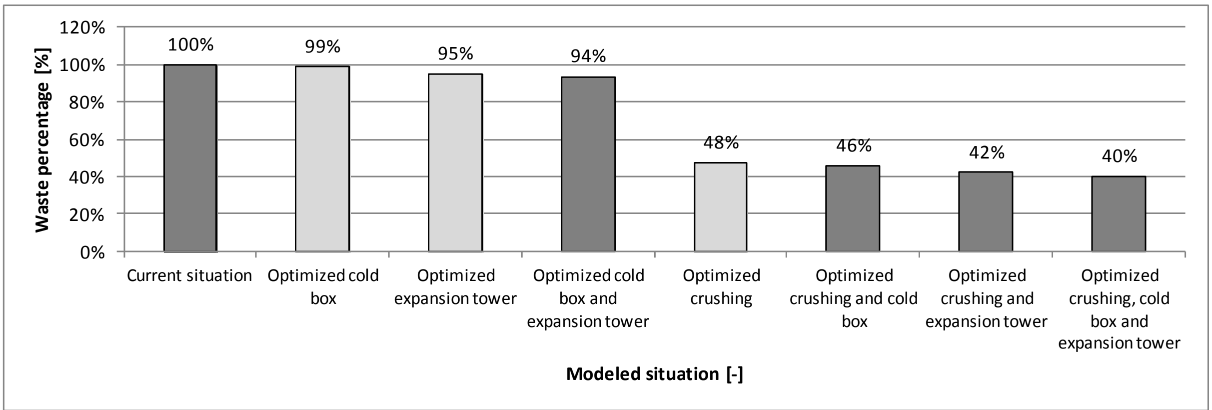


Figure 5.4: Effect of improvements towards total waste fraction

The best results towards waste reduction could be achieved by optimizing the crushing process. This could reduce the waste by 52.2%. Second best is optimizing the expansion tower transport, resulting in a waste reduction of 4.90%. Optimizing the cold box area could decrease the waste flow by 1.16%.

When each of the three improvement process steps would perform optimally, the total waste fraction would be reduced by 59.5%.

To quantify the result of optimization towards tobacco particle size distribution quality, harmonic mean sizes for all scenarios at multiple process positions are given in the figure below.

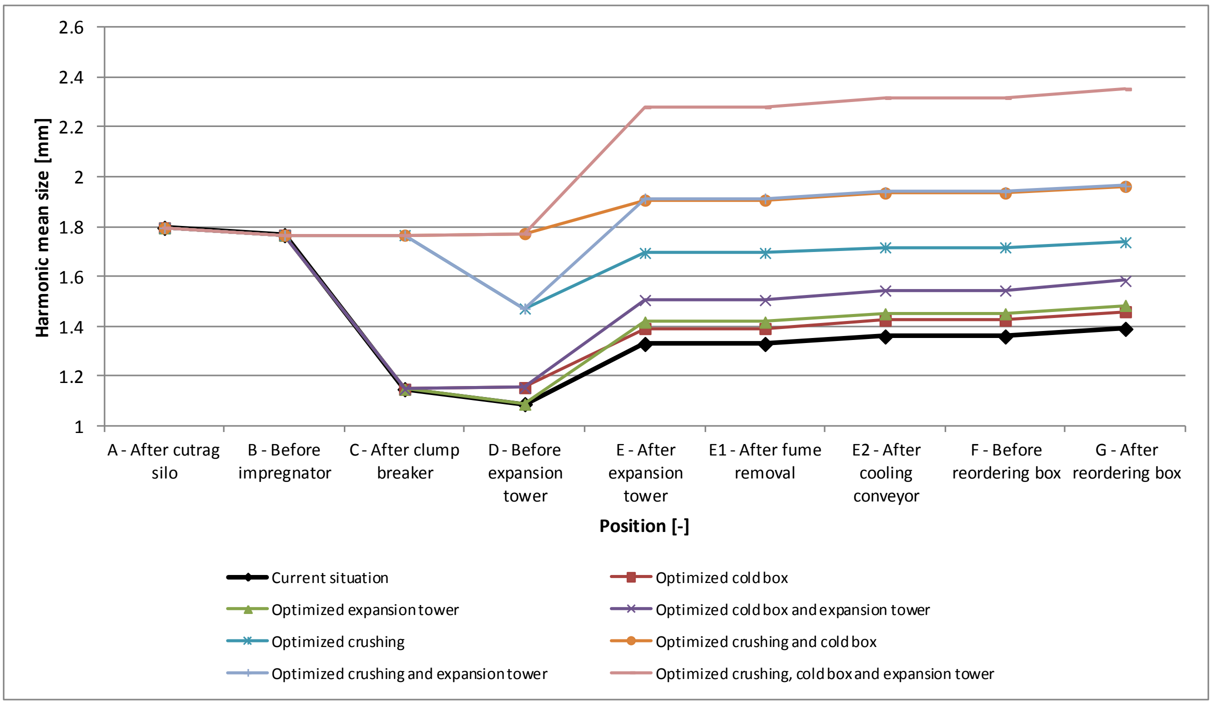


Figure 5.5: Mathematical model harmonic mean values for multiple scenarios

As is shown in figure 5.5 out of the three general improvement scenarios optimizing the crushing process results in the best increase of final tobacco quality, through increasing the harmonic mean size by 25.0%. Second best result is optimizing the expansion tower transport, resulting in a 6.78% increase. Optimizing the cold box area would increase the final tobacco harmonic mean size by 4.96%. Logically the combinations between the three general improvement scenarios are most promising. All three combined could improve the final harmonic mean by 69.3%, and reduce the waste flow with 59.5%.

Table 5.1 shows a summarized overview of the possible profits when reducing tobacco degradation caused at the crushing, cold box and expansion tower process steps.

	Quality [%]	Quantity [kg/yr]	**Value [€/yr]**
Cold box	4.96	3.09×10^3	**14K**
Expansion tower	6.78	13.0×10^3	**59K**
Crusher	25.0	139×10^3	**625K**

Table 5.1: Effect of degradation on quality, quantity and economic value

In the table, quality is expressed as the percentage improvement of the final product harmonic mean size. Quantity is expressed as the recoverable amount of final product at 11.5% OV. The value is expressed as the amount of money related to the recoverable quantity.

5.3 Reduction of tobacco degradation

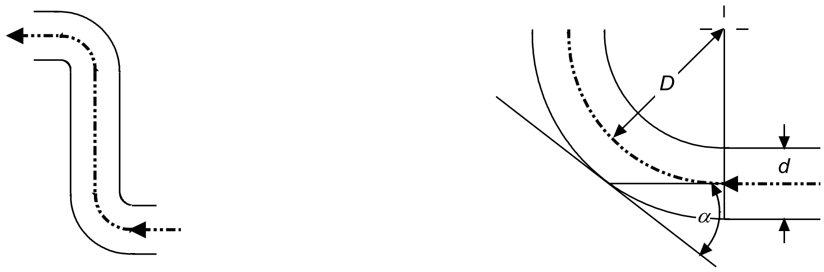
The aims of this section are to:

- *Present the process steps causing tobacco particles to break down in size.*
- *Describe possibilities for degradation reduction.*

As a result of the sample collecting and particle size determination from chapter 3 and results of the mathematical model in section 5.2, three main areas were identified related to tobacco degradation: (1) expansion tower, (2) cold box and (3) crushing.

5.3.1 Expansion tower degradation

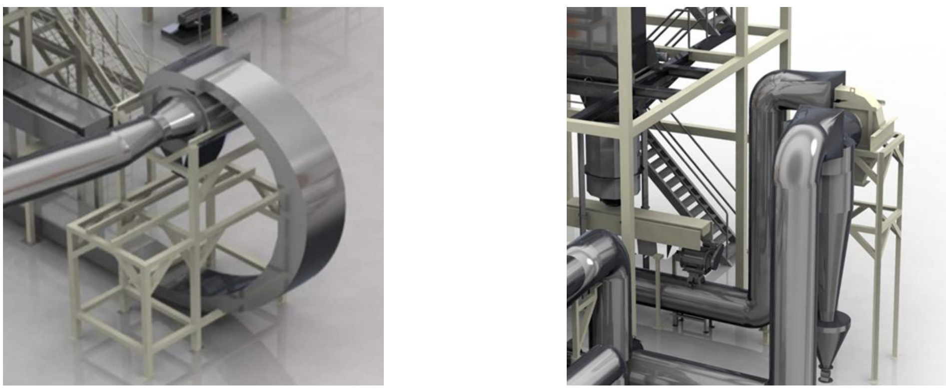
Building on results of the mathematical model, pneumatic conveying in the expansion tower causes a fraction of the tobacco particles to break down. Due to this particle degradation, fines are created which in post process steps are separated from the main flow. Assuming yearly 50 full production weeks, 25 batches of 11,500 kg cut rag tobacco at 20.0% OV, in case of a 100% effective expansion tower this loss would equal 13.0×10^3 kg (€59K) final product (at 11.5% OV, 4.50€/kg).
Looking to the geometry of the expansion tower, because of the S-shape it consists of two bends. Figure 5.6 visualizes a typical 90º bend.



(a) Expansion tower geometry (b) Bend geometry and impact angle

Figure 5.6: Expansion tower and bend geometry

With sharp bends, having a low D/d ratio, the majority of particles will impact against the bend wall at a steep impact angle α. The more severe the impact of the material against the bend wall the greater will be the problem of degradation [23, p515] By having a long radius bend, the impact of material inside the bend would be reduced resulting in less particle degradation. Figure 5.7 illustrates the current S-shape expansion tower design and a long radius C-shape design from manufacturer AIRCO.



(a) C-shape (b) S-shape

Figure 5.7: Expansion tower designs

By using long radius bends, the total waste quantity will be reduced due to less degradation. A maximum of 13.0 × 10^3 kg (€59K) could be gained by optimizing the expansion tower.

5.3.2 Cold box degradation

In the analysis section of this thesis it had been quantitatively proven that degradation of the impregnated tobacco particles during cooled transport in the area between impregnator vessel and expansion tower occurs. As shown in the steady state model given in figure 3.8 in chapter 3, this transporting route consists of multiple process steps. Each of the process steps could cause the tobacco particles to break down. Therefore multiple samples have been collected and analyzed towards particle size distribution to quantify contribution towards particle breakage. Figure 5.8 illustratively shows a cross sectional view of the area, the sample collection positions are denoted with a M-sign.

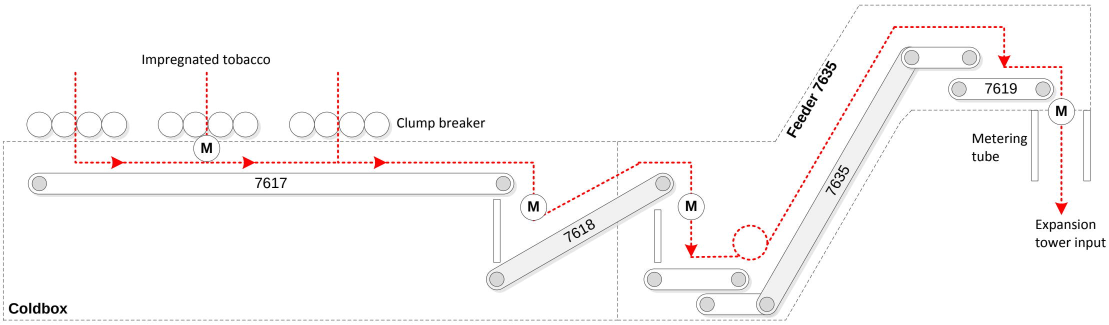


Figure 5.8: Cold box geometry

After collecting samples (i.e. 10 samples per position, 40 in total) and the required conditioning, sieving analysis has been carried out. Figure 5.9 gives the results of the sieving analysis.

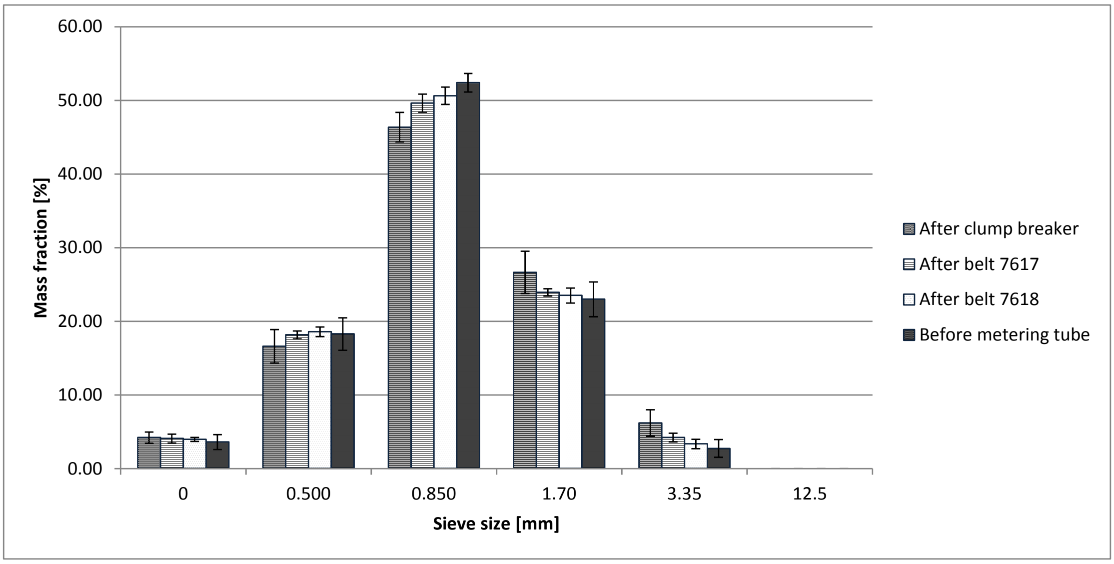


Figure 5.9: Cold box sieving analysis results: particle size distributions

It appears that each process step contributes towards particle breakage. Material degradation in the cold box area is due to free fall of the material in three out of the four process steps: (1) drop height between clump breaker and conveying belt 7617, (2) transition point between conveying belt 7617 and 7618 and (3) transition point between conveying belt 7618 and feeder 7635. Figure 5.10 shows pictures of the cold box configuration.

(a) Belt 7618 and 7617 (b) Belt 7618 (c) Belt 7635

Figure 5.10: Inner cold box layout

According to Lodewijks, material degradation can be compromised during chute design. [24] Figure 5.11 illustratively shows a transfer chute between a feeder and a conveyor.

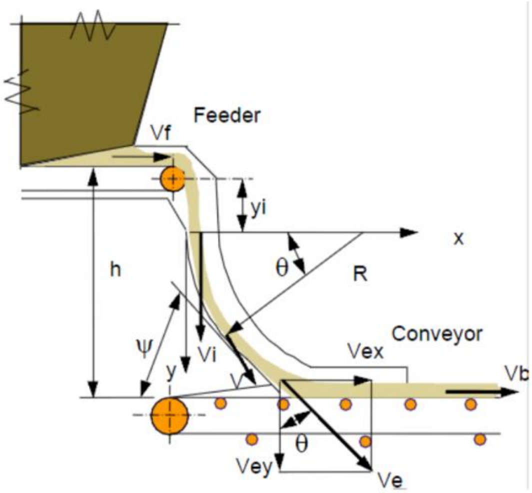


Figure 5.11: Transfer constant radius chute example

The goals during chute design are to minimize speed component v_{ey} and to let speed component v_{ex} equal v_b. Lodewijks showed the influence of multiple chute profiles (i.e. constant radius chute, parabolic chute and combined constant radius + straight chute) towards material stream velocities and required dimension, concluding gains can be made by using non-constant radius chutes.

For chute design, friction coefficient between product and chute material must be known. Determination can be done by using a shear tester. Another complaint is that bulk solids have an internal friction angle to be considered. [25, p221] Since the impregnated tobacco inside the cold box has a temperature of -79°C, and the environment temperature is below zero, determining friction coefficients is not straightforward.

A more uncomplicated way to minimize the vertical speed component of the falling tobacco in order to decrease degradation is by installing straight inclined chutes. Figure 5.12 illustrates straight line chutes for the two transition points in the cold box.

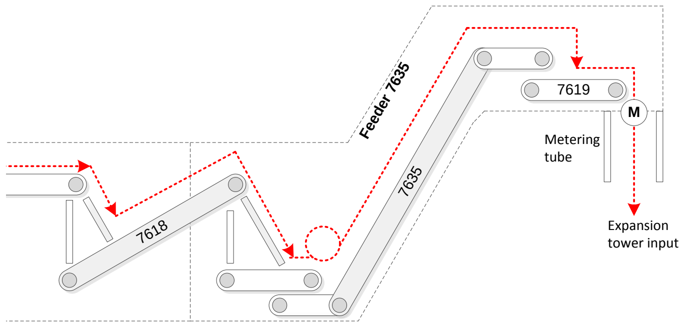


Figure 5.12: An example of straight line chutes

If in one of the transfer points an adjustable chute is mounted, the optimized chute angle can be determined by changing the chute angle until material stream speed is minimized without occurring blockages. When knowing the chute angle, chutes for the other two positions can be designed.

Due to this particle degradation, fines are created which in post process steps are separated from the main flow. Assuming yearly 50 full production weeks, 25 batches of 11,500 kg cut rag tobacco at 20.0% OV, in case of a 100% effective expansion tower this loss would equal 3.09×10^3 kg (€14K) final product (at 11.5% OV, 4.50€/kg).

5.3.3 Clump breaker degradation

At the PMH ET2 process, the clump breakers are used for achieving size reduction of the frozen clump of impregnated tobacco. Size reduction is required for further processing. Based on the sieving size analysis results from chapter 3, the crushing the tobacco with the clump breaker is the main cause of creating tobacco fines in the process. By improving this process step, a maximum of 139×10^3 kg (€625K) final product could be yearly gained. According to Lodewijks, important criteria to consider in selecting a crusher are: [26]

- Will the crusher handle the maximum required capacity to be processed without undue strain or overload?
- Will the machine handle the maximum lump size of the infeed material?
- Will the unit's operating mechanism handle the properties of the material: i.e. friable, tough, sticky, abrasive?
- Is the crusher design and construction suitable for the special application requirements such as resistance to corrosion, maintenance of purity or sanitary requirements?
- Will the crusher produce the output particle size required?
- Will the crusher produce excessive fines?
- Will the equipment operate with minimal noise or vibration?
- How will the material be fed? Conveyed, pumped or dropped by gravity?
- Does the crusher match the connection configuration? Dimensions, round or square?
- Is the crusher suitable for the operating conditions and operating temperature?
- Does the unit meet the requirement for ease of maintenance and interior access?
- Does the crusher have seals adequate for the application?
- Is qualified field service and customer support available from the supplier?
- Is the machine built with high quality materials and workmanship?
- Is the crusher configuration suitable to fit in the available space?

This section describes the conducted studies for improving the crushing effectivity, i.e., creating a minimized fraction of tobacco fines during crushing. In order to investigate possible optimizations, the following actions have been initiated:

- Adjusting characteristics of the current crusher
- Benchmarking with other affiliates for different crushing techniques
- Benchmarking with other industrial sectors for different crushing techniques

During all tests both sample collection and performing sieving analysis are carried out in accordance to the method stated in chapter 3.

5.3.3.1 Adjusting characteristics of the current crusher

The three in parallel working clump breakers are crushing the tobacco at a fixed frequency of rotation. According to Mitchell, Mitchell and Pascoe size reduction is directly proportional to the rotor speed; it controls the amount of fines produced. Slower rotor speeds will reduce crusher wear and produce fewer fines, however it may adversely affect the particle shape of the product. [27, p109]

In order to quantify possible influence of frequency of rotation during crushing, tests have been conducted. By using a frequency speed controller it was possible to adjust the angular frequency ω of the crusher (figure 5.13).

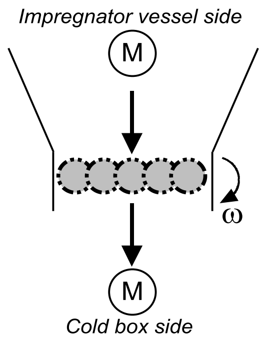
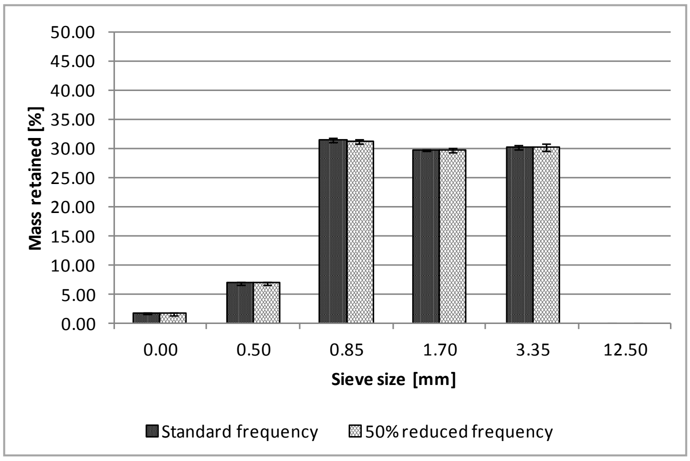
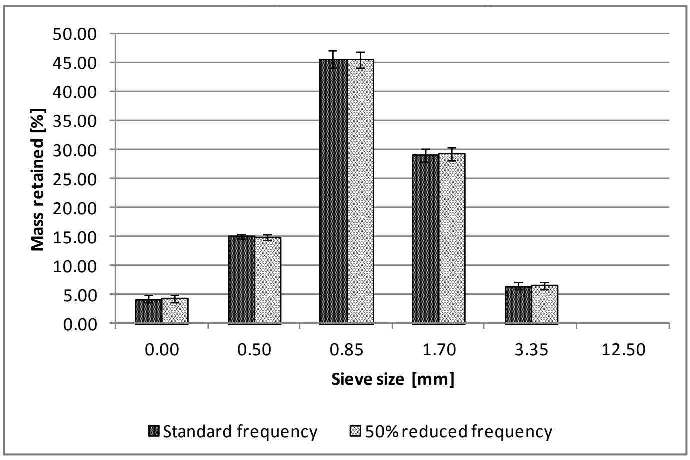


Figure 5.13: Schematic cross-sectional view of the crusher

Two cases have been investigated. For reference first during standard production, $\omega_{standard} = \omega_{100\%}$ and second at 50% reduced frequency, $\omega_{test} = \omega_{50\%}$. Both situations are quantified by taking samples for sieving analysis before and after crushing, as illustrated in figure 5.13. Test results are represented in figure 5.14.



(a) Particle size distributions before crushing



(b) Particle size distributions after crushing

Figure 5.14: Decreased crusher frequency of rotation test results

Based on the results of the performed test, levels of all size fractions remain within boundaries, i.e., deviations are smaller than the accuracy of measurement. Therefore lowering the rotational crushing speed has no significant effect on the particle size distribution of the crushed tobacco flow.

5.3.3.2 Benchmarking with other PMI affiliates

Within PMI there are several production plants producing expanded tobacco by means of the DIET process. This implies that those other plants possibly use different sorts of techniques for size reduction of the clump of frozen impregnated tobacco.

After benchmarking it turned out that only one affiliate, Philip Morris Australia, is using a different technique. Instead of breaking the frozen clump of tobacco down with rotating bars, crushing is done by using a vibrating screen. First the clump breaks in smaller clumps by falling down onto metal beams. Second the small clumps break down in even smaller fractions by a number of vibrations until passing the screen. Photos of this equipment from Philip Morris Australia are shown in figure 5.15.

(a) Side view (b) Top view

Figure 5.15: PMI Australia's vibrating screen crusher

From the point of view of tobacco degradation by crushing, it would be very interesting to collect and analyze samples from before and after crushing towards particle size distribution. Those analysis results could be compared to the PMH ET2 clump breaker analysis results to see if crushing by vibration is a better technique towards creating less fines.

For this thesis, samples in the Philip Morris Australia plant have been collected before and after crushing. As described in chapter 3, 10 samples at each side were collected. The particle size distributions have been determined according to the procedures described in chapter 3.

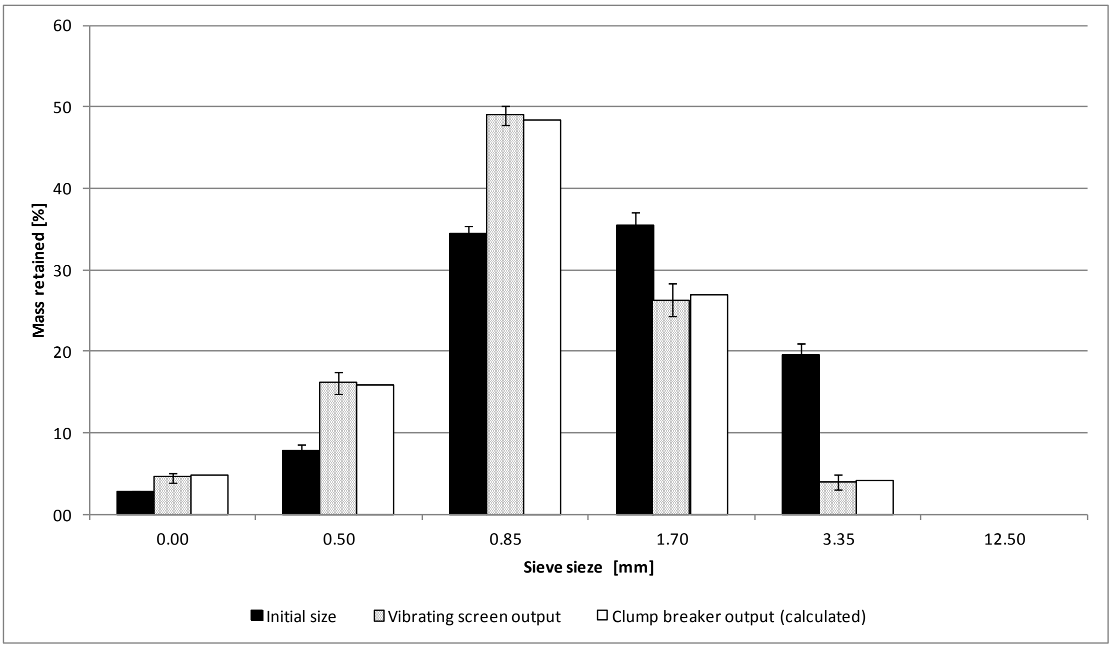


Figure 5.16: Results of the vibrating screen crusher comparison test

Figure 5.16 shows the results from the analysis towards particles size distributions. A calculated particle size distribution data set, calculated by use of the in section 5.2.1 introduced mathematical model, is added to compare the results towards ET2 clump breaker crushing.

Based on this analysis it can be concluded that there are no significant differences between crushing either done by PM Australia's vibrating screen or by the ET2 clump breaker.

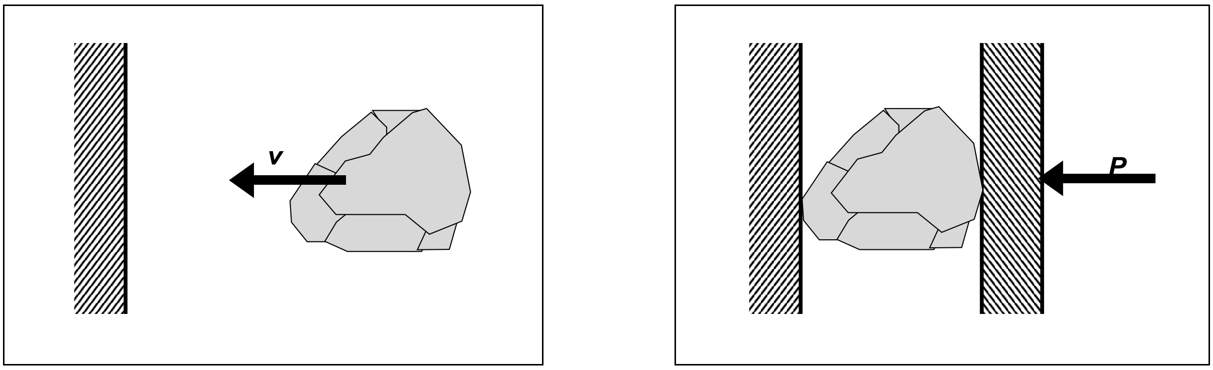
5.3.3.3 *Benchmarking with other industries*

Outside the tobacco industry, other industrial sectors are using multiple techniques for size reduction. Within the metallurgical and mining industry extensive research had been conducted related to crushing techniques and material degradation.

For size reduction in the metallurgical and mining industry, generally there are two main types of crushing: [28, p27]

1. Impact crushers
2. Compressive crushers

Impact crushers use dynamic forces to break a piece of material into smaller parts by impacting particles against a rigid surface. Compressive crushers are squeezing particles between two surfaces to apply size reduction. These two main crusher types are illustrated in 5.17.



(a) Impact (b) Compression

Figure 5.17: Two general types of crushing

Typical properties for crushers used in aggregate production plants are presented in table 5.2. [29]

	Crusher type			
	Jaw crusher	*Cone / Gyratory crusher*	*Horizontal impact crusher*	*Vertical impact crusher*
Breakage method	Compression	Compression	Impact	Impact
Energy consumption / ton	Low	Medium	High	High
Production of fines	Low	Medium	Medium / High	Medium / High
Investment cost	Medium / High	Medium / High	Low / Medium	Low / Medium
Wear part costs / ton	Low	Medium	High	Medium / High

Table 5.2: Typical crusher properties

Based on these typical crusher properties, related to a minimized production of fines during crushing, a jaw crusher looks promising. Results from a study towards production of quarry fines during crushing in aggregate production plants support this. Results from this thesis are given in table 5.3. [27, p40]

	Proportion of produced quarry fines [Weight%]	
Rock type	*Jaw crusher*	*Impact or gyratory crusher*
Sandstone	1-2	15-20
Limestone	6-7	20
Igneous and metamorphic	3-6	10-15

Table 5.3: Quarry fines production results

In order to obtain insight into tobacco fines creation with another crushing technique tests could be performed. Therefore a clump of impregnated tobacco should be collected and reduced in size by the test crusher, after which input and output tobacco must be analyzed towards the particle size distribution for making the comparison to the current crushing technique.

Based on the results of previous mentioned studies, size reduction applied by a jaw crusher looks most promising. For testing size reduction by a jaw crusher, a jaw crusher and a clump of impregnated tobacco are required. This would mean that a clump of impregnated tobacco must be created at the test crusher location, the test crusher must be located near an impregnator vessel in the factory, or a clump of impregnated tobacco must be transported to the test crusher. The best test would be to crush a clump of impregnated tobacco at equal conditions such as in practice. Collecting a total batch of impregnated tobacco (~320kg) and keeping it cooled for an amount of time is not practical due to the size and weight. Creating a clump of impregnated tobacco at a location outside the factory would require an expensive high pressure CO_2 impregnator vessel.

A solution towards the above mentioned problems is to perform the crushing test by using smaller batches. Then both cooling and transportation are easier to achieve. The Recycling Technology laboratory at the Technical University of Delft's Civil Engineering faculty is equipped with a laboratory-size jaw crusher. Specifications of this jaw crusher are listed in the table below, table 5.4.

Brand/type	Retsch Jaw Crusher BB 2/A
Power	220 V 50 Hz 1.5 kW
Filling opening	100 x 100 mm
Jaw material	Manganese steel
Dimensions	1030 x 690 x 90 mm
Weight	300 kg

Table 5.4: Laboratory jaw crusher specifications

(a) Front view (b) Top view (c) Side view

Figure 5.18: The Retch BB 2/A laboratory jaw crusher

After discussing the possibilities for testing frozen tobacco crushing with S.P.M. Berkhout, expert in the field of recycling technologies, preparations have been made for performing the test.
The tobacco for testing purpose was first impregnated at the impregnation vessel in the PMH factory, after which it was directly collected in a dry ice cooled polystyrene container for retaining the original temperature conditions. A total of 5kg tobacco was collected, prepared for transport, transported to the TU Delft Recycling Technology laboratory. At the TU Delft Recycling Technology laboratory multiple tests have been performed. Figure 5.19 shows pictures of the impregnated tobacco during transport.

(a) Dry ice pellets

(b) Polystyrene container

Figure 5.19: Cooled impregnated tobacco transport

The number of samples for each test to be collected for particle size distribution analysis equals 10 for both feed and output of the crusher, as determined in chapter 3. For quantifining possible influence of the jaw crusher output opening size, two tests are perfomed. First at 50% output opening size and second at 100% output opening size. Test results are shown in the figure 5.20.

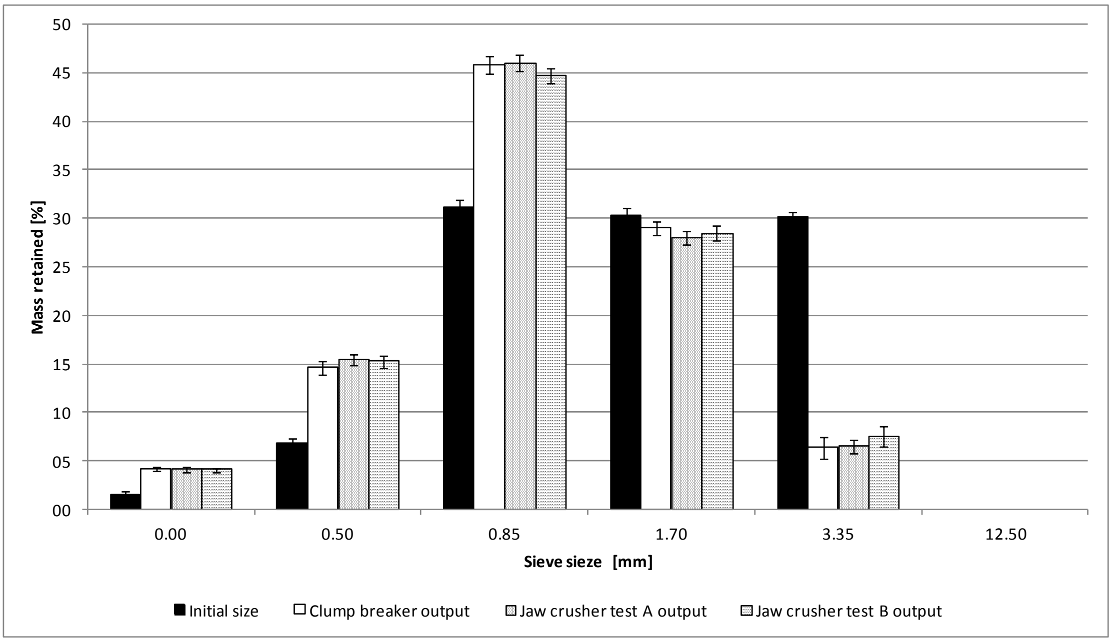


Figure 5.20: Results of the jaw crusher comparison tests

Based on the results of the performed tests, levels of all size fractions remain within reference boundaries. Therefore using the jaw crusher under the given conditions has no significant positive effect towards tobacco quality after crushing.

5.4 Waste flows containing larger size tobacco particles

The aims of this section are to:

- *Present the process steps where tobacco waste is collected.*
- *Describe possibilities for reducing the fraction intermediate and coarse size particles within the waste flows.*

Ideally the particle size distribution of waste flows would be in such a way that the smallest size fraction, fine particles, obtained from sieving analysis would equal 100%. If this is not the case, possibilities to prevent larger size fractions, intermediate and coarse particles, ending up in a waste flow must be studied. When preventing larger size particles to end up as waste is not possible or profitable possibilities to win and add back those particles must be examined.

Figure 5.21 shows the process layout with the six waste collection positions. Table 5.5 shows the possible profits per waste flow.

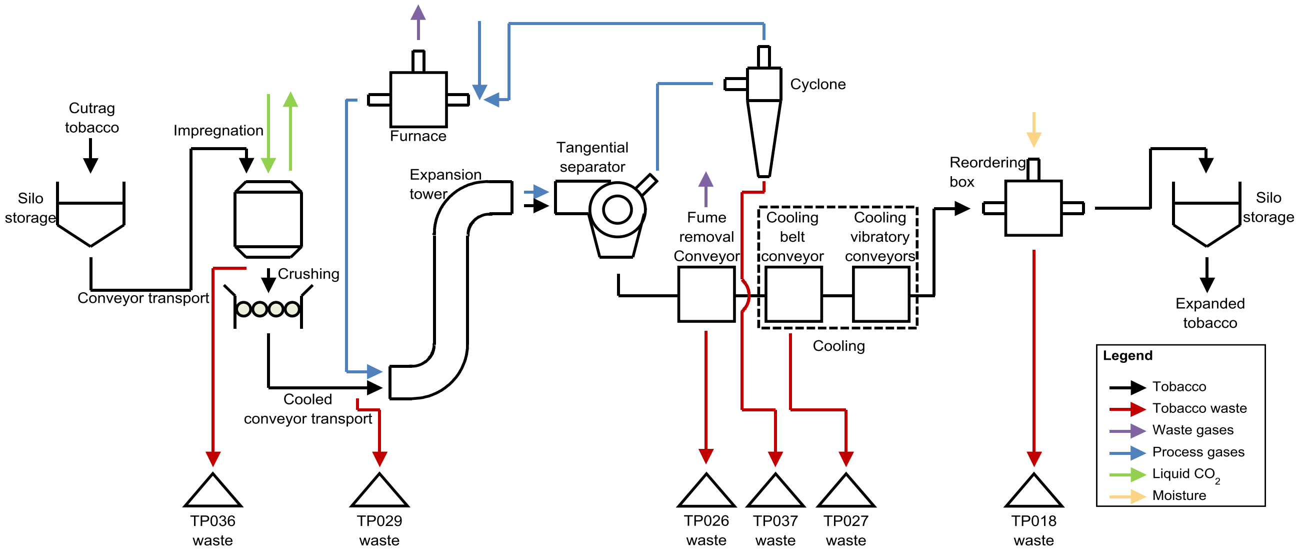


Figure 5.21: Visualization of the ET2 process steps and material flows

	Usable fraction [%]	Quantity [kg/yr]	**Value [€/yr]**
TP018	3.93	2.00×10^3	**9K**
TP026	88.5	11.5×10^3	**52K**
TP027	12.6	12.4×10^3	**56K**
TP029	3.39	0.679×10^3	**3K**
TP036	4.05	0.516×10^3	**2K**
TP037	3.62	2.56×10^3	**12K**

Table 5.5: Losses due to coarse and intermediate particles in waste flows

Waste flow TP026 is having the highest usable fraction, and second highest quantity. TP026 is waste due to overheated tobacco at process startups and stops. A reduced number of blend changes will reduce the number of startups and stops. Currently the planning department already focuses on scheduling as many equal blends in series as possible. Therefore further optimizing TP026 will not be part of this thesis.

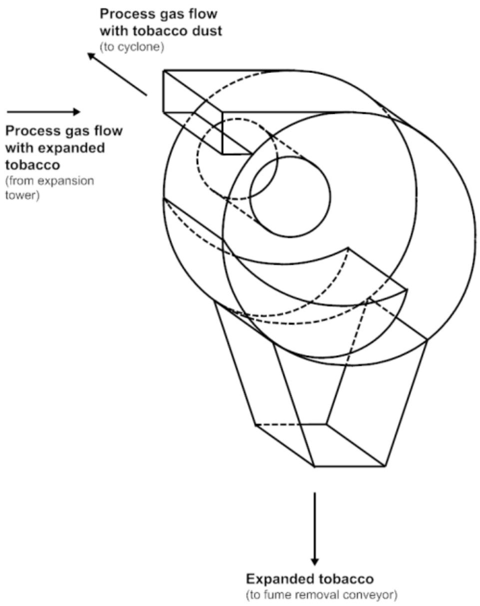
TP027 is covering the highest amount of usable particles, and after TP026 having the highest usable fraction. The waste flows having the smallest usable fraction, i.e., intermediate and coarse particles, are TP029, TP037, TP018 and TP036. Looking at TP037, i.e., cyclone dust, still containing intermediate and coarse size tobacco particles, it implies the tangential separator does not fully separates the tobacco and process gas flows.

In the next sections, possibilities to reduce TP037 and TP027 waste are presented.

5.4.1 Cyclone waste TP037

The waste flow collected from the cyclone which separates small tobacco particles from the process gas flow after the expansion tower contains larger size tobacco particles. This implies that the preceding tangential separator after the expansion tower has not a 100% effectivity.

To analyze the possibilities to prevent the process gas flow out of the tangential separator from containing larger size tobacco particles, the tangential separator must be examined. The separators working principle is based on the combination of centrifugal forces and gravitation. An graphical three-dimensional view and outside picture are presented in figure 5.22.



(a) Schematic three-dimensional view

(b) Side view

Figure 5.22: The tangential separator

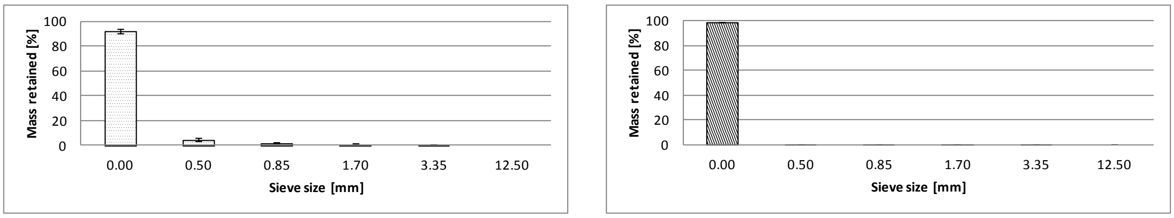
Since in the current situation no attention is given to quality and quantity of the multiple waste flows, it was not possible to determine whether cyclone waste in the paste was containing larger size tobacco particles or not. If the inner mechanics have changed over time due to for instance wear, this could influence the behavior of the separator. To check for this a mechanical check has been performed.

(a) Tobacco flow outlet (b) Bottom plate (c) Air flow outlet

Figure 5.23: Inner tangential separator overview during inspection

Figure 5.23 shows pictures taken during the mechanical check. No defects were noticed, allowing the assumption that the problem of cyclone waste TP037 containing larger size tobacco particles has always been the case.

In order to perform a first check towards separator effectivity, samples have been taken for sieving analysis from the other PMH expanded tobacco process: ET1. Both sample collection and sieving analysis are performed according to the method introduced in chapter 3. Analysis results are given in the figure below, figure 5.24.



(a) ET2 figures (b) ET1 figures

Figure 5.24: Separator effectivity comparison test results

At the ET1 process 99.0% of the cyclone waste consist of particles from the smallest size class, this is 91.9% for the ET2 process.

Assuming yearly 50 full production weeks, 25 batches of 11,500 kg cut rag tobacco at 20.0% OV, 0.545% dry TP037 waste and 11.5% OV final product at 4.50€/kg, the yearly improvable quantity equals 5.05×10^3 kg (€23K). This quantity is higher than the previously calculated amount based on particle size distribution. It is therefore likely that intermediate and coarse size particles still part of the process gas flow after been separated in the tangential separator break down due to the transportation route.

The working principle of the separator is based on centrifugal forces and gravity, in which gravity cannot easily be influenced. Centrifugal forces on the other hand can be influenced. When a mass is describing a circular motion, the centrifugal force F_c (N) equals:

$$F_c = m \cdot a = m \cdot \frac{C^2}{r} \tag{5.19}$$

where m is the mass of a particle (kg), a is the acceleration (m/s^2), C the mean flow velocity and r the radius of the path. [30, p7] The centrifugal force equals the centripetal acceleration multiplied by the mass.

An adjustable parameter is the process gas speed. Increasing the process gas speed would cause the tobacco flow speed inside the expansion tower to increase. For having the same heat exchange between hot process gas and tobacco, the process gas temperature needs to increase as well. According to the process experts, the current furnace which heats the process gas cannot be stoked at a higher temperature. As a result of this, focus towards improvement should be on changing or modifying the current separator.

The mean velocity of a flow through a tube depends on the volumetric flow rate and the tube section area. The relationship is:

$$C = \frac{\dot{V}}{A} \tag{5.20}$$

where C is the conveying air velocity (m/s), $\dot{V}$ is the volumetric flow rate (m^3/s) and A is the tube section area (m^2). [23, p187]

In order to increase C, at a constant value of $\dot{V}$, the tube section area A must be reduced. A smaller section area implies an increased flow velocity. Figure 5.25 illustrates an example of decreasing the section area by narrowing the tangential separator feed tube with an adjustable accelerator plate.

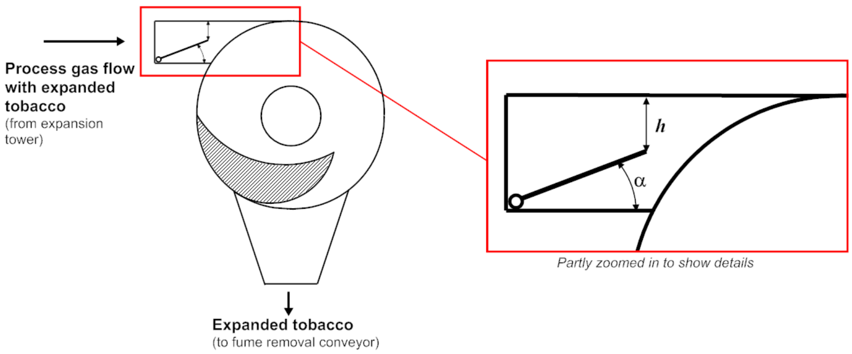


Figure 5.25: Cross-sectional view of the tangential separator with adjustable accelerator plate

By increasing the acceleration plate angle α the tube height h increases. Since the rectangular section area A equals tube height multiplied by tube width, a reduced tube height results in an increased conveying air velocity. An increased conveying velocity increases centrifugal force F_c resulting in an improved separating effectivity. Yearly a total of 5.05×10^3 kg tobacco (€23K) could be gained as a result of improving the tangential separator.

5.4.2 Cooling conveyor waste TP027

Analysis showed that waste collected as TP027 contains larger size tobacco particles. TP027 is composed of waste from five locations: four obtained from the cooling conveyor and one obtained from the conveying belt entering the reordering box. Both conveyors are mesh belt conveyors, allowing small tobacco particles to fall through. Cooled air flowing inside the cooling conveyor casing causes a fraction of larger sized particles to be separated from the main flow.

5.4.2.1 Waste flow TP027 quantification

Waste collection point TP027 covers the waste from five different collection positions. For clarification, figure 5.26 shows a visual representation of the physical situation.

(a) Underside with waste outlets

(b) Mesh belt

Figure 5.26: Cooling conveyor

A first visual check showed that waste from all the five TP027 positions contains tobacco of larger size fractions. In order to quantify possible gains by preventing larger sized particles from being separated from the main tobacco flow or by adding them back to the main tobacco flow, the particle size distribution must be measured. For obtaining this data, samples have been collected for sieving analysis at each position. Both sample collecting and conducting sieving analysis have been performed according to the method explained in chapter 3. The locations of the sample positions are indicated by a character in figure 5.27.

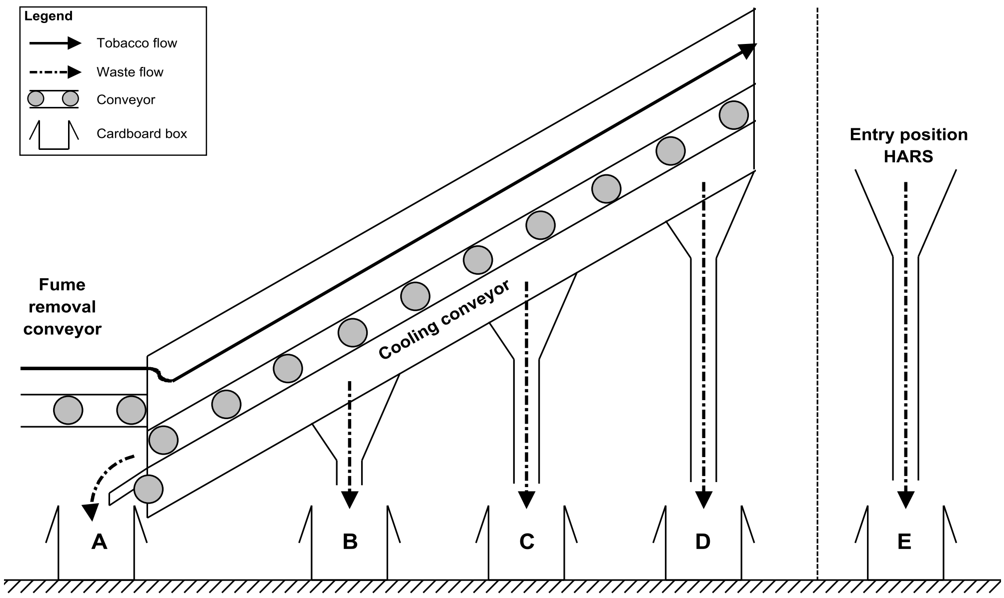
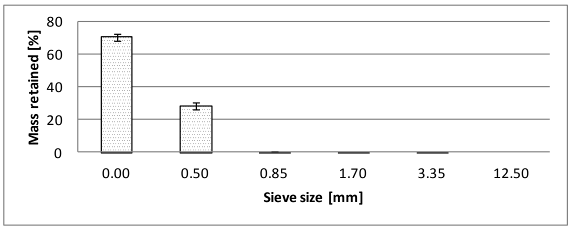
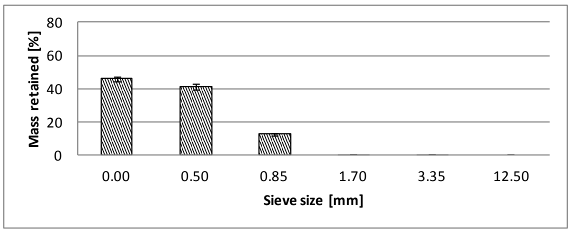


Figure 5.27: Schematic view of waste collection position TP027

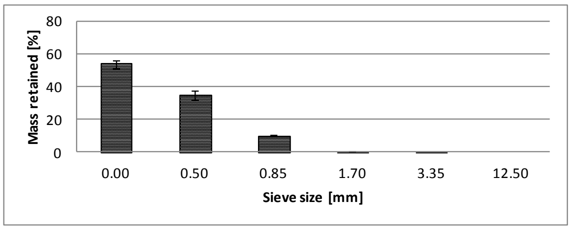
Figure 5.28 shows the results from sieving analyses performed on the samples collected at the multiple waste positions from collection point TP027.



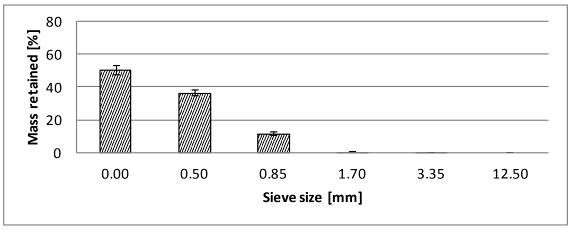
(a) Position A



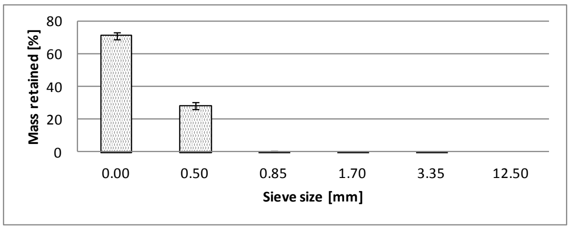
(b) Position B



(c) Position C



(d) Position D



(e) Position E

Figure 5.28: Waste flow TP027 sieving analysis results

It is clear that especially waste from positions B, C and D contains larger sized particles. For final quantification of usable waste fraction, mass flow distributions between the multiple positions must be known. For quantifying mass flows, cardboard boxes from the multiple positions have been weighted during a fixed time. Results of these measurements are given in table 5.6.

TP027 waste positions	A	B	C	D	E
Fraction from total mass flow [%]	20.4	20.3	23.6	21.4	14.3

Table 5.6: TP027 waste quantity measurement results

Based on the with experts agreed add back size of tobacco particles from sieve size classes ≥ 0.85mm and knowing particle size distributions and mass flows, the usable TP027 fraction can be calculated.

Assuming of yearly 50 full production weeks, 25 batches of 11,500kg cut rag tobacco at 20.0% OV, 0.759% dry TP027 waste and 11.5% OV final product at 4.50€/kg the yearly recoverable quantities and values are given below, in table 5.7.

TP027 waste positions	A	B	C	D	E
Recoverable quantity [kg/yr]	0.242×10^3	3.93×10^3	3.97×10^3	4.07×10^3	0.187×10^3
Value [€/yr]	**1K**	**18K**	**18K**	**18K**	**1K**

Table 5.7: TP027 recoverable quantities and corresponding values

In total 12×10^3 kg expanded tobacco per year with a value of €56K could be recovered from the TP027 waste flow.

5.4.2.2 Waste flow TP027 optimization

With the recoverable quantity in mind, optimizing the cooling conveyor area towards waste separation should be considered. Generally there are two possible directions for solutions:

1. Preventing the larger sized particles to be separated from the main flow
2. Separate larger sized particles out of the waste flow and add them back to the main flow

The cooling conveyor aims to cool down the hot expanded tobacco, which influences the tobacco taste. Therefore air flows inside the conveyor casing are critical and are not allowed to be adjusted before they are certified for production. Larger sized particles finally ending up in TP027 waste are separated from the main flow cause of air flows.
Based on the experience of experts, changing air speeds would affect the tobacco taste. For this reason the focus towards recovering larger sized tobacco out of TP027 waste lies on separating and adding them back to the main flow.

Tobacco particles from waste flow TP027 are low on moisture level (3.5% OV) since they almost immediately come out of the expansion tower. Final product needs to be at a 11.5% OV moisture level. According to the experience of experts, adding back a relatively small fraction of tobacco at moisture level < 11.5% OV would not negatively influence the final product quality. For this reason adding back tobacco at 3.5% OV will not require additional moistening. Knowing this, for adding back low moisture tobacco the conventional add back process as explained in chapter 3 is usable.

For researching the possibilities towards separation, tests have been performed with a vibratory sieving conveyor. The test set-up is visualized in figure 5.29.

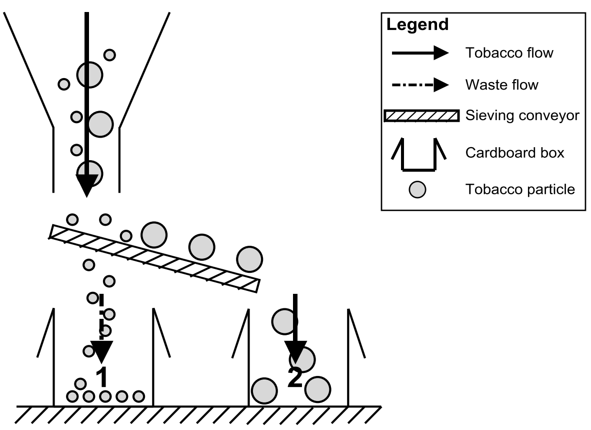
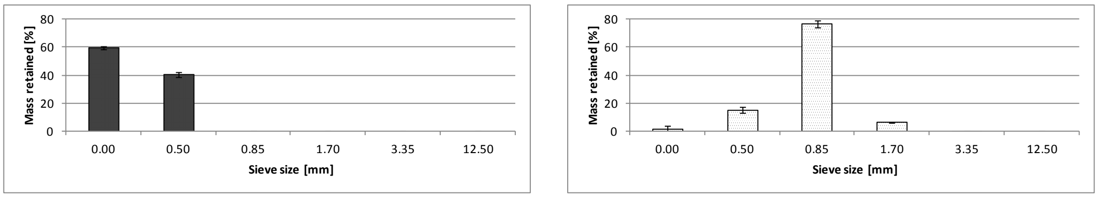


Figure 5.29: Schematic view of the TP027 sieving test set-up

During testing, the sieving conveyor was located under waste position D. The used sieving conveyor contains a screen with openings equal 0.85mm. According to the previous mentioned sieving analysis procedure, samples have been collected at both positions 1 and 2 (figure 5.29) and analyzed towards particle size distribution. The particle size distributions are shown in figure 5.30.



(a) Position 1 (b) Position 2

Figure 5.30: TP027 sieving test results

Based on these numbers, separating usable tobacco by using a vibrating screen conveyor is effective. Particles from sieve size fractions ≥ 0.85mm are 100% separated. Although there is still a fraction of smaller sized particles present in the separated flow (16.6%, which would be still acceptable according to experts). When sieving out the intermediate and coarse size particles and adding them back to the main expanded tobacco flow, this is visualized in the steady state model in figure 5.31.

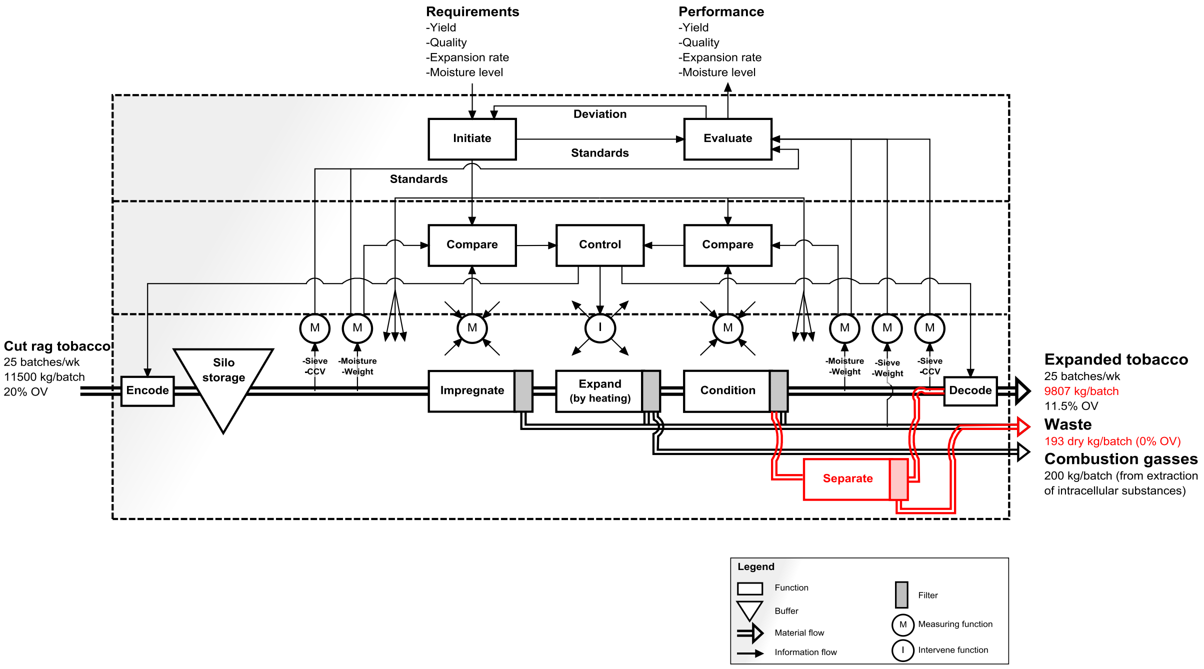


Figure 5.31: Expanded tobacco steady state model with usable waste add-back

The TP027 waste flow, part of the 'Condition' function, gets separated by sieving. The coarse and intermediate particles return to the main expanded tobacco flow, while the fine tobacco particles join the total tobacco waste flow.

6 Implementation plan

Chapter 4 describes the problem statement concerning the process and function control towards tobacco yield. Chapter 5 describes several improvement proposals. In this chapter, an implementation plan is described which makes it possible to get the improved yield situation of chapter 5, from the current situation.

6.1 Tobacco degradation reduction and waste flow optimization

In chapter 5 several improvements are proposed to reduce tobacco degradation and to optimize waste flows, resulting in an increased output flow of higher quality. To implement those improvements in practice several process steps have to change.

6.1.1 Tobacco degradation reduction

For the degradation of tobacco particles during crushing after the impregnating step no significant improvements have been found. However it is advised to proceed the study towards tobacco degradation during this step. Topics that have not been studied are the effect of feed tobacco particle size distribution towards final product quality and the amount of waste. The effect of the filling level of the impregnation vessel towards degradation is not known. Also the effect of impregnation pressure towards degradation level would be interesting to research. This thesis provides for the standards to start such a research.

Due to transition points between belt conveyors in the cold box area tobacco degradation occurs. To reduce this amount of degradation mounting transfer chutes is a solution. Since the transporting conditions are such to keep the impregnated tobacco frozen, it is difficult to determine the optimal transitioning angle. To simply determine the optimal transitioning angle, in one transition point an adjustable straight chute must be mounted. Iteratively by altering the angle its optimal value must be obtained, to minimize the tobacco speed in such a way that no blockages occur. When knowing the optimal transition angle, for the other transition points must be designed, manufactured and mounted.

Due to sharp radius bends in the expansion tower tobacco degradation occurs. To reduce this amount of degradation the sharp radius bends must be replaced by long radius bends. To meet the expansion requirements, the impregnated tobacco needs to receive a certain amount of heat during a specific amount of time. When designing the improved expansion tower those requirements must be taken into account.

6.1.2 Waste flow optimization

TP026 consists of impregnated tobacco from process starts and stops. The planning department must focus on scheduling batches of equal blend type in series. This reduces the amount of TP026 waste. Currently TP026 waste is classified as waste since it contains overheated tobacco. It not known what the influence will be towards final cigarette taste when TP026 waste is added back scattered over a regular batch. To test this, in a test environment tobacco must be composed containing an appropriate fraction of TP026 waste. From this tobacco cigarettes must be made to test towards taste and to obtain smoke numbers.

Waste flow TO027 contains a fraction of intermediate and coarse size particles. Tests have demonstrated that by continuous sieving the intermediate and coarse size particles can be separated during processing. A proper sieving installation having a sufficient capacity must be installed. With the sieving separation, the current TO027 flow is split up in two separate flows. One flow consists of tobacco fines. The other flow consists of intermediate and coarse size tobacco particles, and should be added back to the expanded tobacco flow by using the existing add back route.

TP036 waste can be reduced by narrowing the tangential separator feed side. A adjustable accelerator plate must be designed to fit in the tangential separator's feed side. After installing the accelerator plate its optimal position must be defined. This can be determined iteratively in a number of alterations of the accelerator plate angle. After each alteration the particle size distribution of the tobacco after the expansion tower, and of the waste flow TP036, must be determined. In case of a maximum fraction of intermediate and coarse size particles in the expanded tobacco flow, and a minimal fraction of intermediate and coarse size particles in waste flow TP036, the optimal accelerator plate angle had been determined.

6.2 Control of the System

In section 5.1 an improved steady state model is proposed, that uses several process data flows, which is currently not the case. To implement this in practice, several areas have to change.

6.2.1 Initiating requirements

As stated in section 3.3, to calculate the tobacco yield several process parameters are required. In order to obtain a reliable result each of the measures parameters must be measured and registered properly. Based on the results of section 3.4, the measurement effecitvity can be improved.

To ensure measuring reliability of both weighing belts, calibrations should be performed in accordance with the applicable procedures. In the current situation only in case of suspicion calibrations are performed. For preventing this, once each two months or after every 1000 production hours both weighing belts must be calibrated, which are the current standards for weighing belt calibration within PMI. Besides the frequency of calibration, also the way how to calibrate needs to be reconsidered. When calibrating, a test weight is used. The quantity of weight for this test weight is PMI defined. The current calibrating weight quantity it too low whereby the accurateness of calibrating is not in line with the desired level. When calibrating, the PMI defined weight quantity should be used.

Section 3.4 shows that at both weighing belts, in the current situation there is a deviation between measured tobacco quantity and registered tobacco quantity. To eliminate this, both analog signal weighing belt cabinets should be replaced by digital signal cabinets.

Due to evaporation of the expanded tobacco and the distance between final weighing belt and moisture meter constantly a too large moisture amount is subtracted from the tobacco weight. For eliminating this deviation a suitable solution is to dislocate the moisture meter by placing it on top of the final weighing belt.

Yield results are obtained from each single batch. As is described in section 5.1, when batches of equal blend type are processed in series, currently the end of each batch is manually defined. This results in an unnecessary level of spread within yield results which results in a reduced level of control. To significantly reduce this spread the in section 5.1 introduced batch closure forecasting script should be used.

6.2.2 Evaluation of measurements

On a daily basis yield results are present. The current monitoring system is able to show these results. They should be evaluated on a daily basis by the process supervisors. In case of deviations from the process-based trend, a root cause analysis should be initiated. An example outcome of this could be that the trim setting of a moisture meter must be changed or a weighing belt needs maintenance.

Waste flow amounts are available after each production week. To evaluate the weekly waste and yield results an automated monitoring dashboard has been created which is shown in section 5.1. This allows to track trends of the tobacco yield related performance indicators. Weekly evaluation should be done by the process supervisors and manager. As an example, an outcome of this could be that conveying belt seals need to be renewed or adjusted.

Every month the particle size distribution of the input and output flow is determined and the expansion level is determined. These results should be evaluated by the process supervisors, the process engineer and the manager. In case of deviations from target waste flows and yield results must be reviewed and in case of increasing waste flows their particle size distribution must be obtained. When the input particle size distribution contains a significant higher amount of tobacco fines, the request for a root cause analysis within the preceding process must be initiated and the measuring frequency must be increased. It could for instance happen that the knifes of the tobacco cutting machine are getting blunt resulting in more crushed instead of sliced tobacco.

In order to meet requirements from the possible changing environment, standards for the process as a whole should be evaluated to see if there is space for improvement. This should be done on a yearly basis by the process engineer, process manager and the division manager. An outcome of this could be the start of a study towards the improvement of a specific area within the process.

7 Conclusions and recommendations

This study was aimed to research the possibilities to improve the tobacco yield within the Expanded Tobacco 2 process of Philip Morris Holland B.V. by reducing waste and optimizing control. The goal of reducing waste is to let the process operate more efficiently by increasing the amount of final product.

The ET2 process is divided into multiple process steps. Generally the main functions are to impregnate, expand and condition the tobacco in order to create final product meeting the specific requirements. When looking at the particle size distribution of tobacco, within PMI three size classes are defined: fine, intermediate and coarse particles. A requirement is that the fraction of fines within the final product flow should not be increased.

The analysis on the production process showed that there was insufficient control towards tobacco waste and yield. Several process steps are causing the tobacco particles to break down, whereby undesired fines are created. The relationship between this tobacco degradation and the amount of generated waste during the process was not known. In the analysis it was also identified that waste flows still contain intermediate and coarse size tobacco particles.

For controlling the waste and yield, a redesigned control model has been introduced. With the developed dashboard waste and yield numbers can be tracked and monitored. Relevant measurement devices have been evaluated, the weighing belts at input and output position deviated respectively 0.30% and 0.04%. The distance between output weighing belt and corresponding moisture meter results in an dry weight deviation of 0.28%. These deviations directly influence the main performance indicator dry area yield. Due to insufficient batch closure there was a large amount of spread within dry area yield results. Until mechanical improvements, the measurement device errors could be corrected by implementing correction factors. For reducing the amount of spread within yield results a batch closure forecasting script has been introduced, whereby the standard deviation reduces by 81%. It is recommended to use this script for batch closure. It creates an increased level of control, since real deviations could now be addressed much quicker.

To evaluate the several process steps within the system towards possible tobacco degradation, multiple samples have been collected for sieving analysis. Based on this analysis, tobacco degradation occurs significantly during crushing by the clump breaker and during conveying transport in the cold box. Possible degradation during transport in the expansion tower could not be quantified by sieving analysis due to the actual expansion.

To quantify the quality of waste flows, samples have been collected at the multiple waste flows. Waste flow TP027 contains the largest quantity of intermediate and coarse size particles. TP037 should not contain, but contains, a fraction of coarse and intermediate particles.

For calculating the process behavior towards waste, related to tobacco degradation during the process, a mathematical model has been created. The model also allows calculating the amount of degradation and waste creation within the expansion tower. Based on the measurement and the modeling results degradation causes in increasing order are: cold box, expansion tower and crusher.

When reducing degradation during transport in the cold box area up to €14K could be saved due to an increased amount of waste and final produce quality, i.e., harmonic mean size, could be improved by 4.96%. Conveying transfer points have been addressed as root causes. Ideally the total tobacco impact forces due to free fall at transition points would be zero by having zero belt transitions. A solution presented for the current situation is to mount transfer chutes.

The degradation in the expansion tower is causing a waste quantity equal to €59K. By improving the expansion tower final product quantity could be increased by 6.78%. Having long radius bends instead of sharp radius bends will reduce the impact angle and thus the tobacco degradation will be reduced.

By crushing the frozen impregnated tobacco with the clump breaker particles break down. By improving this process step yearly €625K could be saved and final product quality could be improved by 25.0%. Several options have been studied to reduce degradation during crushing, i.e., change of rotational speed, size reduction by a vibrating screen and size reduction by a jaw crusher, but no significant improvements have been found. However it is recommended to further research the options to improve this process step, e.g., impregnated quantity, impregnation pressure, cut rag tobacco particle size distribution, since it covers the largest scope for improvement.

With sieving analysis and weighing measurements the several waste flows have been evaluated. Each of the waste flows contains intermediate and coarse size particles which are classified to be part of the final product flow. The main scope towards minimizing larger size particles in waste flows should be on TP026 (88.5%, €52K), TP027 (12.6%, €56K) and TP037 (3.62%, €12K).

For minimizing waste flow TP026 (toasted tobacco due to startups and stops), awareness must be enhanced during scheduling. Processing batches of equal blend type in series reduces the amount of process startups and stops whereby the fraction TP026 minimizes. It is recommended to research the effect towards taste of adding back TP026 waste scattered over a regular batch.

The root cause of intermediate and coarse size particles being part of waste flow TP027 is the cooled air flow within the cooling conveyor. This air flow cannot be changed due to tobacco taste related issues. Tests have shown that it is possible to sieve out, and add back, the intermediate and coarse size particles. It is recommended to implement this waste sieving process.

Intermediate and coarse size particles being part of TP036 waste is due to the fact that the current tangential separator is not operating at the aimed effectivity. Research showed that more effective separation is possible. Yearly the profits of optimizing the tangential separator would equal €23K. By narrowing the tangential separator feed side the separator effectivity would increase. It is recommended to further research the effects of this redesign of the tangential separator.

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Appendices

A study towards yield optimization for the Expanded Tobacco II process of Philip Morris Holland B.V.

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Abstract— **This document is the summarized result of a MSc. thesis [1] with the subject of improving the tobacco yield at the Expanded Tobacco II process of Philip Morris Holland B.V. The thesis is aimed to quantifiably identify relevant areas for improvement and corresponding problems. A redesigned control model is quantitatively backed up showing improved controllability. Reducing inter-process particle breakage could lead up to yearly cost savings of €698K. Optimizing waste flows could lead up to yearly cost savings of €131K.**

Keywords— **Expanded tobacco, Cost Reduction, Particle Size Distribution, Sieving Analysis, Crushing, Degradation, Waste**

I. Introduction

The main component of a cigarette is tobacco. Tobacco for cigarette production needs to comply with several requirements. In order to meet those requirements within Philip Morris Holland B.V., part of Philip Morris International, there are several tobacco manufacturing processes to cut the tobacco leaves, add moisture, sauce, semi-finished produces and flavors. Philip Morris Holland has a historical background of frequently expanding the production capacity. During that period there was less focus towards waste reduction. Currently market demands are decreasing whereby the demand for improving process efficiencies increases.

The process generating the largest waste fraction within the Primary department is the Expanded Tobacco II process. The goal of this process is to stretch the tobacco cells in order to create a permanent volume increase of the tobacco. The input material of the process is pre-processed tobacco, i.e., cut rag tobacco. This cut rag tobacco gets impregnated with liquid CO_2 after which the impregnated tobacco is quickly heated to create a high internal cell pressure. This internal cell pressure allows the tobacco cells to stretch. Finally the temperature of the then expanded tobacco is reduced and moisture is added to meet final product requirements. At several areas of the process waste, i.e., tobacco fines, are separated from the main tobacco flow. Within Philip Morris Holland B.V. no prior research has been made on optimizing the tobacco yield within the Expanded Tobacco II process.

This paper is divided in five main sections. This is the last paragraph of the first section, being merely an introduction. The second section is aimed to clarify all the relevant topics that are concerned with the Expanded Tobacco II process at Philip Morris Holland B.V. The third section shows the problems that emerged during analysis of the current situation. The fourth section is aimed to clarify the study towards solutions for the identified problems. The fifth and last section contains the important conclusions and recommendations based on the previous four sections.

II. Expanded Tobacco

In this section the different aspects of the Expanded Tobacco II process are being explained, including describing the materials flows and way of controlling the system.

A. *Why Expanded Tobacco*

The aim of the process is to quickly stretch the tobacco cells in order to create a permanent volume increase. This improves smoking quality and is the most effective tool for tar and nicotine reduction in cigarettes using tobacco lamina. It also reduces the bulk density of the cigarette blend which significantly reduces the cost of manufacturing.

B. *Process Steps*

The three general different process steps are described below. Every batch that is processed by means of the Expanded Tobacco process follows these steps.

1) *Tobacco Impregnation*: The goal of impregnating is to create a crystalline substance inside the tobacco cells, so that heating will cause a large amount of gas that stretches the cells to almost ‘green leaf’ state. After emptying a cut rag storage silo, a continuous flow of tobacco can be achieved.

The tobacco impregnation is a batch process, as the vessel in which the tobacco gets impregnated can only be filled with a limited amount of tobacco. Therefore preceding the impregnation vessel batches of appropriate size are laid out. Impregnating takes place at a high pressure, 30 bar. This is necessary to ensure liquid CO2. Impregnated CO_2 molecules react with H_2O molecules already present in the tobacco cells. The product of this reaction is CO_2-hydrate. After a fixed time of exposure the remaining CO_2 gets drained out. Depressurization beneath the CO_2 triple point at 4.2bar causes the liquid CO_2 partly to vaporize while the remaining liquid turns into solid, dry ice. At atmospheric conditions the CO_2-hydrate is stable at temperatures below -45°. During depressurization (solid) dry ice was formed onto the tobacco fibers. This dry ice has a temperature of about -79°C, allowing the CO_2-hydrate to stay stable during transportation towards the expansion tower. Dry ice itself does not aid the expansion process, like the name Dry Ice Expanded Tobacco would suggest. For creating a maximum amount of CO_2-hydrate and thus a maximum expansion level, cut rag moisture level, temperature, pressure and heat transfer values need to be monitored and controlled.

The dry ice causes all the tobacco fibers to stick together. This results in formation of a massive frozen tobacco clump inside the impregnation vessel. For further processing and transportation, the clump of frozen tobacco needs to be crushed. This is done by the ‘clump breaker’, a crusher with multiple horizontal rotating axes to which pins are attached. After crushing, the impregnated tobacco arrives at a conveyor in the so called ‘cold box’. This cold box ensures low temperature conveying transport for stable CO_2-hydrate. The conveyer ends above a feeder, allowing continuous tobacco flow afterwards. Both the cold box and the feeder are isolated to ensure temperatures below -45°C. During start-ups, stops and blend changes, a cooling installation into the cold box is turned on. Fans blow cold air onto the isolated conveyor belt. This minimizes movement of the air above the belt, to prevent CO_2 evaporation.

Controlled by microwave level switches, the feeder transports the tobacco into a metering tube. From the metering tube transport towards a weighting plate takes place by a supply belt conveyor. To ensure continuous pressure onto this belt, the conveyors before the metering tube are controlled in order to achieve constant flow. After passing the weighting plate, the impregnated tobacco ends up in the input lock of the expansion tower. The speed of the supply belt conveyor is controlled by a feedback control signal from the weighting plate.

2) *Tobacco Heating*: The goal of heating is to heat the impregnated tobacco in such a short amount of time that disintegration of CO2-hydrate inside the tobacco cells causes enough gas and thus inner pressure to stretch the cells to the desired volume. Stretching tobacco cells could be compared to inflating a porous balloon. The inner generated amount of gas must be high enough that even though there is loss of pressure by the cell pores, it creates enough pressure to stretch the tobacco cells.

The heating takes place by a system of tubes and equipment in which process gas circulates. After leaving the input lock, process gas with a speed of 40m/s transports the impregnated tobacco into the expansion tower. The input lock is covered by gaseous CO_2, therefore no ambient air can enter the process gas loop. An excess of air inside the expansion tower will easily cause the hot tobacco to catch fire. Temperature inside the expansion tower will reach 370°C, while the tobacco combusts at 300°C.

The expansion tower is a S-shaped tube with a height of 5.3m. In this tower the tobacco enters the lower turn, and leaves the higher turn. High temperature will force the tobacco to expand. From here the expanded tobacco goes into a tangential separator, in which by centrifugal forces the tobacco and process gasses will be separated. The process gas flows through a dust cyclone separator. This separator separates charred tobacco particles form the process gas. By gravity and volume expansion in the dust cyclone separator the particles will drop down. Clean process gas gets recycled by reheating in a gas fired furnace.

Tobacco separated by the tangential separator ends up in an output lock, from where it reaches the fume removal conveyor. After heating in the expansion tower the expanded tobacco is very dry, hot and gives off irritating fumes. These fumes must be removed, because they would cause change in tobacco taste when condensed back onto the tobacco during cooling. The fume removal conveyor is a mesh belt conveyor in which from below a fan blows air onto the tobacco so that the fumes will be discharged. Solids in the fumes get separated by a pre-washer, and the remaining vapor gets cleaned in a scrubber. Clean vapor is fed to the outside air.

3) *Tobacco conditioning*: The goal of cooling is to lower the tobacco temperature, in order to meet the requirements for the remaining process steps. Before the cooling process starts, there is a dump valve. This dump valve allows off-spec tobacco to leave the system. Control of the valve can be done either by hand or by a system control action. For system control there is a spark detection system placed under the output lock, above the mesh belt fume removal conveyor and in the tubes leading towards the pre-washer.

After passing the dump valve, the hot expanded tobacco enters the cooling conveyor. This cooling conveyor is a mesh belt conveyor where a by pressure differences between above and under the belt controlled closed loop fan system blows cooled air onto the tobacco. The air circulates over a heat exchanger cooled by cooling water. Remaining fumes, if still present, are not allowed to condensate due to risk of change in taste. Therefore continuously a part of the air gets extracted towards the pre-washer and scrubber. At the end of the cooling conveyor there is a transition chute from which flow towards a series of vibratory conveyors is possible. In this transition chute spark detection systems are placed. In case of detection, a dump valve opens and the expansion process stops. The fume removal conveyor and the cooling conveyor will then be emptied at the two dump valves.

Two infrared cameras are also placed in the transition chute, for detection of product with a too high temperature. These particles are called ‘hot bodies’ and in case of detection can be thrown out without interrupting the expansion process. The vibratory conveyors further cool down the tobacco in order to meet the requirements for reordering. Above one vibratory conveyor the tobacco temperature is monitored in order to control the cooling water flow in the cooling conveyor. A moisture meter measures tobacco moisture level.

The goal of reordering, i.e., moistening, is to recondition the dry and brittle tobacco obtained from the expansion tower. In order to achieve the desired moisture level, 12% OV, the tobacco is transported through a Humid Air Reordering System (HARS). This system consists of a conditioning part and an air treatment part.

For conditioning the tobacco is exposed at a humid atmosphere for about an hour. During this conditioning, the tobacco is located onto a vertical spirally rolled-up mesh belt with a length equal to about 550m. The tobacco flows through the spiral from bottom to top, while humid air flows in reverse direction. Water vapor condensates onto the tobacco, and will be absorbed.

The air flow within the HARS gets contaminated by the tobacco and therefore air treatment is required. This is done by refreshment of the air; a part gets extracted through a dust collector, while fresh air enters the HARS. The main air flow is led through an internal dust collector and thereafter cooled. Two fans blow the clean cooled air through three steam injection lances to adjust the desired humidity. Inside the tubes where contaminated air leaves the HARS, a spark detection system is installed. Fire detection inside the HARS is done by a system that monitors scattering and attenuation of a laser beam. In case of detection a fire extinguishing system will be activated. After staying inside for roughly an hour, the tobacco exits the HARS to be weighted and transported towards a silo for storage.

III. Problems in the Expanded Tobacco II Process

This section is used to summarize the identified problems based on thorough analysis by using the Delft Systems Approach as is described by Veeke, Ottjes and Lodewijks. [2]

Problem areas are divided into a control part, a degradation part and a waste flow part.

A. Tobacco Degradation

Waste flows consist of small size tobacco particles. Within Philip Morris Holland B.V. tobacco is classified generally in three size classes: fine, intermediate and coarse size particles. Fine particles are not desired to be part of the final product flow. For this reason the tobacco waste flows cannot directly be minimized or added back.

The root causes of the fraction of tobacco fines ending up as being several waste flows were not known. To determine relevant areas for improvement, the process has been evaluated.

At first the input and output flows were analyzed. Based on their particle size distributions, within the expanded tobacco process degradation, i.e., particle breakage, occurs. To locate root causes of tobacco degradation, at several specific chosen positions within the process tobacco samples have been collected. An overview of the decision making of these positions is depicted in table I.

TABLE I
Sample Position Determination Matrix

Description	Tobacco speed	Other forces	Moist level	Drop height	Sum
Belt conveyors	0	0	0	+	+
Feeder 7602	0	+	0	0	**0**
Belt conveyors	0	0	0	0	**0**
Impregnator	0	0	0	+	+
Clump breaker	0	++++	0	0	++++
Cold box	0	0	0	++	++
Feeder 7635	0	+	0	0	+
Metering tube	0	0	0	0	**0**
Expansion tower	++	0	+	0	+++
Fume removal	0	0	+	0	+
Cooling conveyor	0	0	+	0	+
Vibra conveyors	0	++	+	+	++++
Reordering box	0	0	+	0	+
Belt conveyors	0	0	0	0	**0**

The samples have been characterized with sieving analysis to obtain their particle size distributions. [3] Based on the results of the sieving analysis, main causes of degradation are cause by the clump breaker and the cold box conveying. The clump breaker crushes the impregnated (frozen) tobacco, whereby the harmonic mean particle size reduces by 35%.

Inside the cold box the crushed impregnated tobacco is transported towards the expansion tower, where the tobacco gets heated for the actual expansion. During the conveyed transport in the cold box the harmonic mean particle size reduces by 3.3%.

Since in the expansion tower tobacco expands in volume, with sieving analysis possible degradation could not directly be quantified. Measurement results are depicted in figure 1.

Lastly a degradation related problem is that there is no quantified relation known between degradation and the magnitude of waste flow fractions.

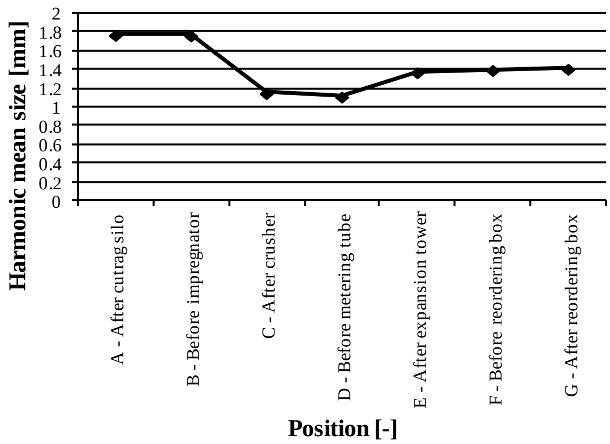

Fig. 1 Harmonic mean sizes of the sieve analysis results per position

B. Waste flows

At the process there are multiple separate waste collection positions which are supposed to contain only tobacco fines. Each of the flows has been evaluated towards quantity and particle size distribution. Measurement results are shown in figure 2.

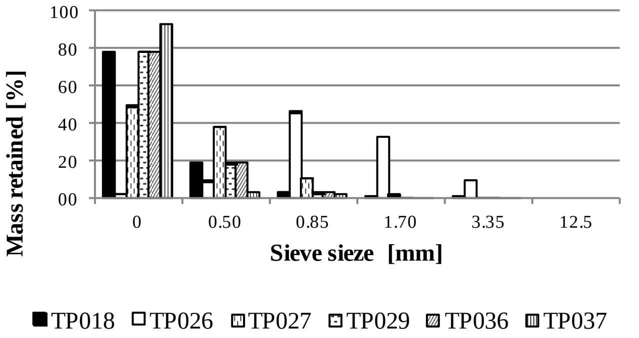

Fig. 2 Sieve analysis results of the several waste flows

Based on this analysis, each of the flows still contains a fraction of intermediate and coarse size tobacco particles. In table II the annual quantity of intermediate and coarse size particles that and up in the several waste flows are listed.

TABLE II
WASTE FLOWS COARSE AND INTERMEDIATE SIZE PARTICLE QUANTITIES

Waste flow	**Quantity [kg/yr]**	**Value [€/yr]**
TP018	2.00×10^3	9K
TP026	11.5×10^3	52K
TP027	12.4×10^3	56K
TP029	0.679×10^3	3K
TP036	0.516×10^3	2K
TP037	2.56×10^3	12K

When reducing tobacco degradation those particles would still end up as being waste, therefore possibilities to optimize waste flows are studied.

C. Control Of The System

A requirement towards sufficient control of a system is that the system must be able to properly measure specific process parameters. [2] The relevant measurement devices have been analyzed. In the current state measurements of multiple measurement devices show deviations with reality. Those deviations have been quantified. In order to calculate tobacco yield, two weighing belt - moisture meter combinations are used, at the input of the process and at the output of the process. For both weighing belts there has been a deviation quantified between the measured quantity and the registered quantity. Those deviations are for input and output side respectively 0.30% and 0.04%.

When the final tobacco moistening has been completed, the tobacco has a temperature around 34°C and cools down during further conveying transport until ambient temperature. Due to a large distance between final weighing belt and the corresponding moisture meter, and the fact that the cooling tobacco loses moisture in between, a too large moisture fraction is been subtracted when calculating dry weight. This error has been quantified and equals 0.28%.

In order to control the system towards waste, relevant results should be evaluated. In the analyzed situation no monitoring takes place towards the quantity and quality of the multiple waste flows. When processing batches of equal blend type, this is regularly done in series-production without gaps in between. To measure the yield of a batch, the operator chooses the moment that a batch has been finished. This influences the yield number and creates false spread.

IV. SOLUTIONS

This section contains solutions to the identified problems of the previous section. First, important conditions for a new control model are described. Then the elaboration of solutions towards tobacco degradation is described, followed by the explanation towards waste flow optimization.

A. Control of the System

In order to implement a sufficient control model towards tobacco yield and waste control, the system must be able to properly measure specific process parameters. [2]

A monitoring dashboard has been created to enhance focus towards yield optimization by waste control. Yield monitoring has been improved by implementing a batch closure forecasting script which reduces the standard deviation over dry area yield results by 81%. Hereby actual deviations and possible problems are much quicker observable. A sheet of the monitoring dashboard is depicted in figure 3.

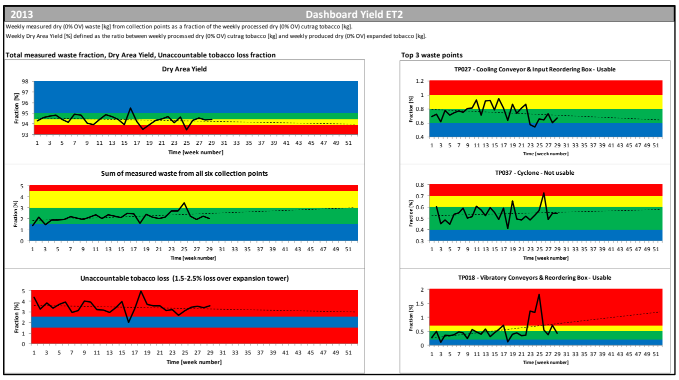

Fig. 3 Monitoring Dashboard

B. Reduction of Tobacco Degradation

A mathematical model had been developed, to calculate the relation between tobacco degradation and waste flow quantity and quality values. [4] Results of the model are that the maximum yearly improvable final product tobacco quantities due to degradation would equal respectively for the crusher, cold box and expansion tower: 139×103kg, 3.09×103kg and 13.0×103kg. An overview of the impact of degradation is depicted in figure 4 on the next page.

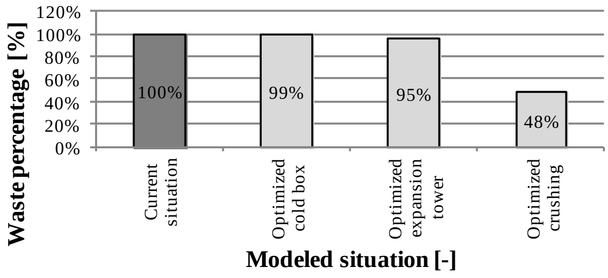

Fig. 4 Modelled waste fractions after degradation optimizations

Due to degradation optimizations also quality of the final product will improve. Figure 5 illustratively shows the effect towards the harmonic mean size at several positions in the system when degradation is reduced.

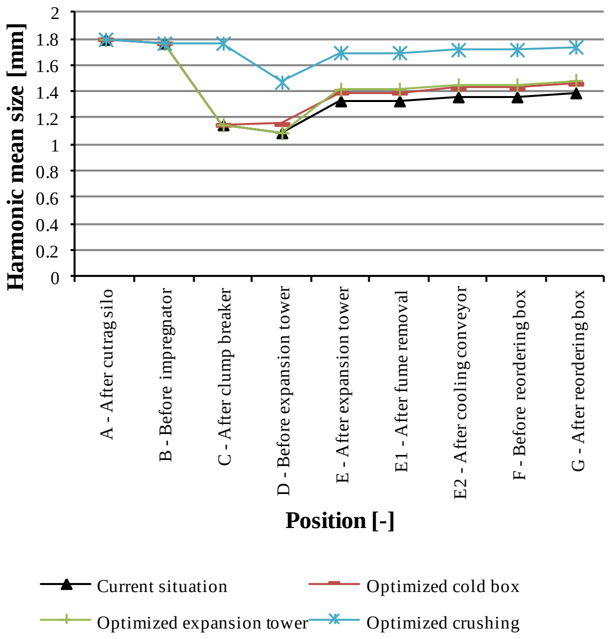

Fig. 5 Quality improvements after degradation optimizations

For the crushing process tests have been performed to quantify the influence of crushing rotational speed towards degradation. Also other crushing techniques, i.e., a vibratory screen crusher and a jaw crusher, have been evaluated. [5] No significant improvements have been found to reduce degradation due to crushing.

The root causes of tobacco degradation during the cold box conveying are traced back to the multiple transition points. Installing transfer chutes will reduce the amount of degradation. [6]

Degradation due to pneumatic conveying of tobacco inside the expansion tower can be reduced by replacing sharp radius bends by large radius bends. [7]

C. Control of the System

When optimizing waste flows most profitable are positions TP026, TP027 and TP028, which contain respectively 88.5%, 12.6% and 3.62% intermediate and coarse size particles. TP026 waste is toasted tobacco due to process startups and stops. It can be reduced by increasing the processing of batches of equal blend type in series.

Positive tests have been performed to continuously sieve out larger size particles from the TP027 flow since directly minimizing is hampered due to taste related issues.

The root cause of TP037 waste containing larger size particles is due to ineffectivity of the tangential separator, the device separating the expanded tobacco from the air flow after the expansion tower. By narrowing the tangential separator inlet the separating effectivity can be improved.

V. Conclusions and Recommendations

For improving control, it is advised to apply the batch closure forecasting script and to improve effectivity of measurement devices.

It is recommended to test the proposed countermeasures towards tobacco degradation in the cold box area. Improving the crusher, cold box and expansion tower could yearly save up to respectively €625K, €14K and €59K. For optimizing the crusher it is recommended to further research the possibilities to reduce degradation during this process step. Enhanced focus on scheduling batches of equal blend type in series will reduce the fraction of TP027.

It is advised to research the effect towards final product tobacco taste when TP026 tobacco is added back scattered over a full batch, profits are yearly up to €52K.

By improving the tangential separator the total waste fraction can be reduced resulting in a yearly saving up to €23K. It is recommended to sieve out the intermediate and coarse size particles and adding them back by using the regular add-back route. Those savings would equal yearly up to €56K.

Acknowledgement

The authors would like to thanks all involved departments for their enthusiasm and support in the proceedings of this research. Hopefully it provides Philip Morris Holland B.V. with useful insights for optimizing their Expanded Tobacco II process.

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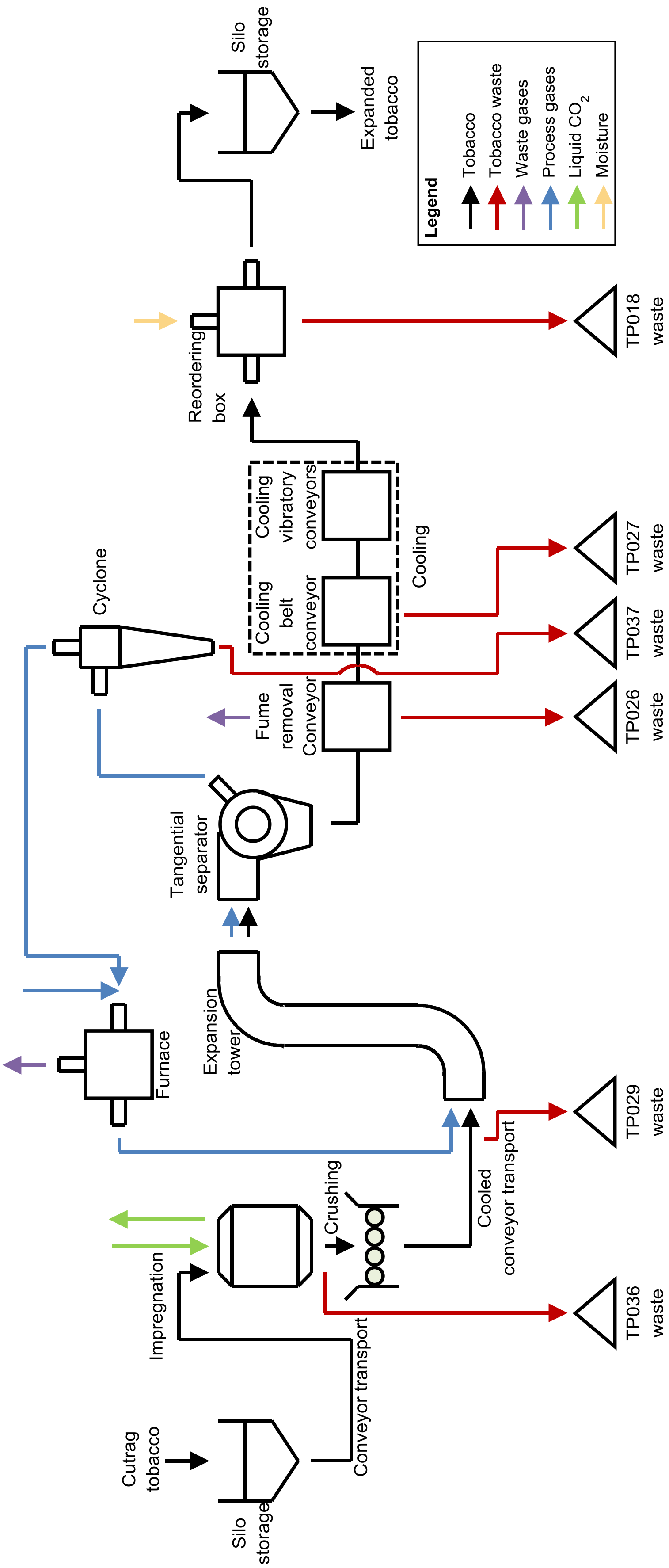
Appendix B - Values of Student t distribution

Values of the Student t distribution, for 95% confidence intervals (α=0.05), for different degrees of freedom $(n-1)$ where n is the number of measures.

n-1	t(α=0.05)	n-1	t(α=0.05)	n-1	t(α=0.05)
1	12.706	21	2.080	45	2.014
2	4.303	22	2.074	50	2.009
3	3.182	23	2.069	55	2.004
4	2.776	24	2.064	60	2.000
5	2.571	25	2.060	65	1.997
6	2.447	26	2.056	70	1.994
7	2.365	27	2.052	80	1.990
8	2.306	28	2.048	90	1.987
9	2.262	29	2.045	100	1.984
10	2.228	30	2.042	110	1.982
11	2.201	31	2.040	120	1.980
12	2.179	32	2.037	130	1.978
13	2.160	33	2.035	140	1.977
14	2.145	34	2.032	150	1.976
15	2.131	35	2.030	200	1.972
16	2.120	36	2.028	250	1.970
17	2.110	37	2.026	300	1.968
18	2.101	38	2.024	400	1.966
19	2.093	39	2.023	500	1.965
20	2.086	40	2.021	1000	1.962

Appendix C - ET2 process steps and material flows



Appendix D - ET2 sieve analysis measurements

Position:	A - After cutrag silo									
Sample [#]	1	2	3	4	5	6	7	8	9	10
Weight 06 [g]	45.81	46.95	43.55	44.01	43.86	43.81	46.96	45.98	44.01	46.86
Weight 12 [g]	45.76	45.43	44.92	46.48	44.37	44.76	45.38	46.43	46.48	45.37
Weight 20 [g]	45.88	45.04	47.80	48.21	47.55	46.88	46.04	45.04	47.21	42.55
Weight 35 [g]	10.06	8.67	11.03	9.83	12.08	8.06	8.67	9.67	9.83	12.08
Weight Pan [g]	2.41	2.06	2.61	2.39	3.04	2.02	2.06	2.06	2.39	3.04
Sum [g]	149.92	148.15	149.91	150.92	150.90	145.53	149.11	149.18	149.92	149.90

Position:	B - Before impregnator									
Sample [#]	1	2	3	4	5	6	7	8	9	10
Weight 06 [g]	44.25	44.92	45.00	45.34	46.79	42.81	45.97	48.35	44.95	44.28
Weight 12 [g]	44.11	44.71	44.28	44.04	45.14	45.46	46.12	46.44	44.62	46.22
Weight 20 [g]	47.96	46.93	47.47	46.76	46.16	47.16	45.82	45.34	46.55	47.96
Weight 35 [g]	10.58	10.39	10.13	10.88	9.59	7.65	9.76	9.91	10.41	10.62
Weight Pan [g]	2.50	2.55	2.64	2.90	2.32	1.95	2.40	2.10	2.33	2.60
Sum [g]	149.40	149.50	149.52	149.92	150.00	145.02	150.08	152.14	148.86	151.68

Position:	C - After crusher									
Sample [#]	1	2	3	4	5	6	7	8	9	10
Weight 06 [g]	9.09	8.98	9.51	8.62	11.97	8.99	9.02	9.36	9.56	11.60
Weight 12 [g]	42.76	41.52	47.06	43.96	42.19	42.96	41.12	47.05	43.78	42.58
Weight 20 [g]	71.32	70.07	64.52	70.02	65.33	71.48	69.99	63.86	70.43	65.53
Weight 35 [g]	22.10	23.30	21.31	22.58	23.59	21.80	23.22	21.19	22.18	23.56
Weight Pan [g]	5.13	6.02	8.58	5.33	6.77	5.15	5.44	9.32	5.57	6.65
Sum [g]	150.40	149.89	150.98	150.51	149.85	150.37	148.79	150.78	151.53	149.91

Position:	D - Before metering tube									
Sample [#]	1	2	3	4	5	6	7	8	9	10
Weight 06 [g]	2.40	3.95	3.81	4.68	4.47	2.65	3.68	4.09	4.07	4.99
Weight 12 [g]	32.78	40.96	38.74	38.18	37.10	32.64	41.56	38.97	37.86	37.79
Weight 20 [g]	82.17	79.43	80.00	74.62	75.29	82.44	79.13	80.03	74.40	75.30
Weight 35 [g]	27.39	22.01	23.58	26.21	26.92	27.39	21.66	22.97	26.67	27.30
Weight Pan [g]	5.28	3.88	4.01	6.51	6.37	5.47	3.52	3.88	6.86	7.18
Sum [g]	150.02	150.23	150.14	150.20	150.15	150.58	149.54	149.94	149.86	152.56

Position:	E - After tower									
Sample [#]	1	2	3	4	5	6	7	8	9	10
Weight 06 [g]	7.95	8.80	9.38	10.58	10.20	7.82	9.19	9.17	10.65	9.41
Weight 12 [g]	33.02	34.93	33.72	34.18	32.96	32.69	34.10	34.01	35.71	36.14
Weight 20 [g]	50.90	46.57	46.24	44.15	45.07	50.41	46.00	46.76	44.23	44.44
Weight 35 [g]	9.72	9.20	8.90	9.26	9.50	9.50	9.86	9.21	9.11	8.83
Weight Pan [g]	2.61	2.26	2.02	2.42	2.44	3.41	1.35	2.35	2.11	1.96
Sum [g]	104.20	101.76	100.26	100.59	100.17	103.83	100.50	101.49	101.80	100.78

Position:	F - Before reordering box									
Sample [#]	1	2	3	4	5	6	7	8	9	10
Weight 06 [g]	10.08	8.40	8.69	8.79	8.40	9.75	8.28	8.68	8.06	8.32
Weight 12 [g]	37.47	34.14	33.04	34.29	33.69	37.22	33.90	32.43	33.96	33.32
Weight 20 [g]	45.44	46.98	46.15	45.52	46.09	46.04	46.20	45.86	45.31	46.45
Weight 35 [g]	6.05	8.65	9.80	9.02	9.72	6.45	8.64	10.08	8.37	9.94
Weight Pan [g]	1.29	1.75	2.54	2.22	2.19	0.51	1.75	2.69	2.67	2.00
Sum [g]	100.33	99.92	100.22	99.84	100.09	99.98	98.77	99.74	98.36	100.02

Position:	G - After reordering box									
Sample [#]	1	2	3	4	5	6	7	8	9	10
Weight 06 [g]	7.65	8.66	9.02	9.79	9.21	8.00	8.71	8.99	10.02	8.98
Weight 12 [g]	34.29	34.82	34.68	34.95	34.59	34.85	34.42	34.45	34.69	34.40
Weight 20 [g]	47.24	45.97	45.01	44.72	45.64	47.09	46.15	45.49	43.86	45.45
Weight 35 [g]	9.44	8.82	9.41	8.20	9.19	9.25	8.39	9.90	8.09	9.18
Weight Pan [g]	1.50	1.39	1.74	2.22	1.51	1.48	1.69	2.11	1.55	2.41
Sum [g]	100.12	99.66	99.86	99.88	100.14	100.68	99.36	100.94	98.20	100.43

Appendix E - Waste flow fractions

Week	Waste flow fraction [%]					
	TP018	TP026	TP027	TP029	TP036	TP037
1	0.3108	0.1119	0.5663	0.1549	0.1015	0.4379
2	0.2850	0.0666	0.5875	0.1675	0.0838	0.5591
3	0.2804	0.0873	0.6991	0.0752	0.0675	0.6191
4	0.2334	0.0968	0.6391	0.5159	0.0841	0.4964
5	0.3628	0.1443	0.6825	0.2769	0.0828	0.5523
6	0.3977	0.0844	0.6705	0.2377	0.0804	0.5857
7	0.4395	0.0547	0.6560	0.0648	0.1034	0.5234
8	0.4352	0.0683	0.7330	0.3788	0.1177	0.5488
9	0.2546	0.0427	0.7269	0.2184	0.1370	0.6073
10	0.2825	0.1238	0.6251	0.1998	0.1124	0.5981
11	0.3436	0.1054	0.7613	0.1822	0.0780	0.4931
12	0.3282	0.1040	0.7252	0.1945	0.0953	0.6342
13	0.3346	0.1474	0.6848	0.1364	0.0726	0.5410
14	0.3266	0.0846	0.6770	0.1637	0.0736	0.5534
15	0.2346	0.1262	0.6611	0.0957	0.0674	0.5431
16	0.4633	0.0950	0.7421	0.2739	0.0940	0.6039
17	0.4144	0.0871	0.6693	0.0748	0.0881	0.4977
18	0.6352	0.1640	0.7725	0.2528	0.0576	0.3894
19	0.1260	0.0624	0.6927	0.1631	0.0934	0.5671
20	0.3831	0.0748	0.8394	0.2066	0.0894	0.4826
21	0.2487	0.0561	0.6809	0.0542	0.0775	0.5840
22	0.4407	0.1278	0.6994	0.1811	0.0869	0.5603
23	0.4791	0.0608	0.7240	0.1526	0.0804	0.7647
24	0.2678	0.1449	0.6895	0.1678	0.0860	
25	0.4888	0.1112	0.7232	0.1488	0.0686	0.6047
26	0.1041	0.0875	0.6199	0.1256	0.0714	0.4510
27	0.3600	0.0609	0.7829	0.0899	0.0929	0.4838
28	0.3442	0.1063	0.7154	0.1672	0.0901	0.4481
29	0.3692	0.1111	0.7434	0.0763	0.0899	0.5346
30	0.4707	0.0993	0.7755	0.1425	0.1382	0.5487
31	0.4368	0.0546	0.7522	0.1329	0.1087	0.5924
32	0.2378	0.1346	0.8103	0.1430	0.1192	0.5009
33	0.5672	0.0382	0.8127	0.1086	0.1086	0.5139
34	0.4851	0.0538	0.9294	0.1699	0.1242	0.6085
35	0.4002	0.0557	0.7131	0.1592	0.0969	0.5744
36	0.5865	0.0555	0.9181	0.1651	0.1292	0.5235
37	0.3089	0.1258	0.9249	0.1535	0.1200	0.5931
38	0.4419	0.0464	0.7843	0.1509	0.1170	0.5546
39	0.5686	0.1290	0.9487	0.2566	0.1134	0.4884
40	0.7121	0.1583	0.8174	0.0750	0.1182	0.5891
41	0.1135	0.2220	0.6383	0.1094	0.0900	0.4079
42	0.4007	0.0949	0.8723	0.2546	0.1136	0.6558
43	0.4425	0.1076	0.7394	0.1785	0.1694	0.4933

Appendix F - Altered crushing frequency sieve analysis measurements

Position:	Before crushing, standard frequency									
Sieve sieze	1	2	3	4	5	6	7	8	9	10
Weight 06 [g]	44.25	44.92	45.00	45.34	46.79	42.81	45.97	48.35	44.95	44.28
Weight 12 [g]	44.11	44.71	44.28	44.04	45.14	45.46	46.12	46.44	44.62	46.22
Weight 20 [g]	47.96	46.93	47.47	46.76	46.16	47.16	45.82	45.34	46.55	47.96
Weight 35 [g]	10.58	10.39	10.13	10.88	9.59	7.65	9.76	9.91	10.41	10.62
Weight Pan [g]	2.50	2.55	2.64	2.90	2.32	1.95	2.40	2.10	2.33	2.60
Sum [g]	149.40	149.50	149.52	149.92	150.00	145.02	150.08	152.14	148.86	151.68

Position:	After crushing, standard frequency									
Sample [#]	1	2	3	4	5	6	7	8	9	10
Weight 06 [g]	9.09	8.98	9.51	8.62	11.97	8.99	9.02	9.36	9.56	11.60
Weight 12 [g]	42.76	41.52	47.06	43.96	42.19	42.96	41.12	47.05	43.78	42.58
Weight 20 [g]	71.32	70.07	64.52	70.02	65.33	71.48	69.99	63.86	70.43	65.53
Weight 35 [g]	22.10	23.30	21.31	22.58	23.59	21.80	23.22	21.19	22.18	23.56
Weight Pan [g]	5.13	6.02	8.58	5.33	6.77	5.15	5.44	9.32	5.57	6.65
Sum [g]	150.40	149.89	150.98	150.51	149.85	150.37	148.79	150.78	151.53	149.91

Position:	Before crushing, 50% reduced frequency									
Sieve sieze	1	2	3	4	5	6	7	8	9	10
Weight 06 [g]	43.89	44.32	45.45	45.09	47.08	42.94	46.38	47.53	45.08	44.90
Weight 12 [g]	44.37	43.88	44.41	43.32	45.54	45.45	46.10	45.94	44.69	46.85
Weight 20 [g]	47.63	46.80	46.60	46.38	45.98	47.47	45.06	45.23	46.23	48.22
Weight 35 [g]	10.85	10.38	9.87	9.98	9.96	7.66	9.21	10.20	10.75	10.77
Weight Pan [g]	1.67	2.71	2.84	2.92	2.36	1.17	2.64	2.90	2.06	2.59
Sum [g]	148.42	148.10	149.17	147.69	150.93	144.69	149.40	151.81	148.81	153.34

Position:	After crushing, 50% reduced frequency									
Sample [#]	1	2	3	4	5	6	7	8	9	10
Weight 06 [g]	9.89	9.00	9.60	8.61	12.08	8.65	8.93	9.77	8.91	11.22
Weight 12 [g]	42.99	42.17	47.70	43.69	42.47	42.61	41.59	46.23	43.01	42.82
Weight 20 [g]	70.45	70.16	65.02	69.71	65.44	71.06	70.36	64.49	70.74	65.62
Weight 35 [g]	21.56	23.19	21.42	22.37	23.65	21.11	22.93	20.67	22.07	23.59
Weight Pan [g]	5.25	6.66	8.34	5.26	7.29	4.89	5.48	8.81	4.73	7.10
Sum [g]	150.14	151.19	152.08	149.63	150.93	148.33	149.29	149.96	149.45	150.35

Appendix G - Vibratory crusher test sieve analysis measurements

Position:	Before crushing									
Sieve sieze	1	2	3	4	5	6	7	8	9	10
Weight 06 [%]	21.66	20.58	22.56	16.98	19.64	20.41	20.70	18.09	16.46	18.12
Weight 12 [%]	37.83	35.39	33.31	38.38	33.11	35.85	32.32	33.60	37.69	37.03
Weight 20 [%]	31.92	34.05	34.23	34.56	35.72	34.86	34.64	36.38	34.64	34.51
Weight 35 [%]	6.44	7.51	7.52	7.50	8.78	6.16	9.29	9.01	8.10	7.23
Weight Pan [%]	2.15	2.48	2.37	2.57	2.75	2.72	3.05	2.92	3.12	3.12
Sum [%]	100	100	100	100	100	100	100	100	100	100

Position:	After crushing									
Sample [#]	1	2	3	4	5	6	7	8	9	10
Weight 06 [%]	4.90	5.91	5.50	2.57	3.08	2.83	5.10	3.78	3.89	2.45
Weight 12 [%]	25.68	31.14	26.22	23.36	24.21	29.21	28.52	27.69	22.68	24.19
Weight 20 [%]	49.44	46.48	47.82	50.57	51.10	49.21	48.26	47.01	49.40	51.23
Weight 35 [%]	16.21	12.88	16.57	18.50	16.92	15.33	13.62	16.07	18.93	16.24
Weight Pan [%]	3.77	3.59	3.89	5.00	4.68	3.42	4.50	5.44	5.10	5.90
Sum [%]	100	100	100	100	100	100	100	100	100	100

Appendix H - Jaw crusher test sieve analysis measurements

Position:	Before crushing									
Sieve sieze	1	2	3	4	5	6	7	8	9	10
Weight 06 [g]	30.36	31.47	29.35	30.85	28.92	30.46	31.05	30.11	29.02	29.85
Weight 12 [g]	30.27	31.00	30.74	29.03	30.63	30.82	30.15	28.83	29.60	32.70
Weight 20 [g]	31.05	31.11	30.92	32.34	31.10	31.14	30.83	32.03	31.69	29.74
Weight 35 [g]	6.69	5.88	8.33	7.15	6.36	6.80	7.54	5.64	6.77	6.94
Weight Pan [g]	1.63	1.89	1.88	1.51	0.98	0.90	1.80	1.62	1.47	2.04
Sum [g]	100.00	101.35	101.23	100.88	97.99	100.12	101.37	98.23	98.54	101.27
Position:	**After crushing, clump breaker**									
Sample [#]	1	2	3	4	5	6	7	8	9	10
Weight 06 [g]	6.43	4.26	6.35	7.04	8.43	5.41	4.31	8.77	5.30	8.37
Weight 12 [g]	28.94	29.85	28.85	29.93	28.64	28.70	27.20	29.73	31.27	29.46
Weight 20 [g]	46.41	45.11	46.29	45.85	44.47	47.38	46.41	45.85	47.86	46.52
Weight 35 [g]	14.96	14.63	15.09	13.33	15.40	14.42	15.65	15.05	13.13	15.73
Weight Pan [g]	4.26	4.55	4.49	4.03	3.63	4.15	3.80	4.14	4.29	4.82
Sum [g]	101.00	98.40	101.07	100.17	100.56	100.06	97.37	103.54	101.85	104.90
Position:	**After crushing, jaw crusher test A**									
Sieve sieze	1	2	3	4	5	6	7	8	9	10
Weight 06 [g]	6.67	8.22	5.64	7.77	5.27	6.51	7.30	5.09	6.34	6.79
Weight 12 [g]	28.56	27.63	29.10	27.57	27.23	28.38	29.33	29.84	29.49	27.56
Weight 20 [g]	47.11	45.14	47.58	45.98	48.13	47.44	49.64	45.36	44.77	46.11
Weight 35 [g]	15.31	16.60	17.60	14.93	15.37	14.34	16.11	14.60	15.98	15.27
Weight Pan [g]	4.15	4.26	4.50	4.42	4.11	3.40	4.94	4.20	4.20	3.49
Sum [g]	101.80	101.84	104.42	100.67	100.12	100.07	107.32	99.09	100.78	99.21
Position:	**After crushing, jaw crusher test B**									
Sample [#]	1	2	3	4	5	6	7	8	9	10
Weight 06 [g]	6.98	6.65	9.59	8.98	7.83	4.76	8.55	7.45	5.62	8.70
Weight 12 [g]	29.27	27.13	27.43	27.17	29.71	28.65	28.68	29.63	29.54	27.28
Weight 20 [g]	44.11	42.50	46.47	42.75	46.01	45.21	45.42	44.75	45.64	44.17
Weight 35 [g]	15.32	14.97	14.01	16.89	15.60	15.07	15.11	15.10	14.32	16.05
Weight Pan [g]	4.13	3.66	4.22	4.44	4.32	4.22	4.23	4.23	3.28	3.95
Sum [g]	99.80	94.92	101.72	100.24	103.47	97.91	102.00	101.16	98.41	100.15