TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

MILJA HUUSKONEN

IMPROVING EXTRUSION PROCESS TOWARDS A CLOSED-LOOP-SYSTEM BY USING LEAN-PHILOSOPHY

Master of Science Thesis

Examiner: Professor Jussi Heikkilä
Examiner and topic approved by the Faculty Council of the Faculty of Engineering Sciences on 7th October 2015

ABSTRACT

MILJA HUUSKONEN: Improving Extrusion Process towards a Closed-Loop System by Using Lean-philosophy
Tampere University of Technology
Master of Science Thesis, 97 pages, 15 appendix pages
May 2016
Master's Degree Programme in Material Technology
Major: Industrial Management
Examiner: Professor Jussi Heikkilä

Keywords: Closed-Loop System, Extrusion, Process Orientated Thinking, Lean, Plastic Recycling

The aim of the research was to find ways in the production of the case company as to how an extrusion process could be improved towards a closed-loop system. The primary goal was to find methods how the undesired output, plastic waste or scrap, could be eliminated. The Group's target is to decrease the scrap percentage to 7.5 % (in the year 2015 it was 10.06 %). The secondary target was to study how scrap could be recycled inside the factory to valuable input, regrind.

The current state of the core company was studied through participant and non-participant observation, through interviews and the analysis of the ERP- and BI-programs and also by working short periods in the production. Observation continued during the research and meant taking part in morning meetings and observing other daily operations. Numerical data showed the efficiency of the current extrusion process. Working in the production made it possible to see the production process from inside. The interviews and the analysis helped to discover the main development issues in the current state.

Literature was used for surveying the requirements for the closed-loop system, for the concept of process-orientated thinking, elements of extrusion and for the study of plastics recycling. The literature about Lean-Philosophy was also important for this research.

The most important results of the research concern development issues and recommendations of the raw material purchase, inventory and material management, the production process, recycling, information flows and daily management. Main problems were related to the lack of systematic and studied methods. Also the use of regrind requires scientifically studied and tested ratios, because its mechanical and processing properties (for instance MFI and bulk density) change during recycling. It was also noted that the performance of employees affects strongly the performance of the extrusion process due to its manual nature. The first recommendation is to correct issues relating to the sources of scrap because biggest financial benefits are related to it. Also the study on regrind ratios should start as soon as possible. This may require forming a project team due to the extent of the topic. The secondary proposal is to carry out issues that facilitate recycling and help to achieve a closed-loop system.

TIIVISTELMÄ

MILJA HUUSKONEN: Suljetun materiaalikierron tavoittelu ekstruusioprosessissa Lean-filosofiaa hyödyntäen
Tampereen teknillinen yliopisto
Diplomityö, 97 sivua, 15 liitesivua
Maaliskuu 2016
Materiaalitekniikan diplomi-insinöörin tutkinto-ohjelma
Pääaine: Teollisuustalous
Tarkastaja: professori Jussi Heikkilä

Avainsanat: suljettu materiaalikierto, ekstruusio, prosessilähtöinen ajattelu, Lean, kierrätysmuovi

Diplomityön päätavoitteena oli löytää keinoja kohde yrityksen tuotantoon, joilla ekstruusioprosessia voitaisiin kehittää muovimateriaalinkierron osalta suljetummaksi. Tarkoituksena oli ensisijaisesti löytää menetelmiä, kuinka prosessin ei-haluttua tuotosta eli muovijätettä voitaisiin eliminoida. Konsernin tavoitteena on laskea syntyvän hukan määrä 7,5 %:iin (vuonna 2015 10,06 %). Sekundaarisena tavoitteena, oli tutkia kuinka tehtaan sisäisesti muovijäte voitaisiin laadukkaasti ja mahdollisimman suurella prosenttiosuudella kierrättää takaisin arvoa tuottavaksi syötteeksi.

Kohdeyrityksen nykytilaa tutkittiin osallistuvalla ja ei-osallistuvalla havainnoilla, haastatteluilla, analysoimalla ja seuraamalla ERP- ja BI-järjestelmiä, sekä työskentelemällä lyhyitä jaksoja tuotannossa. Havainnointi jatkui koko tutkimuksen ajan ja tarkoitti päivittäisiin aamupalavereihin osallistumista sekä muiden operaatioiden seuraamista. Numeerinen data tietojärjestelmistä antoi prosessin nykyisen hyötysuhteen. Työskentely tutkimuksen alussa auttoi näkemään prosessia sisältä. Haastattelujen ja niiden analyysien avulla saatiin karkea tärkeimmät kehitysalueet nykytilassa.

Kirjallisuutta sovellettiin kartoitettaessa suljetun materiaalikierron vaatimuksia ja tutkittaessa prosessiorientoitunutta ajattelua, ekstruusiota, ja muovien kierrätystä tehtaan sisällä. Myös kirjallisuus Lean-filosofiasta oli tärkeässä roolissa.

Tutkimuksen tärkeimmät tulokset ovat kehitysalueet ja suosituksen näiden ratkaisemiseen materiaalinhankinnan, materiaalin- ja varastonhallinnan, tuotantoprosessin, kierrätyksen, informaatiovirtojen ja arkipäiväisen johtamisen osalta. Suurimmat tämän hetkiset ongelmat liittyivät systemaattisten ja tutkittujen toimintatapojen puutteeseen. Myös muovirouheen käyttö tarvitsee tarkemmin määritellyt ja hyväksi todistetut syöttösuhteet, koska kierrätyksen aikana sen mekaaniset ja prosessointiominaisuudet muuttuvat esimerkiksi sulaindeksin ja tiheyden osalta. Huomattiin myös, että työntekijöiden suoriutumisella on suuri merkitys ekstruusioprosessin onnistumisen kannalta sen manuaalisen luonteen vuoksi. Ensisijainen jatkosuositus on korjata tekijät, jotka aiheuttavat hukkamuovia, koska tähän liittyvät suurimmat taloudelliset hyödyt. Myös muovirouheen käytön lähempi tutkiminen tulisi aloittaa mahdollisimman pian. Tämä voi vaatia aiheen laajuuden vuoksi tutkimustiimin. Seuraavana jatkosuosituksen on korjata asiat, jotka edesauttavat suljetun materiaalikierron ja kierrätyksen toteutumista.

PREFACE

This research has been carried out as part of the Master's Thesis of Materials Science program in Tampere University of Technology and has been enabled by a scholarship from TTY Foundation. The case company and customer for the results was an industrial plastics company from Western Finland. Mentors for the research were Professor Jussi Heikkilä from the Department of Industrial Management of Tampere University of Technology and Site Manager, Compounding, Raw material R&D from the case company.

First of all, I express my gratitude to the case company for providing me with such an interesting opportunity for this master's thesis. Special thanks go to my mentors, Professor Jussi Heikkilä and the mentor from the company, who both gave me such good suggestions and comments. Also I would like to sincerely thank all the people from the case company, who helped me to carry out this master's thesis. I wish to express my gratitude especially to all the people from the production who shared their thoughts with me and helped me a lot. Without your openness and friendliness writing this thesis would have been much harder. I would like to also thank Mira who did a huge work and checked the orthography and grammar of the text.

I am grateful to my lovely parents of their support and encouragement. And last but not least, I express my gratitude to my dear fiancé Niko, who encouraged me tirelessly and had so much patience.

In Vaasa, Finland, on 10th March 2016

Milja Huuskonen

CONTENTS

LIST OF ABBREVIATIONS AND TERMS

ABS	Acrylonitrile Butadiene Styrene
BOM	Bill of Materials
ERP	Enterprise Resource Program
FIFO	First In First Out
HDPE	High-Density Polyethylene
JIT	Just-In-Time
L/D	Length/Diameter
LDPE	Low-Density Polyethylene
LLDPE	Linear Low-Density Polyethylene
MFI	Melt Flow Index
MTO	Make to Order
NPV	Net Present Value
PC	Polycarbonate
PE	Polyethylene
PMMA	Polymethyl methacrylate
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
PVC-P	Plasticized Polyvinyl Chloride
PVC-R	Recycled Polyvinyl Chloride
SMED	Single-Minute Exchange of Die
SOP	Standard Operating Procedures
TPS	Toyota Production System
UPC	Universal Product Code
PVC-U	Rigid Polyvinyl Chloride
WIP	Work in Process

Additive	Functional or non-functional, used to modify properties of plastic
Amorphous	Unorganized structure of polymer
Channel	The space between barrel walls and a screw
Chemical recycling	Break-down of plastic to its components by using solvents and other chemicals
Compression ratio	Depth of a feed zone per depth of a metering zone
Cooling bath	A step of extrusion process after an extruder where a hot product is cooled down in the water
Crystalline	Organized structure of polymer
Die	Part of extrusion process where melt is pushed to form

Glass transition temperature	Above it amorphous polymer changes from solid to leather like
Hopper	An opening through which material is fed to the extruder
Hydroscopic	Material that absorb moisture from the air
ISO 14001	Environmental managing standard
Jidoka	Automation with a human touch that detects defects
Kanban	A method of managing production, underpins JIT
Lean	A strategy with a goal give maximum value to the customers, make processes flow and eliminate waste
Little's law	Tautology; work in process is equal to the product of throughput and cycle time
Masterbatch	Concentrated mixture of the base polymer and additive
Mechanical recycling	Separation, cleaning and shredding of plastic for re-using
Molecular weight	The mass of a molecule
Pitch	The distance between two consecutive flights in extrusion screw
Polydispersity index	The molecular weight distribution of polymers
Post-consumer waste	Waste from consumer after the use of a product
Pre-consumer waste	Waste from manufacturing, post-production waste
Process	A collection of activities to produce from input(s) to desired output(s)
Quality	A measure of how well a product or service meets customer expectations
Regrind	Usually mechanically recycled plastic made for re-processing
Scrap	Waste material from plastic production
Screw	The part of extruder where polymer is mixed, heated and conveyed forward
Stabilizer	Reduce decomposition effects of plastic
Takt-time	The rate of production to meet customer demand
Temperature zone	Areas in the extruder that give external heat for melting of polymer
Thermoplastic	Can be moulded multiple times, reversible response to cyclic temperature
Thermoset	Can be moulded only once, heating after the final structure causes degradation
Value chain	A chain of activities that have to be performed to deliver a valuable product or service for the market
Viscosity	A fluid's resistance to flow

1. INTRODUCTION

Creating value for the customer is the key of any enterprise. In manufacturing industry often the core process where the value is physically created is a production which creates from input (raw materials, knowledge, labour hours and energy) desired (products) and undesired (waste) outputs. In a Finnish business environment, where achieving cost competitiveness is challenging, getting a high flow- and resource efficiency becomes a major factor to maximise share of the valuable output of the process. Especially in the case of plastic industry where material costs can cover over half of the total product costs, achieving a good material efficiency is necessary. At the same time changes in the legislative environment push companies to act according to sustainable development. Thus, companies experience challenges of the efficient use of material resources. Closing the materials loop is an effective answer. The closed-loop system means perfect use of resources; input is entirely turned into desired output and if waste is formed, it is turned back to input.

1.1 Background

The case company and the customer of the research is a Finnish plastic manufacturer which belongs to a global Group. It has three units in Finland; a production unit in Western Finland, an internal raw material preparation unit in Southern Finland and a secondary operation unit also in Southern Finland. The production method is an extrusion, which is a continuous process that pushes melted plastic raw materials through a tool with a certain cross-section profiles, pipes, bars and other in the longitudinal direction uniform shapes. The success of the extrusion process depends strongly on the compatibility between melts rheological behaviour and set conditions, equipment and machine.

In the year 2014 the case company used over 1 660 tonnes plastics raw material (in the year 2015 corresponding value was 1 584 tonnes) that covers circa 79% of the total materials input which was 2 104 tonnes (packing materials, metals, plastics). Of that input, 86 % was processed to products and 14 % was undesired output. This consists of landfill waste (4 %), combustible waste (1 %), regrind sold as secondary raw material (3 %) and made regrind to the own process (6 %). The landfill waste is the most undesired share because it consists mostly of PVC that is classified as organic waste. According to the Finnish Waste Law’s Act 331/2013, placing organic waste (the concentration of carbon more than 15 %) to the landfill is forbidden. Finding ways to reduce the share of waste is important also from the financial point of view, because for instance 2014 the total lost value in the form of plastic waste was over 300 t€, when the value of virgin raw material, landfill and combustible waste costs and poor income on sold regrind had been taken into account (see the Chapter 5.1.2 Waste).

The research has been enabled by a scholarship by TTY Foundation. It is carried out as part of the Master's Thesis of Materials Science-program in Tampere University of Technology.

1.2 Objective

The research problem of this master's thesis is to find ways for the case company *how material usage can be turned into a more closed system.* Made plastic waste, scrap, can be mechanically recycled to regrind. *The primary target is to reduce non-valuable waste material output* of the extrusion process and *the secondary target is to increase the use of regrind as a value creating output*. In the year 2015 the actual scrap percentage was 10.06 % (planned 8.12 %), the weight of scrap almost 160 tonnes and the actual scrap value circa 290 t€. The Group's target is to reduce the scrap percentage to 7.50 % which means 71 t€ savings in material costs when compared to the actual scrap percentage. Even more optimistic scrap level 5.00 % would instead mean 144 t€ savings (see Chapter 6.4.2 Scrap and Made Regrind). The total cost impact is even bigger when taking landfill costs, labour hours and other incurred costs into account. The aim of the research was to outline *concrete methods that support achieving the set numerical targets for the scrap level* and help to raise a material efficiency by closing the materials loop.

Regrind differs from virgin plastic raw materials by processing conditions, rheological properties, morphological properties and thermal- and mechanical properties of the end product. Determining the common problems when used recycled plastic materials and finding factors affecting the recyclability should be covered at least in the theory chapters. In addition to material related issues considering the effect of information flows, commitment of employees and attitudes were in the scope because they also have an impact on formation of scrap and on the use of regrind.

The company has tried to solve the issue related to the use of regrind for years but without a real breakthrough. This is why one criterion, when measuring the success of the research, is to look at the process in a fresh light. Self-evident results like the role of better tools in generating scrap are ignored and the aim is to find partly hidden factors in the process.

1.3 Scope and Structure of the Research

With regards to a flow unit (plastic raw materials) the research is limited to cover issues from the raw material purchase to production. Scope of the research has been visualized in Figure 1. Research and development (R&D), sales of products and other financial management were not included. R&D can affect the recyclability of the product especially in the long-term but due to a huge area of the study and the talented project manager in the company; it was not considered necessary to use resources in this area. Also, in this research closing the loop of post-customer waste was not studied. The research problem has been divided into smaller areas according to the value chain; raw material purchase, inventory- and material management, extrusion of established and new products and maintenance, quality control and recycling. In addition to material flows, also information flows and a daily floor level management and commitment of employees has been studied.

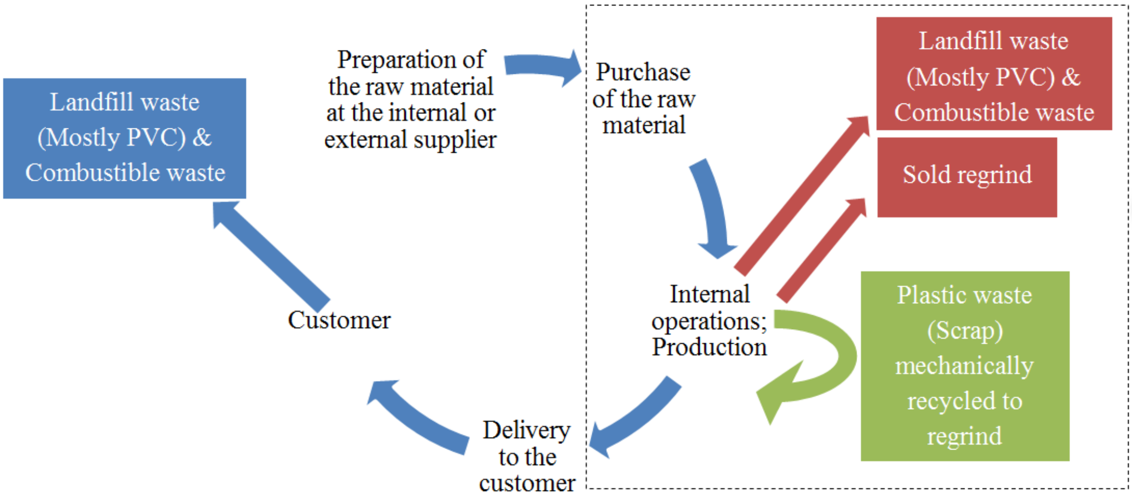


Figure 1 *The focus and scope of the research*

When the research started, it was not clear what things in each area affect the formation of scrap and the use regrind. The overall picture was achieved through participant- and non-participant observation, working in the production and getting numerical data about the efficiency of the current extrusion process (inputs and outputs). Interviews were performed in order to find out which topics to pursue. This was done because employees from different areas around the research problem had a lot practical experience and the research time was relatively short. Collected data was compared to literature about the processes, Lean, extrusion and recycling. Recommendations were based on all collected observations, interviews and literature. Lean was chosen as the main perspective and method because it was introduced in the company a few years ago. It has also a strong connection to process-orientated thinking and the closed-loop system, due to the aim of both concepts being to reduce valueless waste.

Due to the process nature of extrusion and observed symptoms of broken processes Chapter 2 covers process theory and effective control of the process. Fundamentally also *a closed-loop system is a strategy of perfectly controlled flows inside the process.* Process mapping is considered to give tools how process observation could be done better. Measuring the process performance is important in order to get a picture of the current performance and what should be done to achieve a more closed materials loop. Theory of Lean-philosophy covers two main flows inside a process; information and material flow. In the end of Chapter 2 the theory of the closed-loop system gathers, in addition to what was previously learned, things needed for achieving a closed-loop system. At last but not least the role of employees is reviewed. Without their commitment any improvement changes will fall back to as they were. Their role is significant especially in extrusion, because due to its mostly manual nature in the current case process, the performance is strongly dependent on their performance.

Any defect in material or equipment is possible source of scrap. To be able to achieve a closed-loop system and process high quality products with a low scrap level, knowledge about equipment and materials is required. Chapter 3 discusses these issues. Systematic troubleshooting is maybe the most critical step regarding scrap and extrusion problems and can also have huge financial impacts. Down-times and off-quality products are necessary to be able to diagnose quickly when extrusion develops a problem. At the end of Chapter 3 the use of recycled plastics and common problems related to them are viewed. This gives also a theoretical base as to how regrind should be re-used in the extrusion process.

Chapter 4 discusses the used research methods more closely and explains for instance how interviews were carried out. Theme interviews were the most important source of information about the current state because of the relative short observation time.

Chapter 5 lists the observed issues around previously mentioned topics (raw material purchase, inventory and material management, production process, recycling, information flows and managing and people). Overall, the main problems were caused by the lack of systematic and studied approaches. Also daily management, commitment of employees and the attitudes affected the process performance, the amount of generated scrap and used regrind relatively much.

Chapter 6 gives suggestions and example solutions to previously mentioned issues. Conclusion summarises the content from previous chapters, lists possible sources for errors, estimates the success of the research and gives recommendations for further research.

2. CONCEPTS OF PROCESSES, LEAN-PHILOSOPHY AND A CLOSED-LOOP SYSTEM

A closed-loop system or circular economy is often studied with a view to environmental benefits but relatively less with regards to enterprise. However, it can produce great value also to the enterprise due to a higher material productivity, saved waste taxes and increased value to the customer. Fundamentally it is a strategy that means perfectly controlled flows inside the process; input is fully utilized due to the fact that only desired valuable output without leakages is generated and if undesired output is formed, it is transformed back to input. The closed-loop system is not easy to achieve because it requires a thorough knowledge about core and support processes inside the factory, precisely determined material and information flows, good integration with other steps in the value chain and committed employees (operators).

The area of the study is a plastic extrusion process which consists of a raw material input and a plastic profile/pipe output. As well as the closed-loop system, also the success of the extrusion process depends on how well the process is under control. This makes the concepts of processes topical and is the reason why it has got a relatively important in the research. One way to improve the performance of processes and enterprise is Lean-philosophy, which has as an aim to produce the best possible value for the customer and eliminate all waste from the process. Waste means all those issues that do not produce value for the external or internal customer (the next step in the process). Figure 2 visualizes the concept of Chapter 2. The umbrella term is the closed-loop system, under it places the concept of processes and the Lean-philosophy according to which the flows are managed.

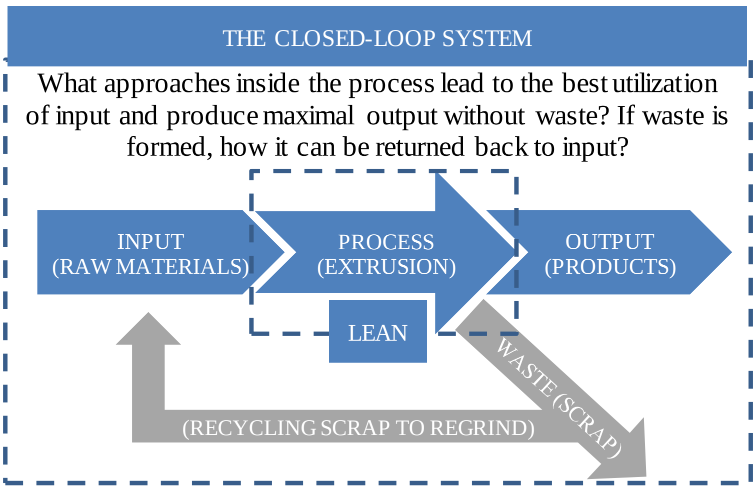


Figure 2 *The concept of the Chapter 2; the umbrella term is the closed-loop system and under it the concept of processes and the Lean-philosophy*

This chapter focuses on the relationship between concepts of processes, Lean-philosophy and finally the closed-loop system. When used together these can be a source of competitiveness, but it is possible only when there is a strong link between the strategy of the closed-loop system and the corporation strategy.

2.1 The Concept of Processes

Organizations comprise of four elements; people, processes, control mechanisms and structure. The reason why processes carry a critical role is despite what we usually think, 85 percent of all problems in organizations can be attributed to processes, control mechanisms and structure and only 15 percent falls to the people (operators of the process). (Madison 2005, p. 3.) Fundamentally everything a business enterprise does to survive is process. The misunderstanding that processes are under control when they in reality are not, can lead to uncontrolled process output (Hunt 1996, p. 1-2). Like Rummler and Brache have wisely said (2012, p. 42);

"Processes are rolling along (or frequently, stumbling along) in organizations, whether we attend to them or not. We have two choices - we can ignore processes and hope that they do what we wish, or we can understand them and manage them."

Improving a process requires abandoning of the traditional task-orientated and highly hierarchical organization. Traditional organizations are departmentalized to parts which all perform their own repeating functions and are controlled by a higher authority. The problem is that none of the functions can themselves achieve organizational goals and employees might not have an overall perspective. (Gray & Starke 1984, p. 175-176.) Unlike a traditional organization, process organization does not highlight hierarchical decision making. Core processes, which have to be performed to produce value to the customer, are defined and process teams are built to maintain those operations. All processes have their own process owners who are responsible for coordinating process teams. Middle management coaches and gives advice to process teams and owners and a small executive team leads the company. (Peltonen 1998, p. 37.)

A change to a process organization is not easy or fast to implement but is usually worth it. It requires time and effort to define the company's core processes that are needed to produce value for the customer. The company's approaches usually change dramatically and the reward system may need upgrading. The transformation to a process organization requires also changes in attitudes; managers have to give teams and employees the right to make decisions and on the other hand employees have to be committed and motivated to work together. (Nieminen 2007, p.40-41.)

As mentioned before, many problems in a company can be linked to their processes. According to Madison (2005, p. 55-59) symptoms of a broken process are:

- *Internal or/and external customers are unhappy – the quality is not as expected and certain things take too long*
- *Processes have to be done many times – scrap, mistakes, incorrect information etc.*
- *Employees report a high frustration – processes and work-tasks are confusing, full of bottlenecks and have design flaws*
- *There is finger-pointing and blaming in processes between departments*
- *Processes are not measured or controlled – output time and quality varies and reacting to undesired output is difficult when there is no standardization*
- *Inventory, buffers and other assets sit idle – materials and information do not flow effectively*
- *Too many reviews – motivation to produce desired quality for the first review decreases*
- *No one is managing the total process – there should be someone who has authority to fix and allocate resources as necessary*
- *Management throws money at the problem without getting improvements - improving operations do not fix the root cause*
- *Managers spend a lot of time with firefighting – without fundamental changes in processes fires most likely recur*

The problem of a traditional organization is that tasks are highly specialized and the whole organization focuses on functions not processes. When items get handled by many people who are in functional silos and not integrated together, they all have different goals. In a cross-functional organization people from different departments work together in *a team* and they have the same goal; to complete a whole piece of work - a *process*. (Hammer & Champy 1993, p. 66.) Teams that consist of people from all departments, who are in touch with the process, have better probability of solving root causes of problems. They have practical experience and different perspectives to the process so the result is probably more comprehensive than decisions made by management who have little to do in a reengineered environment. (Kurnik 2016.)

2.2 Process Mapping

Process mapping consists of those analytical and communication tools which make it possible to identify a company's current "As-Is"-processes and sketch the "To-Be" roadmap for future (Hunt 1996, p. 1). Process mapping can be done on three different levels. The least detailed is a macro flowchart, more detailed is called a functional-activity flowchart and the most detailed flowchart is created at the task-procedure level. (Madison 2005, pp. 21-30.) These all complement each other and are not usually comprehensive enough to be used singly in process improvement projects. The reason for introducing process mapping so carefully is that when developing production towards the closed-loop system, it is necessary to have a thorough knowledge about one's internal processes. Only by mapping current core and support processes one can identify the main problems and small details that create waste and prevent the process from being closed.

A macro flowchart comprises only the most critical elements of process. Because of the lack of elements this flowchart is used only in the beginning of the process improvement projects to catch the "bigger picture". (Madison 2005, p. 22.) Figure 3 below shows a very simple macro flowchart of a plastic extrusion.

Figure 3 *A very simple macro flowchart of plastic extrusion process, a box = an activity, a diamond = a review, an arrow = the direction of the flow, a triangle = a storage, the big D (not in the figure) = delay (adapted from Madison 2005, p. 19-21)*

A functional activity flowchart represents people who are working in the process. With a functional activity flowchart the user is able to spot problems and disconnects between departments or individuals, see who takes the value-added steps and who does not and see where most of the work is done. (Madison 2005, p. 23-25.) Figure 4 shows a part of an imaginary functional activity flowchart about introducing a new product after research and development.

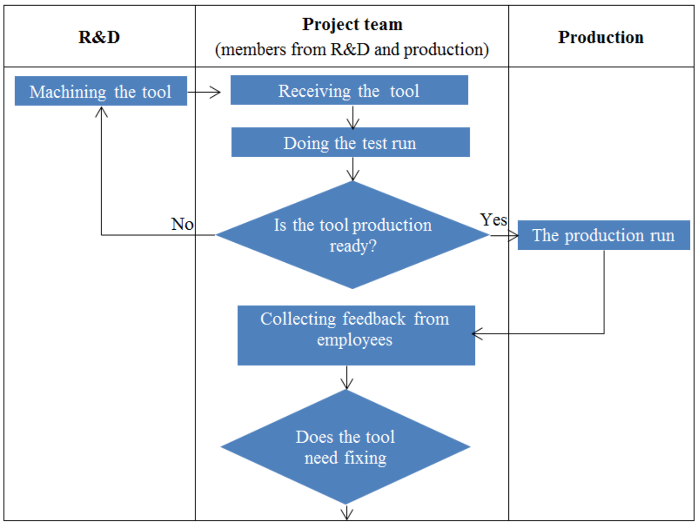


Figure 4 *An imaginary functional activity flowchart about introducing a new product after R&D (adapted from Madison 2005, p. 23-25)*

After spotting a problem in the functional flowchart, the root cause should be identified and here the task procedure flowchart becomes useful. (Madison 2005, p. 30.) Figure 5 shows a task procedure flowchart about a general quality check in the case company's production.

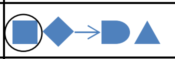
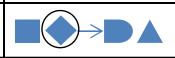
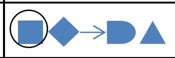
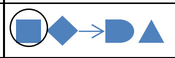
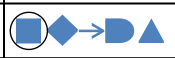
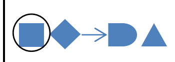
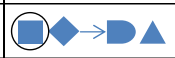
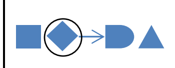
Sequence	Time	Symbol	Frustration	Description	Why do we do this step?
1	3 s		low	Taking random profile or product for testing	To get a test sample which represents a batch
2	10 s		low / medium / (high)	Checking semblance (colour, gloss)	To find out if a test piece meets specifications
3	10 - 60 s		low	Measuring dimensions with a caliper	To find out if dimensions meet specifications
4	30 s		low	Cutting one-meter-long piece of the profile	To get a meter weight
5	20 s		low	Measuring the mass of one-metre-long piece	To get a meter weight for calculation of material consumption
6	20 s		low	Writing down the run speed	To find out if we meet productivity goals and if we are in time with production
7	20 s		low / medium	Comparing results to standards	To find out if our results in line with standards
8	10 s - …		low / medium / (high)	Making the decision: is the test sample passed or does the process need corrective actions	To find out if the process needs corrective actions

Figure 5 *A functional activity flowchart of the quality inspection in the case company's production; sequence = the step number, time = how long a certain step takes, frustration level, description of the step and the reason why the step is done (In some cells there are many options depending on a product) (adapted from Madison 2005, p. 33)*

Four lenses used to analyse flowcharts; frustration, time, costs and quality. When improving processes to the closed-loop system all of these are important. Frustration usually correlates with quality so by reducing it, it is possible to improve quality and avoid waste. Thus it often points to bottlenecks and disconnects in the information flow. (Madison 2005, p. 88-90.) According to Lean-philosophy waiting is waste (expect rare cases, like whiskey aging in barrels) what makes the time lens very useful to spot and remove unwanted process steps. With the third lens, cost, it is possible to calculate the return on investment generated from process redesign. The quality lens is important with regards to scrap because all activities that are not done the first time cause waste. (Madison 2005, p. 91-115.)

After finding a root cause of waste and solving a problem, the aim is to prevent it from happening again. There are many error proofing techniques that are based on minimizing human errors with simple ideas. (Madison 2005, pp. 126.) Human errors increase when people are tired in night shifts. Lack of sleep predisposes people to decisions without enough assessment and decreases performance. (Suomen Lääkäriliitto 2005.) When night shifts are reality in a company's production, all procedures should be designed to be so easy to follow and perform that also people working at night can cope with those. Mistake proofing technique, poka-yoke, is a useful way to reduce human errors and reduce variation in activities. It makes it either impossible for an error to occur or makes it possible to detect an error immediately, once it has occurred. (Tague 2005, p. 351–356.) Many benefits relate to poka-yoke techniques; they promote individual responsibility for quality ownership, are efficient but with little investment, detect errors as soon as possible, focus on waste and scrap reduction in defects and processing and provide immediate feedback (Burton & Boeder 2003, p. 118).

2.3 Measuring the Performance of Processes

Measuring the performance of a process is important when trying to achieve the closed-loop system because without measuring the performance it is impossible to control, manage, make intelligent decisions or improve business processes (Trade 1995, p. 4-7). It should always be tied to the organization's goal or objective and reflect customer's needs. (Trade 1995, p. 4-7.) It is important to survey what those indicators are that can be used to measure the company's own goals and the effectiveness of processes (Martinsuo & Blomqvist 2010, p. 4).

Measured processes can be divided into two main groups. Core processes are tightly connected to a customer outside the company and in this case they consist of the sales, research and development (R&D) and extrusion production. When achieving the closed-loop system all are needed and should have the same goal. The sales is responsible for communicating with the market and identify if there is demand for recycled products and what kind. R&D is responsible for creating new and modified products (of partly recycled materials) in order to fulfil customer's desires. Production is responsible for realizing demand as products (of partly recycled materials). (Slack et al. 2001, p. 18.) Support processes are connected only to company's internal customers, for example to the next process and are needed to maintain effective operations (Martinsuo & Blomqvist 2010, p. 4).

Quality, speed, dependability, flexibility and cost are the main objectives of processes and that is why they are also good measuring areas. Good quality requires that all other mentioned issues come into effect. A good indicator for it in the closed-loop system is the scrap level or the number of defects per unit. Speed can be measured for instance as actual versus theoretical throughput time (affecting also the flow and resource efficiency). (Elearn 2005 p. 47-48.) In the case company a good indicator for dependability is realized extrusion runs without problems versus realized runs with extrusion problems and extra scrap. Flexibility can be measured as time taken to change schedules and cost as utilization of resources (Elearn 2005, p. 59). The performance indicator should let us know how well we are doing, if we are reaching our goals, if our customers are satisfied, if our processes are in statistical control and where improvements are necessary (Trade 1995, p. 4).

Only collecting statistics does not lead to improved performance or achieved goals. As important as collecting statistics is to analyse it in the right way and implement the results and feedback in operations. (Elearn 2005, p. 63.) During the analysis the raw data is converted into understandable performance measures and this is compared to goals or standards (Trade 1995, p. 10). This should give feedback to the process input and be a trigger to systematic corrective actions, which are also connected to the organization's goals and effectiveness. (Martinsuo & Blomqvist 2010, p. 3.) Figure 6 shows a simple feedback loop (Trade 1995, p. 9).

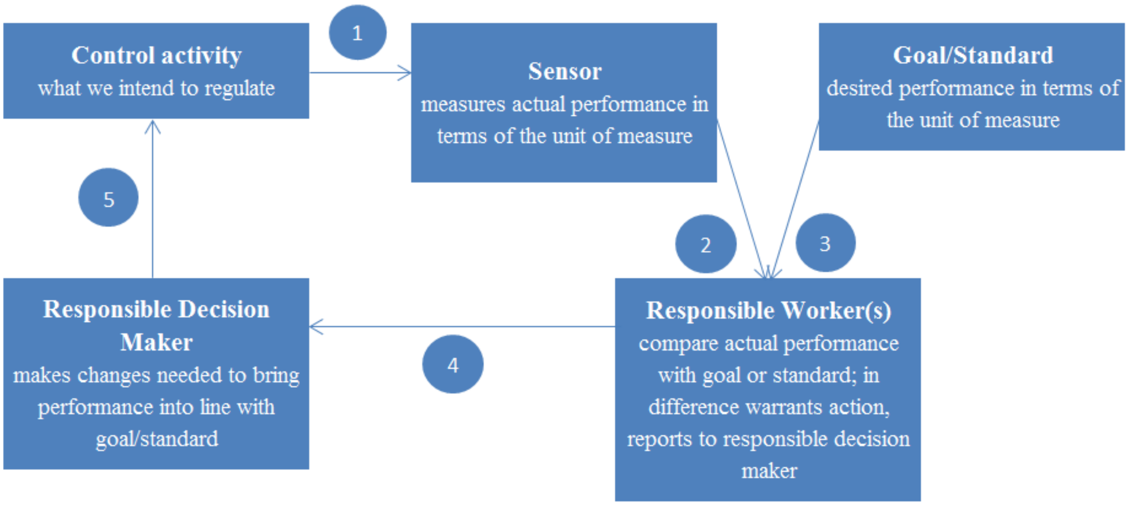


Figure 6 *Feedback Loop in Process Improving (Trade 1995, p. 8)*

The loop starts when a sensor evaluates actual performance (1) and reports that to a responsible worker (2). He or she compares that to the information from the goal or standard (3) and if there is a difference, the worker reports to a responsible decision maker (4). The responsible decision maker verifies information and determines if a corrective action is needed to bring the performance back in line with the goals (Trade 1995, p. 8).

2.4 Lean-Philosophy

Lean-philosophy derives from Toyota Motor Corporation and especially from Toyota Production System (TPS) which is famous of its performance level all around the world. Many companies have tried to achieve the same as Toyota by transferring TPS methods like Kanban, Single-Minute Exchange of Die (SMED) and other tools to their production. Many times the reason why they have not succeeded in the desired way is that the core idea of Lean-philosophy was misunderstood. To be Lean, it is not sufficient to just implement Lean tools or methods. Lean is more – it is a philosophy. It starts from the vision and continues with everyday learning, challenging and pushing the performance to a higher level. Paradoxically all activities, connections and production flows are rigidly scripted but at same time operations are extremely flexible and adaptable. (Spear & Bowen 1999.) In TPS and Lean-philosophy four basic rules act as a guide for all completed activities, decisions and improvements. According Spear and Bowen (1999) rules are;

1. *All work shall be highly specified to content, sequence, timing and outcome.*
2. *Every customer-supplier connection must be direct and there must be an unambiguous yes-or-no way to send request and receive responses.*
3. *The pathway for every product and service must be simple and direct.*
4. *Any improvement must be made in accordance with the scientific method, under the guidance of a teacher, at the lowest possible level in the organization.*

The flow efficiency is the core idea of Lean-philosophy and a requirement also in a closed-loop system. It means that rather than maximizing the use of resources we focus on *getting the processed unit to flow effectively across the organization*. Flow efficiency can be calculated by *dividing the time when the flow unit (a product) gets direct or indirect value by lead time*. However, traditionally organizations are focused on the resource efficiency, on the best possible utilization of resources and getting low unit costs by economics of scale. The resource efficiency can be calculated by *dividing resource usage per period*. (Modig & Åhlström 2013, p. 9-19.)

Unfortunately implementing the complete resource and flow efficiency at the same time is impossible due to three factors; Little's law, bottlenecks and variation in the process. Little's law says that lead time is work in process (WIP) multiplied with cycle times (CT). When it comes to the resource efficiency it is better if there are flow units waiting to get processed, but this increases WIP and further lead times. That means that the flow efficiency decreases. Bottlenecks are operations whose capacity is lower than the others' and as a consequence their capacity limits the whole system's capacity. Variation leads to long lead times (and poor flow efficiency) when utilization rate (and the resource efficiency) increases. Getting simultaneous resource and flow efficiency requires zero variation, which is impossible to achieve. (Modig & Åhlström 2013, p. 47-67.)

Focusing only on good resource efficiency is a poor solution due to long lead times, a large amount of WIP and the need of re-initiation which all cause new secondary needs. Long lead times lead to difficult production forecasting, probable form of scrap due to the need of working hastily when demand is hard to fulfil and further fixing problems caused by scrap (secondary need). Large amount of WIP leads to a need for storage and re-initiation causes a mental set-up time (both secondary needs). Because secondary needs do not produce value, they are categorized as waste. If it takes more time and resources to fulfil secondary needs than performing value-adding primary tasks, is it possible to call a resource efficiency-orientated organization effective? This brings us back to the *Lean* and why it is many times the key for improving the performance of processes - *it makes operations flow*. (Modig & Åhlström 2013, p. 47-67.)

Lean-philosophy tries to achieve perfection by maximizing the quality experienced by the customer, maintaining continuous flows and reaching the non-waste state. (Stevenson 2012, p. 44-45.) If Lean is thought of as a pyramid, values are in the top and the highest abstract level. Below values are principles and methods and in the lowest abstract level are tools. (Modig & Åhlström 2013, p. 129). This is shown in Figure 7.

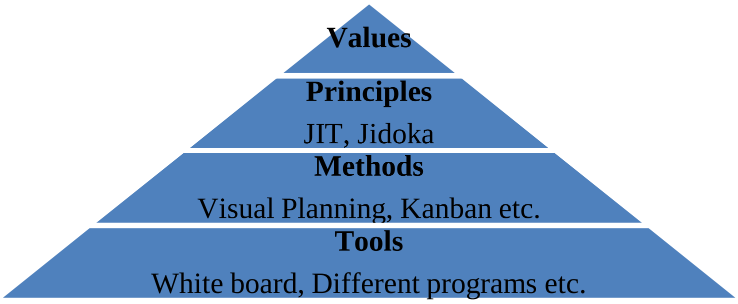


Figure 7 *Abstract levels of Lean-philosophy (adapted from Modig & Åhlström 2013, p. 129)*

Values are placed in the deepest and the most abstract level in the mind and change slowly (Elo-Pärssinen 2007, p. 47). When using values for executing Lean-philosophy, the goal is to try to reduce variation in people's set of values. With principles we try to reduce variance in the way how people think. Principles have to carry out values of Lean-philosophy. The most important principles of Toyota are Just-In-Time (JIT). Only by changing values of people and the way how they think can lead to permanent changes. Methods (like jidoka) are standardized operating models that enable the best implementations of principles in practice. Lean-tools are visible, tactical and operating parts of the Lean-system. (Modig & Åhlström 2013, p. 129-139.)

2.5 Managing Material Flows by Using Lean-Philosophy

Processes consist of material flows and information flows but in a supply chain process a third flow can be identified - the cost flow. For keeping them to flow Lean-philosophy tries to reduce waste from them. Waste, in Japanese "muda", is like a rock in a sleigh. It does not produce value or help the process to develop and progress. Instead, it makes processes heavier than they actually would be. There are eight categories of waste: transporting, inventory, moving, waiting, over-processing, over-production, defects and wasted skills. These all affect also the efficiency of material flow. Transporting and moving are useless for material processing. Stocks act as a buffer but tie up great capital and may hide defects. In addition, it lengthens the total lead time (waiting), takes up space and causes waiting for raw materials and products. (Xinyu & Jian 2009.) Over-processing is one source of scrap if sufficient quality is tough to be deficient. It also means that production is not based on demand. (Burton & Boeder 2003, p. 100.)

In an ideal situation raw materials flow continuously without interruptions through the process for end-products, ready to be supplied to the external customer. This is too much to implement at once so at first a place to focus, called the pacemaker, is needed. It is the most important process where a product takes the final form for the customer. Ideally, the pacemaker sends demand signals upstream in the flow to other production processes which respond to requirements smoothly and fast. The pace is defined as a takt time - the rate at which customers require finished units. (Rother & Harris 2008, p. 1-12.)

In the area of material flows Lean-philosophy requires small batch sizes, a pull-production control system, standard work and jidoka. Batch sizes should be as small as possible. The ideal Lean-system would only use one-piece flow and manufacturing is based on demand only. (Yamagar & Ravanan 2010.) The pull-system is opposite to the common push-system and it assumes that signals of needs move upstream. Kanban is at the core of pull production and it improves flexibility in responding to customer demand, simplifies the procurement process, uncovers hidden waste in processes and eliminates unnecessary paperwork. (Burton & Boeder 2003, p. 120-122.)

2.6 Managing Information Flows by Using Lean-Philosophy

The right information, in the right place and at the right time is necessary to reduce errors, maintain quality and add value to the next internal or external customer. As mentioned before, in a process-orientated organization organizational limits have to be broken. This also applies to information sharing. Hoarding information in departments or optimizing it partially does not serve the common goal of the organization.

Correct information routes make the information available when it is needed and support fast decision making and problem solving. “Grey-areas” should be eliminated to ensure efficient operations. Traditional organization departments often take responsibility for their own operations only and forget that they have to work to fulfil the common external customer’s needs. A typical example is the interface between manufacturing and R&D departments when a new product is being introduced. Many studies have shown that cooperation, regular feedback and rich interaction between these two parties will lead to many benefits; better matches between a new product and product capabilities, reduced manufacturing costs, improved quality and shorter time to market. In addition to manufacturing and R&D the third function, services, should also be included in cooperation. Creating conditions for integrated knowledge-based approaches across functions gives value for the entire firm. (Olausson & Berggren 2012.)

According to Lean-philosophy information should move effectively upstream. Especially when people express frustration they should be heard. Routine information can simply be collected from downstream with the help of check sheets and pre-designed forms, but more complex information needs bringing a person from downstream to upstream to the redesign project. In this way information comes directly from the source. Relevant information should also be shared widely once it is available. Pledging information leads to mistakes, rework and scrap. It should also be remembered that when information moves from person to another a broken-phone effect is always a possible source of error. The more handoffs there are, the bigger the opportunity for errors. (Madison 2005, p. 264-265.)

Bullwhip or Forrester effect is a major source of uncertainty for enterprise. The further away the demand is diverted from the customer, the higher the frequency of the demand is. This may cause hurry to fountainhead of the supply chain even the customer demand in another end of the chain is not significantly increased. Typical reasons are chain structure (for instance not integrated software between customer and supplier), unreliable production system (long lead times), inaccurate forecasts, promotional pricing or manipulation of information. The uncertainty related to the bullwhip-effect can be controlled by cooperation and transparent information sharing. (Heikkilä & Ketokivi 2005, p. 118-119.)

Visual control is the most important control mechanism of Lean-production. It focuses on the process and makes comparing between the current performance and the desired one easy and clear. Visuals (like charts) enable managers to focus on good points in discipline and attach it to the processes. Every process should have its own visual control(s), which show if the process has been performed, when it has been performed and by whom. Core processes and desired activities determine the type of visual control. (Mann 2010, p. 53-74.) For example when achieving the closed-loop system, we can view used, wasted and recycled materials (in kilograms, euros or percentage) per team or per line set. Visual control connects people to their processes and makes everyone to take responsibility due to the fact that nothing can be hidden (Mann 2010, p. 77). If for example the scrap percentage per team is visible, no one can hide the truth and on the other hand people become aware how they are performing.

People should have enough standardized information how activities should be done or there will be high variation in output or results. This is because all people are following the same process in a different way. This will lead to quality problems, scrap and increasing need for traditional checks and reviews. (Madison 2005, p. 262, 266.) Also creating a learning organization requires standardized work because the link between the work and the result has to be clear. Without the link it becomes unclear which activity brings along desired results. (Spear & Bowen 1999.)

2.7 The Concept of a Closed-Loop System

Like all big changes and Lean-philosophy, also turning the enterprise green and towards a closed-loop system starts from the top of the organization and so does the vision of the desired future state. It is a process that requires effort from all departments. It is like a chain - if one link in the chain fails, the whole chain breaks. That makes the process-orientated organization and good integration between core operations topical. Because the closed-loop system is a strategy and a choice between many options, it requires a long-term commitment. On the other hand it can have a positive effect on competitive success, because it is difficult to replicate (because of long developing time and social complexity). (Heikkilä & Ketokivi 2005, p. 29-32.)

Every material and information flows have to be sorted out from an overall level to a detailed level (Wills 2009, p. 6). Measuring the current performance and finding and eliminating all leakages where material turns from a value adding source to waste, is the first step, but creating conditions under which the closed-loop cycle is possible, is even more important. Figure 8 below shows a traditional linear value chain and a closed-loop value chain.

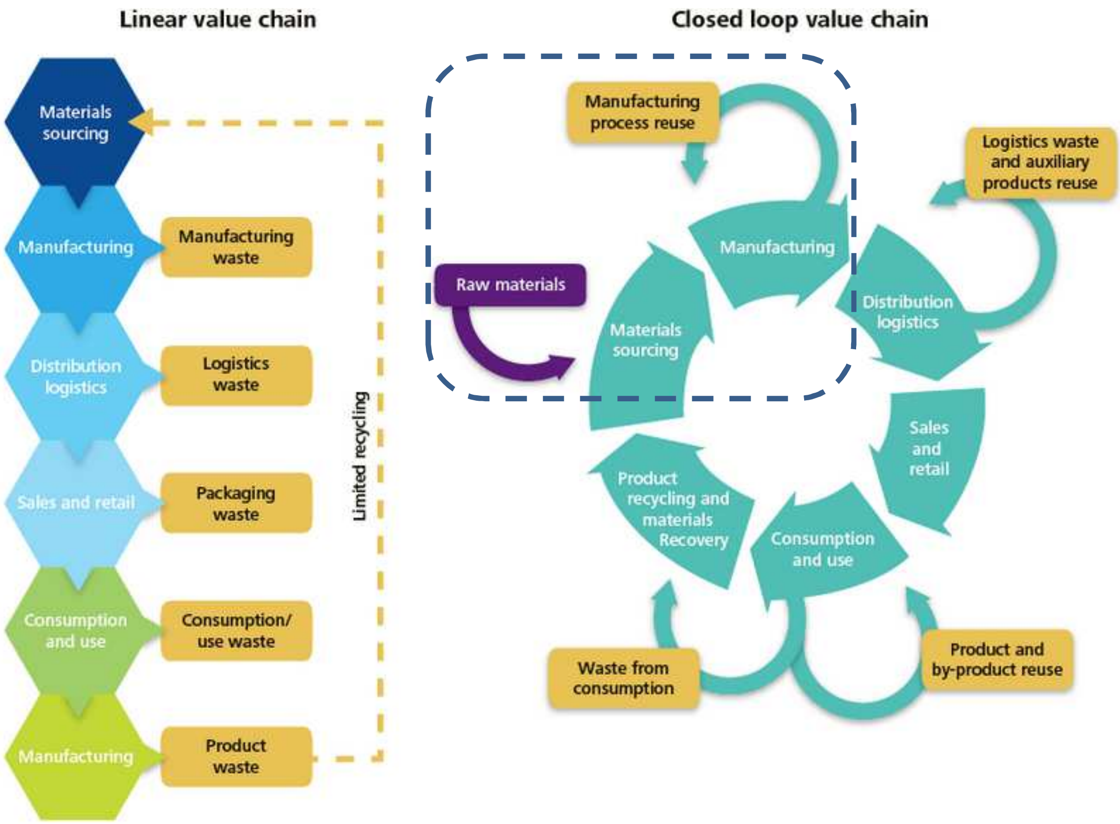


Figure 8 *A linear and closed loop value chain models (Hutter et al. 2010)*

Green values are becoming more and more substantive and the greening of manufacturing is a phenomenon. Like Lean, also "going green" by a closed-loop system has similar type of economic and business benefits: cost savings, increased customer loyalty and attraction, increased employee attraction, ability to grow, innovation and new technologies and increased profit and shareholder value. Cost savings are a direct result of cutting waste. It is not only material costs which will reduce, also the landfill payment and other indirect costs (such as labour cost of handling waste) will drop. Increased customer loyalty and attraction is also a valuable result. Nowadays when global competition is a norm, in addition to attracting new customers and breaking into new markets, it can be hard keeping the markets share and the customers we already have. When legislation and directives are pushing and media and markets are directing us to consider environmental issues in operations, going green and staying green can be a valuable competitive advantage. Businesses that do not adopt green values take the risk of being left behind by competitors who do, or will be forced by governing agencies and legislation to go green. (Wills 2009, p. xvi-xvii.)

Studies have shown that employees also want a company that cares about how it impacts on or contributes to society. Ability to grow means that the money which was spent before on the production of waste may after the elimination of waste be used for new investments and increasing business. It also means decreasing dependence on limited natural resources, like oil. Innovation and development of new green technologies can give direct environmental and cost savings and increase productivity, reduces lead times, increase capacity and increased profit and value for the customer. (Wills 2009, p. xviii-xxi.)

A closed-loop system requires integration with previous steps in the value chain. In the case of extrusion this means that plastic raw materials from the supplier have to be recyclable and easy to process with a low scrap level. Integration mechanisms depend on the level of coordinated operations. Overall, they can be divided into three groups; structural (based on organization structure), functional (approaches and principles) and strategic mechanisms. (Heikkilä & Ketokivi 2005, p. 176-195.)

2.8 Involving Employees

In addition to material and information flows, a closed-loop system consists of operators who are working inside the process (in the case of extrusion profile manufacturers). Involving people is the most challenging part of Lean-philosophy. It is still worth it, because without changing the scheme of thinking, the results of the process will not change (Burton & Boeder 2003, p. 14).

In the process organization the decision making falls to lower levels of the hierarchy because usually people who really are working with tasks have the best improvement ideas about those. The managers’ task is to ensure that every important task in the organization will be done. Their role is also to understand and analyse the process, give feedback to the process owner, establish the process and improve it under the strategy. (Laamanen 2002, p. 119-126; Madison 2005, p. 262.) I think the relationship between an organization and employees can be well summarized by the following statement by Mårten Mickos (Lappalainen 2015);

”A modern organization is like a school of fish, operating at great precision through subtle coordination of vast numbers of essentially equal members. The organization is led from the front, centre, back and sides. A common vision and common values keep the group together. The group is powerful, effective and protected. Everyone has a voice. All are needed; no one is irreplaceable.”

The performance of the organization basically originates from human behaviour. To be able to achieve a high performance two things become important: competence (technical skills and social skills to work in team) and motivation. (Lawrence 2014.) One way to define competence or know-how is to define it as a possibility to succeed in a specific task. The more skills you have at certain tasks, the more likely it is that you know how to do it best. (Laamanen 2002, p. 179.) Talents are the most gifted employees who have given a lot to the organization. Talents can be very valuable to an organization and talent management that is connected to the strategy is crucial for most of corporations’ business operations. (Lumme-Tuomala 2015.) Motivation is also important. In Toyota where the organization’s performance level is high people are not only motivated to personal success but also to the success of the team and the company. Overall, there is not just one source of motivation and many things reinforce or weaken our behaviour at same time. (Lawrence 2014.)

A genuine commitment to changes can only come through personal experience and ability to influence and this should also be taken into consideration while turning the organization towards the closed-loop system. Emotions affect the actions of people, at least as much as rational thinking, whether we wanted or not. Briefings are usually not sufficient and people need to realize and experience at first-hand the benefits brought about by a change. It should still be accepted that there usually always is resistance to change and a quick start is more important than the pursuit of opponents. They should be listened to and their opinions respected but after all managers have the responsibility for change. (Laamanen 2002, p. 256-270.)

By building payroll and other reward systems that encourage the performance of desired activities, important operations can be underpinned (Laamanen 2002, p. 140). The important point in Lean-philosophy is that people are not paid for their time; they are paid for the value they have created for the customer. That makes people in the organization focus on pleasing the customer, when they feel that the customers pay their salary. In this way the whole organization’s value system may transform from protective to productive. (Hammer & Champy 1993, p. 73-74.)

3. EXTRUSION AND RECYLING OF PLASTIC

Extrusion is a continuous process that works by forcing melted polymer through a die under controlled conditions produces profiles with uniform shape and density. The reason why so many basic things have been gone through is that *a closed-loop system in the extrusion environment requires perfect control of all materials and equipment.* That makes the knowledge of both crucial in the view of reducing scrap, reusing regrind and a closed-loop system.

3.1 Process Steps of Extrusion

The limits of the plastic extrusion process are the receiving of polymer raw material and the shipping of the finished profile or pipe (or other in a dimensional direction uniform product) to the customer. All the process steps shown in Figure 9 have to be correctly performed to ensure products that meet specifications and to prevent formation of non-planned scrap.

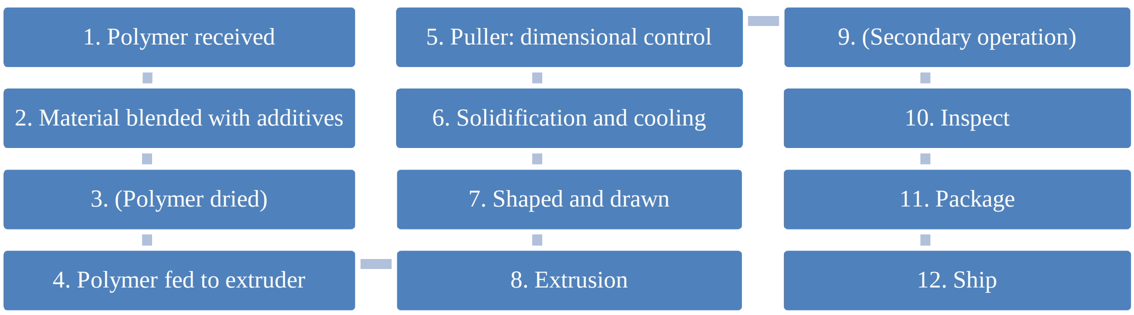


Figure 9 *Schematic of a basic plastic extrusion process, drying and secondary operations are optional (Giles et al. 2005, p. 1)*

Some basic things should be remembered when reducing scrap in extrusion steps. To prevent product cross-contamination all storage silos, dryers, surge hoppers and extruder hoppers must be properly cleaned when raw material in them is changed to another (steps 1-4). In order to produce uniform products and reduce scrap, it should be noted that when mixing pellets and powder, powder can flow between the pellets and cause variation of the composition over time (at the beginning of the run more powder and at the end of run more pellets). (Giles et al. 2005, p. 4-5.) This same effect can happen with regrind and powder, so feeding from different feeders to the same throat is recommended.

Hydroscopic materials and materials stored in a cold warehouse that are brought into a warm environment require drying to avoid condensation of moisture on the surface of the pellets, flake or powder. Drying temperature and time should always be determined and tested to avoid over-drying or degradation at too a high temperature. Measuring the moisture content, especially with PC and ABS, is essential. Incorrect drying can lead to many material problems and decrease the quality of the final product. Splays, bubbles and foamy products are common problems. (Giles et al. 2005, p. 208.)

Before starting-up the production line, the standard operations (SOP) should be compared with previous run records to find out if there is something to be taken into account. Also verifying that all equipment is functioning properly is a basic thing to do. After the extruder has been running for a few minutes, determining if the product meets specifications (by taking samples) helps to improve the process and reduce scrap. (Giles et al. 2005, p. 67-68.)

In the extruder polymer material is conveyed from the feeding zone, through the compression zone and homogenization zone to the die. In the screw material is melted and mixed. Melting happens due to external and internal energy (see Figure 10). External heat consists of electricity or heated fluids outside of the barrel. However, internal heating is the primary way to melt resin (80-100 % of the heating energy) and it consists of friction and molecular relaxations. (Giles et al. 2005, p. 3; Hanhi et al. 1999.) There are three types of mixing operations in extruders: longitudinal mixing or coarse mixing, dispersive mixing or continuation of the disperse phase and radial mixing or distributive mixing (Subramanian 2011, p. 89).

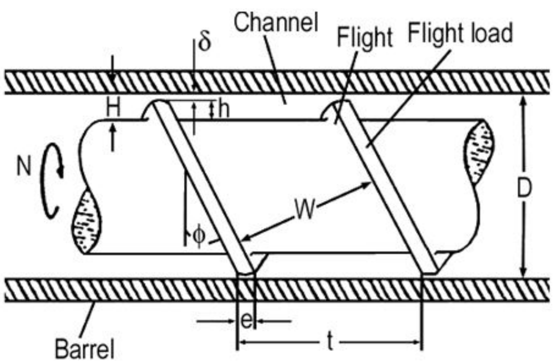


Figure 10 *Melting of flow in the cylinder (Hanhi et al. 1999)*

When moving forward in the screw, polymer chains are mixed and non-orientated but when polymer comes to the die, chains have to partly orientate. When extruded profile exits the die, polymer chains relax and swell. A puller is needed to orientate and shrink them to the desired shape. The draw depends on the puller speed and the extruder output. There is only one optimal puller speed in a given throughput rate and die cross-sectional area. (Giles et al. 2005, p. 8.)

Solidification and cooling after the die are usually done with water and air. Semi-crystalline polymers have a solidification temperature (for crystalline areas) and amorphous polymers have a glass transition temperature at which they transform from leather-like or soft to solid. Uniform cooling is a critical step to produce desired dimensions, warpage-free parts and acceptable performance. With semi-crystalline polymers the right cooling rate is needed to produce the right amount and size crystals. (Giles et al. 2005, p. 9-10.)

As already mentioned, puller and throughput rate determine the dimensions of the profile. Puller pressure has to be high enough to prevent slippage of the profile and at the same time low enough to prevent crushing the product. Slippages lead to variation in the pulling rate and again changes in dimensions. (Giles et al. 2005, p. 11.)

Finally cutting and other optional secondary operations like decoration are done. Inspection can be manual or automated by a video camera or other method. Packing can also be manual or with large batches automated. (Giles et al. 2005, p. 3; Hanhi et al. 1999.)

In every batch a few samples should be stored. These samples are useful in the event of a customer complaint. They act as a test piece and comparison copies and help to solve problems or errors present in customer’s pieces. (Giles et al. 2005, p. 11)

3.2 Extrusion Equipment

The screw is the most important part of the extruder and basic screw nomenclatures are shown in Figure 11. The screw transports material forward, contributes to the heating of the polymer and homogenizes the material. (Rauwendaal 2014, p. 70.) It also pressurizes the material, so that it is able to push through the die (Hanhi et al. 1999). Length per diameter ratio of the screw, L/D, is directly connected to the extruder throughput. It can be calculated by dividing the length of screw from flight to flight by outside diameter of the screw. When L/D increases, also melting and mixing capacities increase and allowed run rates grow. Throughput increases exponentially when the single screw diameter increases. Shorter L/D extruders instead have lower initial investment cost, less residence time in the extruder when processing temperature-sensitive materials and require less torque. (Giles et al. 2005, p. 13-14.)

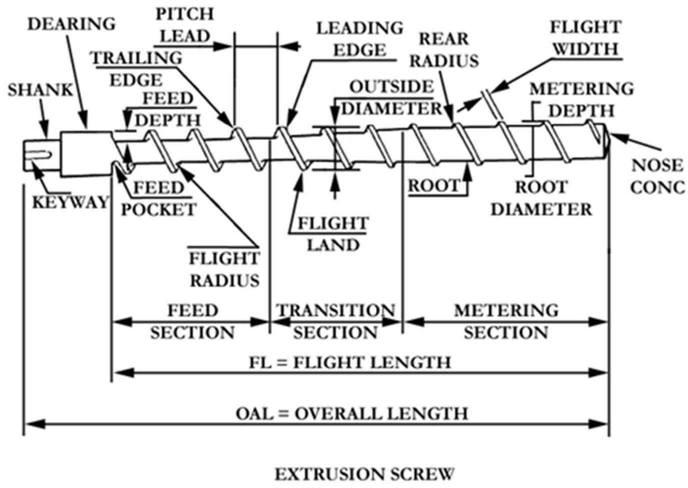


Figure 11 *Definition of screw elements (Hanhi et al. 1999)*

The wear of the screw has a significant effect on the quality of products because it increases melt temperatures. The level of negative effects depends on the amount of combined wear (barrel and screw), viscosity of the polymer, head pressure and screw speed. Just 0.508 mm wear in the screw diameter will reduce output rate by circa 10 %. Because of the strong correlation between wear, quality and output rate, measuring and monitoring the wear of screws and barrels is important with regards to scrap and financial issues. (Steward 2015.)

Single screw extruders are most widely used and the most important type of extruders in the polymer industry. A single screw extruder has only one compression stage but three distinct geometrical sections. These sections are shown in Figure 12. The first section right after hopper is called the feed section or solids conveying zone. This section usually has deep flights and material is still mostly in a solid state. The second section is called the compression or transition zone. Usually the height of the screw flight reduces in a linear fashion thus causing a compression of the material in the screw channel. In the third section, the metering zone, just before the die, flights are shallow and material is in a molten state. (Rauwendaal 2014, p. 13.)

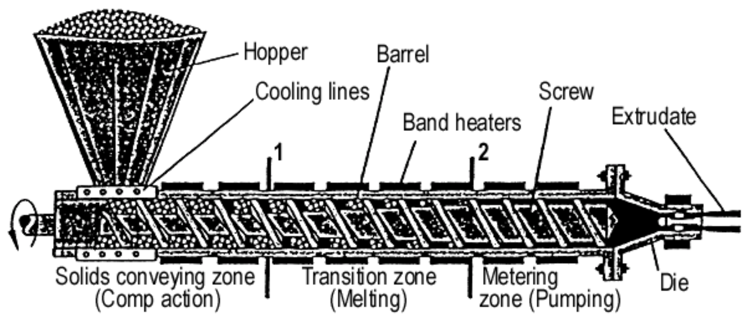


Figure 12 *Single screw extruder (Hanhi et al. 1999)*

Twin screw extruders are extruders with two Archimedean screws but there is an enormous variety of different types, which differ by design and in other properties. Twin screw extruders can be divided by geometric configuration into five different classes. Intermeshing extruders have two different types; co-rotating (rotate in same direction) and counter-rotating (rotate in different directions) extruders. Furthermore, non-intermeshing extruders have three different types; counter-rotating extruders, co-rotating extruders and co-axial extruders. Twin screw extruders are mainly used with thermally sensitive materials (like PVC-R) and in speciality polymer processing operations like compounding. They have better feeding and conveying properties for difficult feeding materials (like powders). (Rauwendaal 2014, p. 24-25, 697-699.)

In the extruder, before the die, there is often a breaker plate. It is a thick metal disk with many holes parallel to the screw axis. A breaker plate forces the polymer melt to flow in a straight-line fashion and prevents the spiralling motion that may cause extruded profile distortion. (Rauwendaal 2014, p. 72.) It also provides a controlled amount of back pressure (Hanhi et al. 1991). Another reason for using a breaker plate is that it improves heat transfer between the metal and the melt when the heat transfer distance is reduced. This leads to better thermal homogeneity of the polymer melt. (Rauwendaal 2014, p. 72.)

In the cases when the extruder barrel does not match up with the entry opening of the die, an adaptor is used between them. In the die polymer flow adopts the shape of the flow channel. Pushing the polymer through it requires pressure due to the die's resistance to the flow. The die's flow surfaces have to be smooth and usually heated to avoid the material sticking on. The pressure in the die is called the die head pressure. It is caused by the die and flow process, not by the extruder. It is a sum of the temperature of melted polymer, flow rate, rheological properties of polymer and the shape of the die. When polymer leaves the die, its shape is corresponds to the cross-sectional shape of the final portion of the die flow channel. (Rauwendaal 2014, p. 15-16, 72.) However, die swell complicates die design because the swelled profile is greater than the orifice from which it came. (Hanhi et al. 1999.) This can be seen in Figure 13.

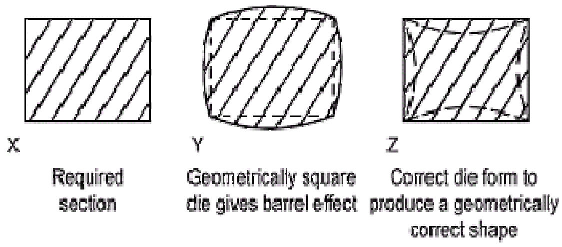


***Figure 13** Effect of die geometry (Hanhi et al. 1999)*

The plastic output from the die is an equation of drag flow, pressure flow and leakage flow (see Figure 14). The drag flow moves out from the extruder but the pressure flow (generated by the die pressure or the head pressure) forces the material backward into the metering zones. (Giles et al. 2005, p. 22.)

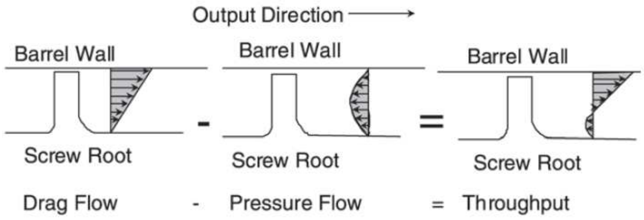


Figure 14 *Plastic throughput profiles from the die (Giles et al. 2005, p. 22)*

Cooling is a difficult part of the extrusion process and a necessary evil because any amount of extruder cooling reduces the energy efficiency of the process. Air cooling and fluid cooling are the two most common methods of cooling. Singly used air cooling is not usually intensive enough but useful because the change in temperature occurs gradually. Water cooling is much more intense but it constitutes a non-linear effect and it is more difficult to properly control. (Rauwendaal 2014, p. 79.)

3.3 Plastic Materials

A good knowledge of used extrusion materials is principal to being able to make consistent decisions, finding corrective actions when problems occur and developing a better output from the extrusion process. Molecular weight (g/mol) and the degree of polymerization describe the length of polymer chains but because all polymer chains do not grow to the same length (polydispersity) and there is a distribution of molecular weights, the average molecular weight is used.

High molecular weight polymers have higher crystallinity, better impact and wear resistance, high deflection temperature and better stress crack resistance. They can also be harder to process. Polydispersity index and an average molecular weight are directly related to the melt flow properties. Furthermore, they affect the processing performance, like the extrusion output rate and pressure. The increase in the length of molecule also raises the resistance to the flow. Changes in the molecular weight distribution may cause extrusion problems because variations in the molecular weight distribution affect the temperature dependence of melt elasticity. (Subramanian 2011, p. 11-12.)

Rheological properties, especially viscosity (η), of the polymer determine its behaviour during processing. When the temperature increases, the viscosity of polymers (and all liquids) decreases. This effect is usually stronger with amorphous polymers than partly crystalline polymers. Instead, increasing pressure will also increase viscosity. Because of this care should be taken when processing polymers because it may have a huge impact especially with amorphous polymers which are more sensitive to pressure changes. (Syrjälä 2013, p. 2-10.)

Melt flow index (MFI) is determined as mass flow through capillary (g/10 min). The higher the melt index, the lower the viscosity of the polymer. (Syrjälä 2013, p. 18.) Studies have shown that several commercial polyolefin (different grades of polypropylene, high density polyethylene and low density polyethylene) with lower MFI have higher thermal stability due to the higher activation energy needed for thermal degradation. MFI depends on the resin's average molecular weight, polydispersity index and branching characteristics like the degree of branching. (Abbas-Abadi et al. 2012.)

In addition to previously mentioned rheological properties, plastic materials also undergo different and complicated other thermo-mechanical processes during heating and cooling. Semi-crystalline plastics have a phase transition during temperature changes. Below glass transition temperature (T_g) the amorphous part behave glassily and above it the amorphous part of the polymer comes rubbery or leather like. Crystalline polymers do not have a glass transition temperature and their melting temperature is usually higher due to more energy being needed to melt the structure. Polymers with a high degree of crystallinity tend to be brittle because of the weak crystal-crystal interface. (Subramanian 2011, p. 13.)

The most common extruded plastic materials are acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polyethylene (PE), polymethyl-methacrylate (PMMA), polystyrene (PS) and polyvinylchloride (PVC). ABS is a copolymer of acrylonitrile, butadiene and styrene. With high butadiene concentration the impact strength is good and with high styrene concentration manufacturability becomes easier. With high acrylonitrile concentration chemical resistance and hardness are better. (Giles et al. 2005, p. 207-208.) ABS is usually filled with rubber particles or rigid inorganic particles, such as calcium carbonate, kaolin and glass bead and talcum powder. Fillers reduce production costs and at the same time enhance tensile strength, impact toughness and stiffness. (Subramanian 2011, p. 22.) ABS is mildly hygroscopic and pellets need careful drying before processing. The absorption rate depends on the relative humidity of the air, pellet size, temperature, time and the ratio of monomers. Regrind and pellets need longer drying time than powder due to the longer diffusion bath in large size particles. (Giles et al. 2005, p. 207-208.)

PC is an amorphous polymer with outstanding optical properties. It is also attractive due to its impact resistance and good strength at elevated temperatures. PC also possesses good dimensional stability. It has some limitations like poor scratch resistance and susceptibility to bubbles at elevated temperatures. (Subramanian 2011, p. 28.) Polycarbonate requires drying as moisture leads to a hydrolysis reaction in the extruder which causes polymer backbone breaking, lowering of the molecular weight and reducing impact properties. Acceptable moisture content is 0.02%. (Giles et al. 2005, p. 214.)

PE's molecular weight and crystallinity (and further density) determines the properties and performance of the resin. It has three main forms; low density (LDPE), high density

(HDPE) and linear low density polyethylene (LLDPE). When the density decreases, environmental stress cracking resistance increases. However, it has many advantages; inexpensive nature, chemical-, electrical- and water resistance. LDPE is soft, flexible and unbreakable while semi crystalline HDPE is harder, stiffer and it combines low cost, excellent manufacturability and good toughness. (Subramanian 2011, p. 14-16.)

PMMA is a transparent polymer. It has good mechanical properties and a low weight but also a brittle nature. (Subramanian 2011, p. 22-23.) Drying of PMMA before extruding is important because of the hydroscopic nature of the resin (if the resin is not shipped in moisture-proof containers). Inadequate drying may lead to splays on the surface, foamy structure and internal bubbles. A too high temperature may lead to softening of the amorphous resin, allowing the pellets to stick together and become a solid mass in the dryer. (Giles at al. 2005, p. 212-213.) After processing, PMMA needs careful cooling to prevent distortion (Subramanian 2011, p. 23).

PP is a semi crystalline low-cost resin which is easily compounded with fillers and reinforcement. It has a high heat distortion temperature and offers excellent chemical resistance, environmental stress cracking resistance and surface hardness. (Subramanian 2011, p. 16-17.) PP does not absorb moisture and does not require drying unless the resin has been stored in a cold warehouse and moved to a hot environment (Giles et al. 2005, p. 213).

PS has two main forms; a transparency general PS and an opaque (due to rubber modification) high impact polystyrene HIPS. PS has a brittle nature because of its structure. PS has excellent flow characteristic and HIPS has better melt strength and easy processing properties. Both have low shrinkage values with a high dimensional stability during moulding. Polystyrene is not hydroscopic and does not require drying if the raw material is stored in a warm warehouse. (Giles et al. 2005, p. 215)

PVC is an amorphous resin which can be divided into two groups depending on plasticizer condition; un-plasticized rigid PVC (PVC-U) and plasticized flexible PVC (PVC-P) (Giles et al. 2005, p. 216). Generally PVC is transparent with a bluish tint. It has outstanding chemical and high abrasion resistance but it is attacked by many organic solvents. (Subramanian 2011, p. 18-19.) PVC has significant advantages in applications where energy efficiency and a low thermal conductivity are needed. This is why it is widely used in window profiles because it has three times better heat insulation efficiency than aluminium profiles. (VinylPlus 2015.) The weakness of PVC is its thermal stability, which leads to the requirement to use thermal stabilizers. PVC has a risk of degrading if processing temperatures are high and if there is empty space within the extruder, die or adapters where the resin can stagnate. The risk of degrading increases over long runs. The result is initially dark streaks and may lead to total degradation and a dark useless material. (Giles et al. 2005, p. 216.)

3.4 Troubleshooting in Extrusion

Extrusion problems can have huge financial impacts which make systematic troubleshooting perhaps the most important topic in extrusion. Down-times and off-quality products are indispensable to a quick diagnosis when extrusion develops a problem. (Rauwendaal 2014, p. 763.) In order to be able to identify root causes and institute corrective actions, it is necessary to understand both the materials and the equipment and how they interact with each other. In other words, *you have to know the process*. (Giles et al. 2005, p. 251.) Also, because extrusion is "a black box" process you have to be sure that measured process variables are reliable. Rather than blindfolded actions, problems should be solved with analytical methods. This requires a good instrumentation because without it troubleshooting is a guessing game at best. (Rauwendaal 2014, p. 763.) Usually problems consist of many root causes and according to Burton and Boeder (2003, p. 15) can be determined by using the following formula:

Problem = ***f*** *(Root Causes)*

Fixing one extrusion problem requires eliminating all root causes and that makes problem solving complicated. If the problem gets smaller or goes entirely away, it is an indicator that the right root cause has been addressed. According to Spear and Bowen (1999) using the Socrates method of iterative questioning and problem solving can help with making corrective actions;

- *"How do you do this correction?"*
- *"How do you know you are doing this correction correctly?"*
- *"How do you know that the outcome does not cause new problems?"*
- *"What do you do if you have a new problem?"*

The importance of instrumentation cannot be overemphasized and without it problem solving may become very costly. Other prerequisites are a good understanding of the process, collecting and analysing historical data, team building, good information of the equipment conditions and good information of the feedstock. Team building is important because many extrusion problems are complex and solving them requires input from different departments (maintenance, engineering, purchasing etc.). Construction of a timeline, which includes previous processing information from the extruder (temperatures, pressures, motor load, line speed, barrel dimensions, screw dimensions etc.), information from the raw material and other variables, is a good tool for solving problems under current conditions. It helps in comparing current conditions to previous ones and facilitates identifying what changes in conditions upset the process. In Figure 15 is an example of the timeline. (Rauwendaal 2014, p. 763-767.)

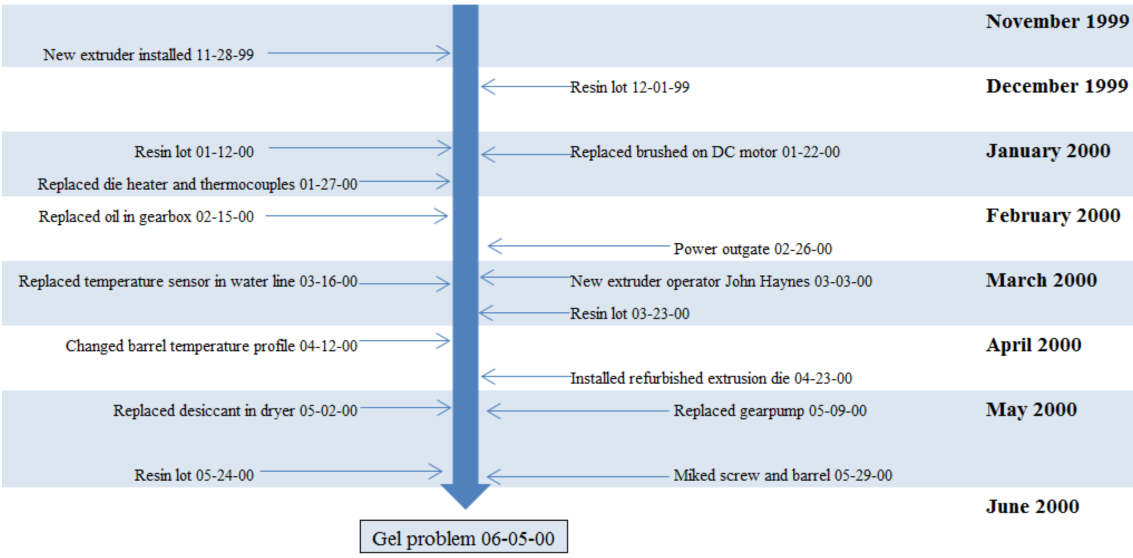


Figure 15 *The timeline collects historical data and leads up to the current problem (adapted from Rauwendaal 2014, p. 766)*

According to Mann (2010, p. 164) every problem solving process, no matter whether it is a mechanical extrusion problem or a product problem, should follow the following format:

1. *Identify and define the problem*
2. *Quarantine the problem and take other immediate remedial actions*
3. *Involve the appropriate, knowledgeable people*
4. *Conduct the root cause analysis*
5. *Identify root cause solutions, asses them and test the preferred alternative*
6. *Implement the root cause solution*
7. *Monitor and revise the solution as indicated by performance data*

When an extrusion problem occurs, the worst solution is trying something without a valid reason. The next worst approach is "gut feeling" that is based on experience or something that has been done or seen previously. A better approach is to ask a fellow employee if she/he has had a similar problem before. The best way is to use scientifically surveyed sources. The appendices A-C show some of the most common mechanical extrusion problems, product problems and profile and pipe problems, possible causes and corrective actions. One should bear in mind that when making any changes it takes time to reach from extrusion line to equilibrium. If a change does not have an effect, it is recommended to go back to the beginning before changing a new variable. Samples should be taken from each processing condition change to determine the best direction to take for future process changes. Systematic documentation is extremely important and every line needs its own log book. (Giles et al. 2005, p. 221-225.)

3.5 Scrap in Extrusion Process

When comparing the benefits of reducing scrap material to reusing regrind, it is obvious that prevention of scrap is the primary option. It is economically profitable because with plastic products, materials costs may cover over half of the price of the end-product. “Producing waste” consumes energy and increases the work contribution to processing. Taking into account waste management taxes, which can be hundreds of euros per ton, there is no question what is the best choice economically.

There are four main sources of pre-consumer scrap material: start-up material when the extrusion process has been brought to equilibrium, shut-down material when the run is finished, products that do not meet customer specifications and scrap generated by errors in the extrusion process. (Giles et al. 2005, p. 523.) Problems in any previously mentioned extrusion equipment or materials may be a source of scrap. Because of start-ups and shut-downs it is critical to use efficient change-over methods (Rauwendaal 2010).

Analysing scrap in the production starts simply by measuring it and continues by comparing it to industry standards (Rauwendaal 2010). Start-up material is tricky to eliminate due to the nature of the extrusion process. It takes time to pull material through the machine and find the equilibrium. Also shut-down material is difficult to eliminate in change-overs if colour, material or cross-sectional dimensions change. However, with the right procedures both can be significantly decreased. Scrap material caused by errors in the run and from out-of-specifications products on the other hand are unnatural sources of scrap. Many of them have been discussed in previous chapters and will not be mentioned in this chapter. Due to material cost being the largest cost factor in most extruded commodity products, huge cost savings are possible (Rauwendaal 2010).

Reducing scrap material starts from controlling the process (Rauwendaal 2014, p. 85). Standardized work and good practices in start-ups, turn-downs and change-overs can reduce time and lost money. There is no universal start-up or shut-down procedures (Frankland 2011). When starting a run everything needs to be prepared before putting any material inside the extruder and this should be the focus of the attention. Also when shutting down the run, everything should be done as fast as possible to minimize waste of material.

Foam extrusion is a way to make lighter products and reduce material costs. It should still be remembered that it requires a substantial technical expertise and process know-how. The development work can take years and require effort and money to achieve a stable extrusion process with quality products. This is why the foam product process will not always pay for itself. (Rauwendaal 2014, p. 763.)

3.6 Using Recycled Plastic Materials

Many drivers push the use of recycled plastic materials and making this possible is also the most important part of a closed-loop system. It is true that the main drivers of market pressures are customers and competitors. The legislative environment also creates new pressures and opportunities for enterprise. (Slack et al. 2001, p. 76.) Recycling can be a strategy and create competitive advantages. For instance Veka, the world's largest producer of PVC-U windows, have used this strategy after Germany changed its legislation regarding landfill waste. Customers regarded the recycling of end-life-products as valuable, Veka gained a sustainable source of cheap materials and insulated itself from the oscillating price of new plastic. (Slack et al. 2001, p. 77.)

Plastic waste can be divided by formation type into two categories; pre-consumer and post-consumer waste. With PVC, pre-consumer waste covers about 12 % of the total volume of the PVC waste (in the EU). Post-consumer waste covers the larger percentage, about 88 %. Recycling of pre-consumer PVC-waste is better due to the lower collection and processing costs and 85 % of pre-consumer waste goes to recycling. The post-consumer waste recycling rate is much lower, only circa 3 %. (Brown et al. 2000, p. iii.) In Finland about 57 % of PVC waste is plasticized and 43 % is rigid form (Poropudas 2011, p. 3).

Recycling of PVC waste became topical in the beginning of year 2016. It has been defined in the Finnish Waste Law's Act 331/2013 that after 1.1.2016 organic and biodegradable waste with a concentration of carbon of more than 15 % (according to the total amount of carbon or the loss of ignition) is forbidden to be placed in the landfill. (Government Decree on the landfill of waste 331/2013, 53 §.) New legislation complicates post-production waste management. Still, eliminating all PVC-waste is almost impossible due to the nature of the process. Also recycling all PVC-scrap may be difficult to implement partly due to the large size of the scrap. For instance start-up waste may be too large-sized for grinding. (Window Industries 2008.)

The economics of the recycling process is given in the following equation (Brown et al. 2000, p. 17):

Net costs of recycling = Gross costs of recycling - Income from sale of recycled material or Value of recycled raw material when used in production

Gross costs of recycling = Mobilization costs + Processing costs

With pre-consumer waste the role of mobilization costs is smaller than with post-consumer waste because there are large quantities of recyclable materials available. Processing costs are also smaller with pre-consumer waste because usually there is no need for washing or cleaning and the batches contain only one type of plastic material. The recycling process is profitable when gross costs of recycling are smaller than the income from sale of the recycled material (the price of recycled PVC is about 70% of the virgin material price). (Brown et al. 2000, p. 18.)

3.6.1 Methods

Plastic recycling can be divided into four main categories shown in Table 1 below. The primary method is mechanical recycling into products with equivalent properties. The secondary method is mechanical recycling into products with lower properties. The Tertiary recycling method is chemical recycling into chemical components and quaternary method means usually incinerator. Plastics have a good calorific value but recycling has been shown to save more energy than that produced by energy recovery (also when taking into account energy used to collect, transport and re-process plastic). In theory most thermoplastics can be recycled in the closed-loop system, especially in the case of pre-consumer waste, stabilized against degradation during reprocessing and subsequently. Other options are landfill (the most unwanted), re-use and in the case of biodegradable polymers recycling back to nature. (Hopewell et al. 2009.)

Table 1 *Terminology used in different types of plastics recycling and recovery (Hopewell et al. 2009)*

ASTM D5033 Definitions	Equivalent ISO 15270 Definitions	Other Equivalent Terms
Primary recycling	Mechanical recycling	Closed-loop recycling
Secondary recycling	Mechanical recycling	Downgrading
Tertiary recycling	Chemical recycling	Feedstock recycling
Quaternary recycling	Energy recovery	Valorization

General mechanical recycling process steps are shown in Figure 16 below. The first stage is mobilization which includes collection and sorting of waste. The second stage is processing and its steps are dismantling, cleaning, shredding and extrusion. Dismantling is required only when the product consist of two or more incompatible plastics or is too big for shredding without cutting it into pieces. (Brown et al. 2000, p. 16.) The size of the plastic item determines the size and type of equipment required. If possible, shredding should be done in another building or room to minimize the noise, dust and the risk of cross-contamination (Giles et al. 2005, p. 523.) Shredding is used to reduce size and increase the surface area enough to enable re-processing. After shredding flakes are often ready for re-processing. Another option is to extrude flakes with new stabilizers into pellets that can be re-used. (Brown et al. 2000, p. 16.)

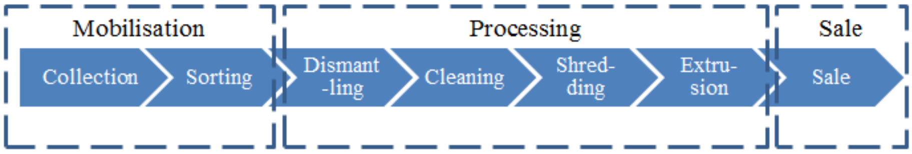


Figure 16 *The stages of mechanical recycling of plastic waste (adapted from Brown et al. 2000, p. 16)*

Chemical recycling is less sensitive to unsorted or dirty plastic waste but its big disadvantage is that it may consume more energy than it relatively produces. The idea of chemical recycling is to break up polymer waste into chemical components by heat, chemicals and other agents. The chemicals produced can be used in petrochemical industries. (Sadat-Shojai & Bakhshandeh 2010.)

3.6.2 Recycling of PVC

In this master's thesis PVC is a major point of interest due to the legislative environment. It is also the most used raw material in the case company's production. As stated before, recycling of PVC becomes desirable because its high chlorine content prevents it from being used as a source of energy in incinerators. In addition, the possibility of toxic dioxin and furan formation makes PVC burning very difficult. Separation of PVC waste from other plastic is important because polyolefins (mainly PE) have a poor compatibility with PVC. It is possible that the polymer has already partly degraded or even cross-linked in the course of past heat treatments and/or service. Degradation leads to changes in the molecular weight and distribution which affect the mechanical properties of PVC. With plasticized PVC the stabilization system needs to be known. Collectively, it is important to have detailed information about PVC scrap before using it. (Chanda & Roy 1998, p. 975-977.)

Shear stress during mechanical recycling often leads to the fusion of PVC plastic particles and significant changes in the original structure into a network of entanglements. This affects both physical and mechanical properties. (Sombatsompop & Thongsang 2001.) Thus, PVC has a limited thermal and photo stability. Additional stabilizers may be used to prevent dehydrochlorination and discoloration because the amount of primary stabilizers often decreases during reprocessing. This leads to a reduction in properties with temperature alterations and, in particular causes a diminution in mechanical properties. PVC also easily turns from yellow to brown (or even black) at relatively low temperatures. This decomposition happens when the elimination of hydrogen chloride (HCl) leads to formation of one double bond and a polyene sequence in the backbone (see Figure 17). These polyenes (a mean length 5-25 conjugated double bonds) absorb visible light and cause colour changes. (Sadat-Shojai & Bakhshandeh 2010.)

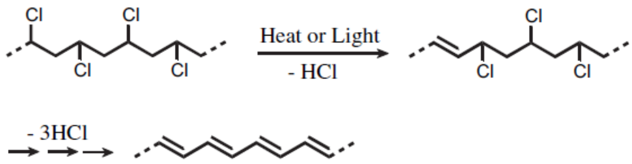


Figure 17 *Formation of double bonds which leads to a change in colour (Sadat-Shojai & Bakhshandeh 2010)*

A recommended ratio of virgin PVC and recycled PVC flakes depends on the desired properties. Sombatsompop and Thongsang (2001) have studied this from the rheological, morphological, mechanical and thermal properties point of view. They found that adding the recycled PVC into the virgin PVC resin caused an increase in melt shear stress and a decrease in MFI. The die swell ratio did not change with the PVC blend. They also found that the higher the recycled PVC loading was, the greater the hardness and density of the blends were. Also the glass transition temperature, the heat deflection temperature and the degradation temperature depend on the used PVC blend ratio. Sadat-Shojai & Bakhshandeh 2010.)

The optimal ratio of virgin and recycled flakes depends on wanted properties. The best ratio for getting the highest Shore hardness is about 80 % recycled PVC and 20 % virgin PVC (pipe PVC). This is due to the higher density of recycled PVC which possibly is associated with the degree of gelation which occurred during compounding. The same ratio is also good for getting the optimal impact strength. For the best ultimate tensile strength 20 % recycled flakes and 80 % virgin PVC is recommended. The sample with the higher impact strength showed ductile fracture and with lower impact strength the sample was showing some indications of brittle fracture in Scanning Electron Microscope-micrographs. The glass transition temperature decreased when the amount of recycled PVC flakes increased. The same effect was noted with the heat deflection temperature and the degradation temperature. Recycled flakes had greater viscosity and lower MFI (higher shear stress) which is probably because recycled PVC had more processing time and this makes its molecular structure more compact and dense. (Sadat-Shojai & Bakhshandeh 2010.)

3.6.3 Common Problems When Using Recycled Plastic

Crystalline polymers lose part of their mechanical properties within heat aging. This is a key phenomenon that should be taken into consideration when using recycled raw material. This was explained in relation to PVC in the previous chapter. Another reason for mechanical properties failure is micro crack formation on the surface. This is due to oxidation and controlled by diffusion. Heat aging can be avoided (or limited) by stabilizers but the amount of primary stabilizers in old material is usually low. The restabilizer recipe depends on polymeric matrix type, polymer morphology, structure and type of targeted application. (Kartalis et al. 2002.)

Poropudas (2011, p. 40) has listed with reference to The European Council of Vinyl Manufacturers website problems regarding recycled plastics. Polyolefin, PS and PET have been showing discoloration which is due to oxidation and formed double bonds but can be corrected with stabilizers. Another problem is changes in MFI. That can be too high (polyolefin, due to decomposition) or too low (polyolefin, due to cross-linking). As noted before, Sombatsompop and Thongsang (2001) also found that the melt flow index decreases when the proportion of regrind PVC content grows. On the other hand, Meskanen & Järvelä (2000) have shown that cleavage of chains leads to a decrease of melt viscosity, widening of the molecular weight distribution and an increase of shear thinning. These can lead to over-occupancy and flashes. When MFI is too high, a possible solution is to use process stabilizers to prevent decomposition or use repairing molecules. Alternatively when MFI is too low, material can be mixed with another material with higher MFI. Another solution is to use process stabilizers to prevent cross-linking. (Poropudas 2011, p. 40; The European Council of Vinyl Manufacturers.)

Other problems are formation of smells, distribution of blends to lamellas and defects on the surface of the material. Smells are due to impurities and decomposition and can be avoided by using a vacuum during processing and also by using process stabilizers. Formed lamellas are due to incompatible components. This can be solved by using higher shear forces in the process and using compatibilizers. Defects caused by impurities, volatiles or decomposition can be avoided with a better filter system, processing in a vacuum or using process stabilizers. It was noted earlier that aging and micro-crack formation on the surface of the material is one source of poorer mechanical properties and impurities are one reason for this. This can be avoided by using a filter system. (Poropudas 2011, p. 40; The European Council of Vinyl Manufacturers.)

Regrind has a lower bulk density which can cause problems if regrind is used in large ratios. Typically extrusion screws can handle a range of bulk densities but if it (regrind and virgin material together) grows to 20-25 %, extrusion problems probably occur. This is due to feed-section channels having a specific volume and if the entering mass which depends on the bulk density varies; the output of the extruder becomes unstable. The easiest solution is to use regrind with such low ratios that it has a minimal effect on processability. Another solution is to use a higher compression ratio than is required for an all-pellet feed material. This is not easy, because the bulk density and flow-properties should be determined for each regrind ratio and batch. (Frankland 2013.)

Due to variability in the study results and possible difficulties during processing experimental work is needed before using regrind in the product runs. It should be made sure that the properties of partly recycled products are acceptable. (Giles et al. 2005, p. 523.) On the other hand Poropudas (2011, p. 88) studies show that changes are not significantly different (for instance the glass transition temperature increased from 53 °C to 55 °C) and do not greatly affect the product.

4. RESEARCH METHODS

The research was challenging because I did not have any knowledge about internal operations (production, recycling, R&D, etc.) before starting. On the other hand this was an advantage because the current state and its development issues were able to be studied in a new light. An overall picture about the current state was built step by step. The research process is shown in Figure 18.

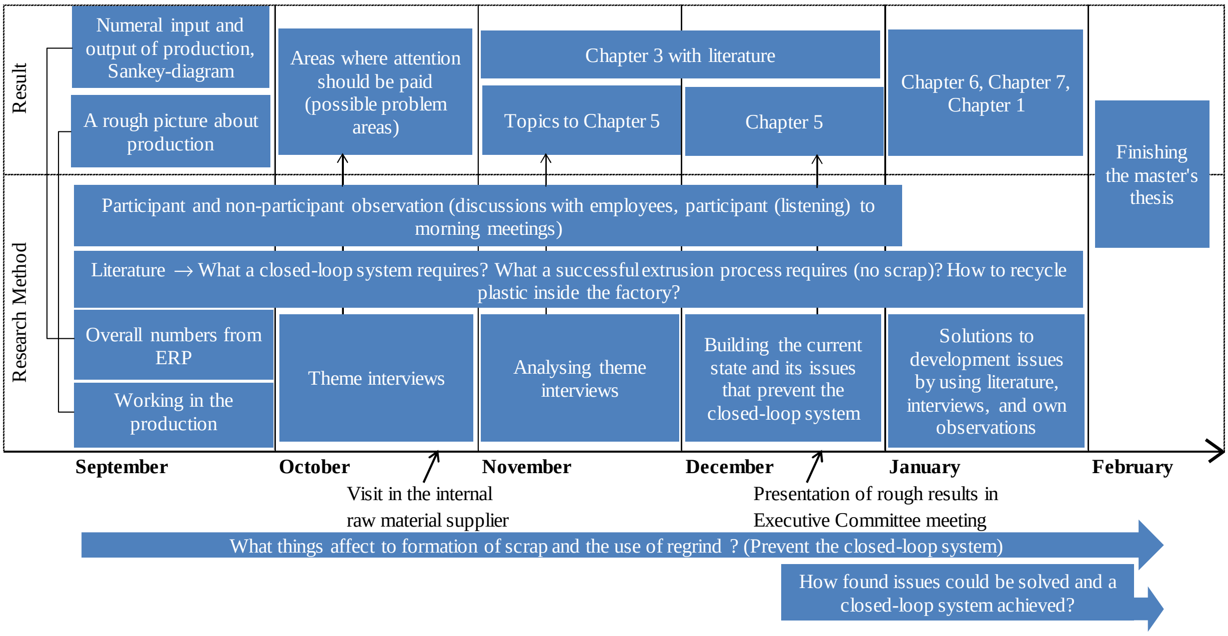


***Figure 18** The research process, the horizontal axis represents time and increasing knowledge*

The research started by gathering input (used materials and the share of regrind) and output figures from the production process (products, the share of made regrind and the share of waste) from the information systems of the case company. This revealed the extent of the scrap problem; how much scrap is formed, what the share of made regrind of scrap is and how much regrind is actually used. At first the basic operations were explored by working in the production. During the research also participating and non-participating observation was done to get a deeper knowledge of the operations. The research process continued with interviews, analysing them, building the current state and its development issues and devising solutions to factors that prevent the closed-loop system from being completed. Literature was used to map what the closed-loop system requires, what the successful extrusion process requires and how plastic waste can be recycled inside the factory. During the research two questions were continuously asked:

- *What affects the formation of scrap - how eliminate scrap-waste?*
- *What affects the use of regrind - how to increase used regrind?*

Both of these have to be true in order to be able to achieve a closed-loop system. Research inside the company and the role of literature is viewed closer below.

4.1 Research within the Company

The aim of the research was to find factors that cause scrap and factors that affect the use of regrind and find new approaches to production, which help to reduce the amount of waste material and help to use it again in the process. The attempts to reduce the formation of scrap in the company have not been fully successful. New products come to production with a high frequency and the range is large. This is challenging because sometimes it takes a long time to find the right material, extrusion conditions and equipment to produce products with a low scrap-percentage. At the same time formed scrap should grind to high quality regrind and be reusable. Reusing is difficult because if any extrusion problems occur, they cause new scrap. In the desired closed-loop system the formation of scrap is under control, the use of regrind reliable and efficient and all plastic waste can be recycled within the company.

The research was mostly qualitative. The case company has a Business Intelligence-program (BI-program) and an Enterprise Resource Planning-program (ERP) but the problem is that the information in these programs is not reliable enough to make long-term conclusions by only using statistical data. Measuring methods have changed and for instance calculation of scrap percent is different now than when compared to a year ago. Because of this it was not considered reliable to use computational methods to optimize the process.

4.1.1 Steps of the Research

In September when the research was started, the process where a closed-loop system should be put into practice was totally unknown. An overall picture had to be built before problems could be spotted. Working short periods in the production came across as the best method to get to know production operations because fundamentally the problem is very practical. It was also necessary to understand the employees' daily job. It is important that the planned new methods are easy to follow because overly difficult and laborious activities will be ignored in the long term and render the solutions useless. When the employees feel that they are considered in the improvement of the processes, they comply more with the rules and the processes will not begin to revert back to how they were. Starting the research from the base of the hierarchical pyramid was also the right approach in the view of Lean-philosophy because according to it information should move to upstream. During the work phase notes were written in a note book.

In addition to working on and knowing the internal processes, the input and output of the process were studied at the beginning in September. Sankey diagram was created in order to understand the process efficiency and the shares of different inputs and outputs. Made plastic waste, made regrind and used regrind were indicators of the extent of the problem. In this step the ERP and BI-programs were used to get material reports.

Participant and non-participant observation was started in September and continued until the beginning of January. Non-participant observation served the purpose understanding current practices in the production and other functions around it. It consisted of taking part (listening and watching) in daily morning meetings, weekly meetings, in one meeting about material management (the aim was to solve the problem about lost materials and shortages) and in one meeting with a waste management company. Daily morning meetings were a great way to observe what problems repeated often in the production that also caused scrap. It was also a good way to observe how systematic operations and the use of regrind were. Non-participant observation was non-structural but notes were always written. Notes were also analysed and the number of issues was followed (for instance how many times raw materials ran out during an extrusion run). For some issues photos were also taken (waste skip, the current state of warehouse etc.). Participant observation consists of free non-constructed discussions with employees and officers. Also these were written down in a note-book. By using both of these techniques a picture of the "As-Is" process was formed. It was appropriate to take a neutral approach; listening rather than actively suggesting change. If the role of the researcher had been too active, the observed situations would not have been "authentic".

Also the use of the BI- and ERP-tools was started in September and continued until the end of the research. Made and used regrind, scrap per item and scrap per tool were followed on a weekly basis and documented once a month in Excel files. If something unusual (for instance a very big scrap percentage of product) was noticed, it was investigated what the root cause was for it. Observations were written down in a note book. The Visual Planning & Production Follow-Up program was useful for spotting problems with extrusion runs, to see how much time was used to quality rejects or because of lack of resources. The root causes behind significant issues were analysed. The issues and reasons behind them were also recorded in a note book.

In October, when a rough picture of the production processes and the company was in place, interviews started in order to get a more comprehensive picture of problem areas. The interviews were a good way to map the long-term problems because the research time was relatively short. The interviews revealed the areas where attention should be paid (preliminary topics to Chapter 5). In October also a visit was paid to an internal supplier in southern Finland. The aim was to understand the value chain better and investigate if there is something to take into account when redesigning the production methods. The visit included a guided tour of the raw material preparation unit, which was recorded by taking notes and performing a group interview.

The interviews were completed in November and then analysed. Clarifications included; what is the reliability and validity of the mentioned issue (things that cause scrap or hinder the use of regrind), what are the root cause(s) of it, what is the role of it in the bigger picture and in the closed-loop system, who or what processes can affect to it and what other things should be taken into consideration. By using this information, through personal observations, with the help of Visual Planning & Production Follow-Up-program data (significant quality rejects that caused also a lot of scrap) and BI-program data (unplanned big scrap per item-records, used regrind), a rough outline for Chapter 5 was done.

The previous research process continued in December and Chapter 5 was finished. Again, participant and non-participant observation were done to get a deeper insight into the problems. The BI-tool gave valuable information about big scrap percentages of certain products and made versus used regrind. Rough results were presented and accepted in the Executive Committee meeting in the middle of December.

In January (and partly already in the end of December) solutions to collected development issues were outlined. In this step all collected observations, analysed interviews, literature and information from the BI-tool was used. In the most important role were Lean-literature and the four rules by Spear and Bowen (1999). Also documentations about interviews carried an important role. It was critical to map all relations between the noticed variables and problems (what is the real root cause and what contributes to it). By mapping variables, finding sources of scrap and mapping links to current employee responsibilities, it was easier to share new responsibilities fairly and create process control methods without blind spots. Standardized and easy to follow directives were important in order to minimize negative effects (scrap, un-used regrind) and increase the share of regrind.

In the end of January the master’s thesis was sent to pre-examination and at the end of February the corrections were made to the content. After that the master’s thesis was sent for grammar and orthography check. The final version was ready in the March.

4.1.2 Interviews

Interviews were important to view the research problem from different perspectives and to map relationship between operations. Because the company and the extrusion process were unknown to the researcher, it was vital to interview people who have a long working experience. They gave valuable information about basic things that should be taken into consideration about production. This helped to set out a framework (like what are responsibilities of employees, what are daily works, etc.). But more important was that they outlined daily problems that cause scrap or affect the use of regrind. That information was used for topics in Chapter 5.

Theme interviews were used in the research. The reason behind the decision was that it let people speak freely about the topic. It was not always clear what the problem is and some perspectives and issues were hidden, so it was a good way to let people tell all the things that affect their work and what they see as important in reducing waste material and increasing its re-usage. The theme interviews did not contain any ready lens or attitudes as to how things should be done. It has to be remembered that people unconsciously see things mostly from their perspective. Sometimes people had strong attitudes and feelings, so it was necessary to filter information to get reliable results. (Hirsjärvi et al. 1997.)

The people who were interviewed were chosen around the production process, which is the platform where a closed-loop system finally should be installed. In this context it is like a steam engine and other support functions keep it going forward. These support functions include purchasing, production planning, warehouse and inventory management, internal logistic and quality control. Interviewed were:

- two profile manufacturers (production) in separate interviews
- one trimmer (production)
- two officers from the internal supplier in a group interview
- one shift leader (production)
- one person responsible for material and inventory, who also worked in internal logistics
- two people from maintenance

Financing, sales or governance were not included in the scope of the research. Product development is not a factor in master’s thesis markings and that is why no interview was done with them but interviews were replaced by free discourses. Overall, a product development should be synchronized to production to minimize waste, speed up the development of new products and finding effective ways to produce new products, but there was not enough time to study this area at length.

The topics were chosen to cover as many areas as possible. This was done because the importance of each area with regards to a closed-loop system was not certain. If the interview topics would have been too limited, some important issues would not have been covered in the research. Before real topic questions, an easy question was asked to get make people feel relaxed and confident. It was: *“What are your main tasks and responsibilities?”* After that one question was asked on each of the following themes:

- often repeated issues in the production that cause scrap
- troubleshooting
- handling of scrap after it has formed
- the use of regrind
- quality control

- new products
- information flows
- continuous development

Generally almost similar questions were asked of all interviewees, but depending on the function of the interviewee some questions were skipped or highlighted. For instance with maintenance a topic about often repeated machine problems that cause scrap was highlighted, but the question about quality control was skipped.

Questions were asked neutrally. For instance a question about quality control was not “What *problems* are there in the quality control?” Usually it was “What do you think about current quality control procedures?” or “Can you tell me about current quality control procedures, please?” By asking neutral questions the aim was that the problem did not seem larger than it was in reality. The questioning technique largely affects the reliability of the answers because when asking in a negative manner, some good things may be forgotten and the situation looks worse than it is. In the beginning of each interview it was said that questions are only suggestive and people are free to talk about everything that comes into their mind about scrap or regrind. This was done to avoid a situation where something important would have been left outside the interview.

Interviews were recorded (an average length was one hour) and permission for that was always asked in the beginning. Only one interview was not allowed to be recorded. Interviews were listened to later and transcribed. After that they were analysed by highlighting important things and making mind maps. Again, the aim was to highlight issues that cause scrap or affect the use of regrind.

The most important results of the interviews can be seen in the Chapter 5. However, it was noticed that:

1. Raw material purchase should be partly more integrated to the production process
2. Extrusion of established products need more standardized and controlled approaches
3. Putting new products into production is fairly difficult
4. Re-use of regrind is tricky
5. Vertical information flows needs fine-tuning
6. Involving employees has an important role.

The answers were weighed up as to reliability and validity. *Reliability* means how reliable and repeatable results are. It can be divided into two categories; stability and consistency. *Stability* means how long-lasting the used method is. *Consistency* measures how good the correlation is between results if propositions are shared to two groups. (Hiltunen 2009.) Stability should be treated with caution because for example the mood of the interviewee influences the results. An attempt was made to separate the effect of the mood of the answer but sometimes it was hard. Because all interviewees were unknown to the interviewer, it was hard to say, if they were tired, angry, or something else that could affect the results.

Consistency was also an important thing to take into consideration because the perspective of the production employees and officers is very different. It was possible to see that employees were sometimes tired and frustrated if they had faced problems recently. Officers of course also face extrusion problems and help to solve them but their work is also much lighter. Frustration is what differentiates these two groups. That makes the consistency between interviewed people weak.

Regarding reliability it should be remembered, that what people have encountered only a little while ago, gets more importance than things that people have encountered a month ago. For instance if some extrusion problem had occurred, even if it happened only a few times in the year, it would seem important. Also things, with which they often struggle, feel more important even if they are not so significant in the bigger picture.

Validity means whether a method measures the phenomenon that we want to explore. That depends on how good questions an interviewer has prepared and whether the target population has been chosen well. (Hiltunen 2009.)The validity of interviewees was pretty good because they are those persons who in practice affect the flow of material. The chosen interview method, theme interview, helped with the validity of questions. Questions are flexible and people have a possibility to give more freely of their opinions when compared to a very structured interview with a selected list of questions.

The interviews were processed anonymously. Names or dates of interviews are not published to guarantee interviewees' anonymity and free expression of opinion. If dates had been published, it would have been possible to link the date to the interview booked in the calendar. For this reason interviews are not included in the references.

4.2 The Role of Literature

Literature was part of the research from the beginning until the end (see Figure 18). With the help of the literature the requirements of a closed-loop system and successful extrusion operations were outlined. The study of Lean-philosophy methods was necessary for solving the research problem.

It was hard to find suitable literature concentrating on a closed-loop system. Most literature was focused on an environmental perspective, which of course is important, but much harder was to find literature about the closed-loop system inside factories. The solution was to divide the concept of the closed-loop system and its literature into sections:

- *Processes* - Lean-philosophy and a closed-loop system requires process- orientated thinking
- *Lean-philosophy* - strategy of how a closed-loop system could be achieved

    → A concept about a closed-loop system and Chapter 2

- *Extrusion* - a basic knowledge about the case process
- *Recycling* - how plastic recyclable inside the factory

    → The most important things about the extrusion process, recycling of plastic and Chapter 3

The literature of process improvement was a good starting point. Madison's book "Process Mapping, Process Improvement and Process Management: A Practical Guide for Enhancing Work and Information Flow" (2005) was the first book studied. It was a good eye opener to what processes actually are. The process topic was studied in depth through articles and studies about processes in business enterprise. After that it was supplemented with literature on Lean-philosophy. An attempt was made to find connections between these, to get comprehensive perspectives that fit the concept of closed-loop systems. The involvement of the employees was reviewed in the view of processes and Lean-philosophy. The Chapter 2 covers concepts of processes, Lean-philosophy and a closed-loop system.

It was decided to divide literature and theory into two different chapters. Chapter 3 is purely related to material and extrusion equipment. Material and extrusion handbooks were used to find out material and equipment characteristics around the research problem because generating the closed-loop system requires a good knowledge of both. Guidelines of troubleshooting procedures were written by using handbooks because they were problematic at the case company. Extrusion troubleshooting has also a critical role with regards to scrap. The tables regarding troubleshooting are an attempt to get a systematic and scientific basis to the complex and variable extrusion process.

Recycling of plastic was studied only with the help of literature and previous studies because there was no time for trials. It was investigated what changes happened during plastic recycling because at the moment it has not been studied with scientific methods and has many problems. The use of regrind has to be reliable and not cause scrap because using regrind blindfolded makes the problem worse than new scrap. Many things like changes in MFI, different bulk density when comparing to powders or granulates and colour changes were discovered. These all should be taken into consideration when effective use of regrind is achieved. The problem with this area was that many studies have been done about post-consumer waste but much less about pre-consumer waste. Changes in plastic during processing are also very unique, which affects the reliability of the results. Sometimes results were opposite in different studies. This underpins the importance of experimental study of correct regrind ratios in the production.

5. THE CURRENT STATE IN THE CASE COMPANY

Core functions of the case company are extrusion production, R&D, sales and customer service. All operations are customer-orientated due to products having to meet special customer specifications. Most of the production follows a make-to-order (MTO) manufacturing process and only a small buffer is used with the most important and biggest customers. This sets high requirements for production because it has to meet demand relatively fast and be at the same time flexible to fulfil customers' special needs. Also production and material management have to be reliable because the delivery times from suppliers of special plastic raw materials and master batches can take several weeks. This kind of business requires also a good knowledge of the customer and active communication with them.

Factors that cause scrap and issues that should be considered during recycling and reusing plastic are listed according to identified areas found through observation and interviews. Development issues are divided into their own chapters based on processes around a closed-loop system topic. One should still remember that the closed-loop system is a strategy, not just a project and it requires the participation of the whole organization.

It should be taken into account that the following chapters focus on development areas. This should not lead to a misunderstanding that overall things are not well organized. In every production there are always development areas and here we will focus on them. Many things in production were managed well and this is viewed in Chapter 5.8.

5.1 Input and Output

Figure 19 shows a Sankey diagram of input and output materials in the case company's production from year 2014. Percentages express the amount of total input and output (kilograms per total input or output kilograms). With the plastic input, numbers in brackets indicate the share of the total plastic input. Amounts are calculated by kilograms, which lead to situations that the use of metals and packing materials looks high in percentage terms.

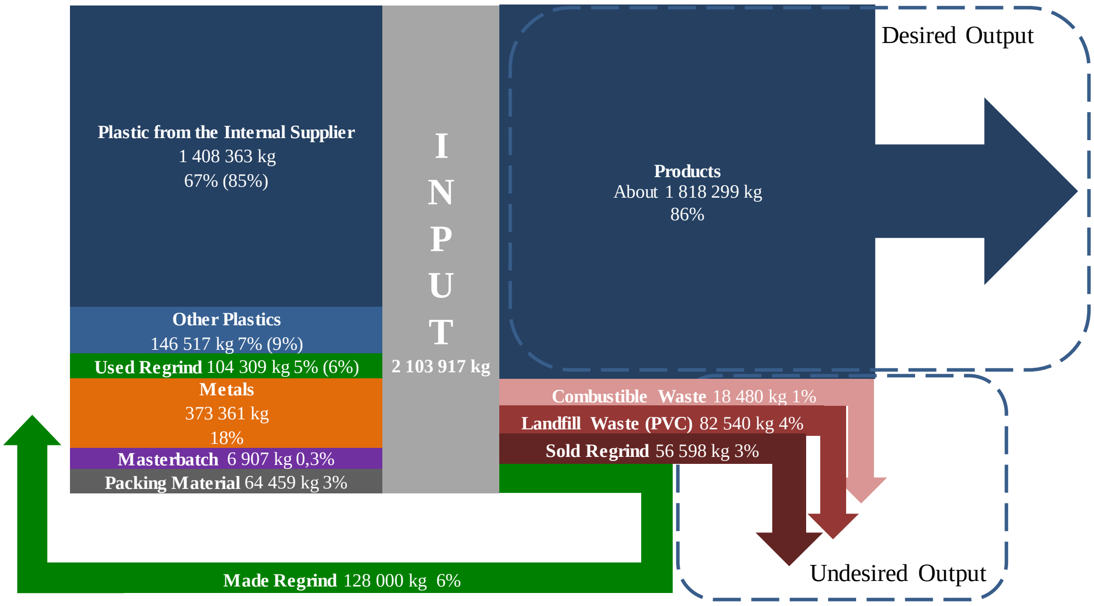


Figure 19 *The Sankey-diagram: inputs and outputs of the production process in year 2014 (ERP, the waste follow-up report from the year 2014)*

According to the Sankey diagram it is possible to make a material balance for the year 2014 shown in Figure 20 below. At the top is total input consisting of plastic, packing material, metal and master batch and below desired, secondary and unwanted output.

INPUT		[KG]	[%]	
Plastics from the Internal Supplier		1 408 363	67 % of Total Input	85 % of Plastics
Other Plastics		146 517	7 % of Total Input	9 % of Plastics
Regrind		104 309	5 % of Total Input	6 % of Plastics
Total Plastic Input		**1 659 189**	**79 % of Total Input**	
Masterbach		6 907	0.3 % of Total Input	
Packing Materials		64 459	3 % of Total Input	
Metals		373 361	18 % of Total Input	
Total Input		**2 103 917**	**100 %**	
OUTPUT		[KG]	[%]	
Landfill Waste (Mostly PVC)	Unwanted Output	-82 540	4 % of Total Output	
Sold Regrind	Unwanted Output	-56 598	3 % of Total Output	
Combustible Waste	Unwanted Output	-18 480	1 % of Total Output	
Made Regrind	Secondary Output	-128 000	6 % of Total Output	
Total Desired Output		**1 818 299**	**86 % of Total Output**	

Figure 20 *The material balance of the case company's production of the year 2014 (ERP, the waste follow-up report from the year 2014)*

Most of the plastics come from the internal supplier. The amount of other plastics consists mostly of engineering plastics. Used regrind consist mostly of made regrind in the year 2014, but part of it is from the year 2013 also. Packing materials or metals are not considered in the research. In relation to metals, some recommendations have been given about copper. Master batches are mostly pigments. The relative amount of them is small but when taking the high prices into account their usage should also be optimized.

Sold regrind consists of plastics that are not able to be used in the company's own production because of the colour or other unsuitable properties with regards to recycling. Made regrind is a questionable input because according the concept of the closed-loop system, it is more desirable than landfill waste, but it is not either primary output. Desired output is calculated by subtracting unwanted output from input. Another way would have been to calculate it by taking produced profiles in metres and multiplying that with the meter weight. This was a too complicated method and in this context rough numbers were informative enough.

5.1.1 Used Materials

This chapter takes a look at the raw materials used in 2014. The material review is done to get an overall picture of plastic raw material input, the extent and variety of it and how material usage is divided. When the range is widened, the flexibility to meet customer specifications increases, but at the same time, the material and inventory management becomes more difficult. When the variety of raw materials is huge, the information management about raw materials become more complex. However, in a subcontracting company it is more important to tailor raw material recipes to the most important customers.

Table 2 lists the ten the most used plastic raw materials in the year 2014. As can be seen from the table, there is one plastic raw material MD-100125 that is above all others that is consumed (17 % volume). Prefixes MD and MC tell that raw material is made by internal supplier with the exception of R-4000278 and R-4000277 that also have been prepared by them. With other materials prefix R means plastic from an external supplier. Prefix G tells that material is regrind (not shown in the table). The problem, which we will review later, is that the number code after a prefix is not same with a virgin material and relative regrind. That makes the connection indistinct.

Table 2 *Top 10 plastic raw material consumption (ERP)*

Plastic Raw Material	Consumption [kg]	Volume of Total Plastic Consumption
MD-100125	287 786	17 %
R-4000278	143 511	9 %
MC-100010	108 798	7 %
MC-100009	99 635	6 %
MD-100079	98 085	6 %
MC-100172	68 192	4 %
R-4000277	47 022	3 %
MD-100154	39 439	2 %
MC-100044	39 423	2 %
MC-100040	37 224	2 %

In year 2014 there were 64 different raw materials used with consumption over 1000 kilograms. Total number of different plastic raw materials with own recipes is huge, 182. Of these raw materials 128 were made by the internal supplier and last 54 raw materials were from external suppliers.

5.1.2 Waste

In addition to the desired output, there was 14 % undesired output; landfill waste, sold regrind, made regrind and combustible waste (see Figure 19 and 20). The primary objective is to eliminate all of these. The secondary objective is making it possible to use landfill waste and sold regrind in the company's own production. Combustible waste consists of combustible plastic and other waste, mostly packaging material. The amount of plastic is unknown because plastic is not separated from other waste, but the target is to return it to production. However, regrind is an expensive raw material with more difficult processing properties and it has few prerequisites. Making it possible to re-use made regrind in the extrusion is the first thing (with a possibility to feed from two funnels). Another thing is that regrind is used effectively and relatively fast. It takes up space and the more regrind there is in the warehouse, the higher the mental threshold is to use it. In addition, the material should be at least theoretically possible to re-use. There is no financial sense in grind or store material that is not re-usable or that cannot be sold.

As mentioned before landfill waste is mostly PVC waste (rare colours of rigid PVC and coloured foam profiles) and start-up scrap. PVC plastic from products combination of plastic and copper wire is also categorized as landfill waste due to possible small contaminations of copper in the plastic after separation. Copper has a risk of wearing extrusion machines. The amounts of theoretically recyclable PVC waste (coloured foam profiles and some very rare colours which are not suitable for sale) is unknown but have in any case a financial potential. There are not enough big crushing mills available in the production for start-up waste. With start-up waste, elimination is at the moment the only way to reduce financial loss and environmental impact. Figure 21 shows the typical contents of a skip.

Figure 21 The typical contents of landfill waste; start-up waste, PVC from products with copper wire, coloured foam profiles and rare colour rigid PVC (a photograph 15.9.2015)

Regrind that cannot be used in own production at the moment but is recyclable, is sold to a recycling company. This volume consists of certain types of PC, PS, PVC, PMMA and ABS. The reason why some materials are categorized for sale is that some of their properties, like transparency and electrical conductivity change in an undesired way during re-processing. Table 3 shows the amounts of sold regrind and the distribution of sold material types is shown in Figure 22.

Table 3 *Sold regrind in the year 2014, measured in kilograms and euros (material codes based on the system used in 2014 and have partly changes in the year 2015) (BI-program*

	Net invoiced amount [€]	Net invoiced quantity [kg]	% of Net invoiced amount [€]	% of Net invoiced quantity [kg]	€/kg
G-0000032	281	1654	2,7%	2,9%	0,17
G-0000036	121	709	1,2%	1,3%	0,17
G-0000053	217	987	2,1%	1,7%	0,22
G-0000081	7277	39986	70,5%	70,6%	0,18
G-0000095	1026	6034	9,9%	10,7%	0,17
G-2000012	154	615	1,5%	1,1%	0,25
G-2000013	940	4797	9,1%	8,5%	0,20
G-2000017	309	1816	3,0%	3,2%	0,17
	10325	56598			

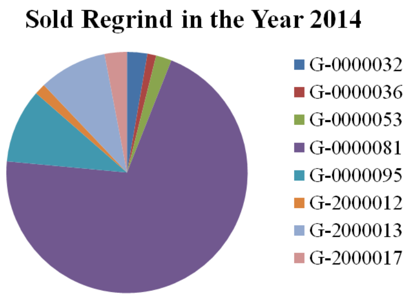


Figure 22 *The distribution of sold regrind in the year 2014 (material codes based on the system used in 2014 and have partly changed in the year 2015) (BI-program)*

As it can be seen from the picture and the table, the biggest source of sold regrind is rigid PVC. In financial terms and measured in kilograms, it means a proportion of circa 71 %. This consists of PVC in different colours which are not separated from each other and contaminated waste. This raises the question what is the profitable amount of different colours and materials? The more colours there are, the more difficult the re-usage is and in turn, product variety flexibility is higher, the customer satisfaction is better and more new customers may be obtained. In turn, inadequate handling is the biggest reason why rigid PVC has to be sold as secondary raw material. If there were systematic ways to separate and recycle also coloured PVC plastic without contamination, it could be used in theory.

The amount of made regrind is continuously measured and followed in the BI-program. From the amounts of made (circa 128 000 kg) and used regrind (circa 104 300 kg) can be seen that not all made regrind was used in production. The factor causing this error is that some of the used regrind had been made in the year 2013 and some of the made regrind had been used in 2015.

The financial potential of reducing waste is huge. In the year 2014, was generated:

- Landfill waste: 82 540 kg
- Sold regrind: 56 598 kg
- Combustible waste: 10 000 kg (Estimated share of plastic from 18 480 kg)
- Unused regrind per year: 23 700 kg (128 000 kg - 104 300 kg)

→ Total amount: 172 838 kg

Table 4 demonstrates four scenarios for eliminating waste and using regrind. Calculations are based on different uses of made waste and regrind with actual scrap percentage from the year 2014. *The average value of virgin plastic material is 1.81 €/kg* (roughly estimated: value of made scrap/quantity of made scrap in the year 2015). Due to this supposition the calculations are not exact (plastics have different kilo prices) but are an indicator of saving potentials. The average value of regrind when compared to the virgin material is 70 % (Brown et al. 2000, p. 18). *The average selling price of regrind is 0.18 €/kg. The landfill cost was circa 0.19 €/kg* (VAT 0 %) and *for combustible waste the cost was about 0,066 €/kg* (VAT 0 %).

***Table 4** Four scenarios for using regrind (data is from the year 2014, based on actual scrap percentage) (ERP, BI-program)*

Scenario	**Value/ Loss [€]**	**The Loss When Compared to Scenario 1 [€]**
1. Total amount that would have been used in own production (The estimated value of virgin material)	312 837	
2. Total amount that would have been used as regrind in own production	218 986	- 93 851
3. Total amount that would have been possible to sell	31 111	- 281 726
4. Current state (Estimated that unused (mostly mixed colour) regrind is sold)	-1 752	- 314 588

The current state based on following points:

- Landfill waste: 82 540 kg * (- 0,19 €/kg) = -15 683 €
- Sold Regrind (see table 6): + 10 325 €
- Estimated combustible plastic waste: 10 000 kg * (- 0,066 €/kg) = -660 €
- Unused regrind if sold as secondary raw material: 23 700 kg * 0,18 €/kg = +4 266 €

  → The sum: - 1 752 €

There is over 314 000 € savings potential in waste and regrind due to high landfill costs, combustible waste costs and poor returns from sold regrind. In addition time, labour hours, space in the warehouse and other indirect costs (electricity, insurance etc.) allocated to plastic material could be eliminated. (This is based on the supposition that regrind is stored in the warehouse after grinding.)

5.2 Raw Material Purchase

Plasticized and rigid PVC are prepared in the internal supplier's production. Also both, powder and granulated forms are prepared. The whole process is very automatized and mostly operated from a control room by using a special program. Only small amounts of additives are manually added. Also the cleaning of mixers is done manually. When changing a prepared raw material for another, some amount is poured into a waste bag. Produced raw materials are shipped in big bags. The bags used in the raw material transportation are shipped back to the internal supplier after they have been emptied in the production. In theory this system is one possible source of scrap if there are contaminations of old material remaining in the bag, but this was not seen as a problem as they were sorted before refilling.

Based on interviews and conversations in the case company there were different experiences in relation to homogeneity of the raw material produced by the internal supplier. Some employees had experiences that sometimes when changing a raw material bag during a run, an extrusion was disturbed due to different melt flow properties. Other employees said that this effect was stronger with powders than granulates. Especially with PVC-P the problem is highlighted. Material and sharp corners set high requirements for quality. Employees working with PVC-P felt that the problem did not exist before when using an external material supplier. Nowadays occasional contaminations hamper the extrusion runs.

The question about homogeneity of the raw material is problematic because some employees did not have the same experiences and no studies were made on the question. It was also possible to see some confrontation between the internal supplier and the production. The difference in opinions regarding the heterogeneity of the raw material could also be explained by the skill levels of employees or other misconceptions. What is also important, some employees, who thought that raw material is partly heterogeneous, felt that they are not listened to and their opinion does not seem to matter. The employees working with extruders and raw materials are good sources of information when there is something unusual in the process.

There is an inadequacy with the internal reclamation system. This has slightly improved but is not systematic and automated enough yet. There was no system that would have been used in all cases. Sometimes an employee said about problematic material to another employee, who told about it to a shift leader, who conveyed the message to a production planner and he called to the internal supplier's responsible person. Because of the many steps before the message gets there, the information gets delayed, there is a risk for a broken-phone effect and some relevant information may disappear. According to the discursions documentation of the reclamation was not good enough and sometimes when a raw material problem occurred, only the material code was passed on to the responsible people at the internal supplier. It requires a much more comprehensive, standardized documentation with photographs to solve a root cause and prevent the problem from occurring again. Also a lack of commitment could be detected when it came to dealing with complaints in the production. It was sensed that this was maybe partly because of the absence of a scheme and partly because of prejudices about attitudes to reclamations at the internal supplier. Even though both units belong to the same company and concern there has to be a clear and direct customer-supplier relationship. Customer's needs form the basis of what are the value indicators and specifications to meet and the number one priority in every process has to be producing the desired value to the customer. (Spear & Bowen 1999.)

5.3 Inventory and Material Management

When scrap is formed it consumes material but after it is grinded, scrap is transformed to new material, regrind. These have to be equal to each other or material is "lost for nothing". Again, this causes errors in stocks, misleads production planning and may lead to situations where according to the ERP stock is available for extrusion but in reality there is not enough material. Furthermore, this leads to formation of scrap due to material run-out during extrusion and a new start-up (with start-up waste) is needed. Incorrect calculations were another reason why material consumption was not always up-to-date.

5.3.1 Raw materials

During research it was observed that sometimes raw material test results were obtained after the raw material had already shipped from the internal supplier. This is problematic because if something unusual happens, the mistake has already been passed on. Especially according to Lean-philosophy this is not the right approach. During the conversations with employees from the production and officers it appeared that many times even if it was noted that the raw material was not primary, there were attempts to use it in another application. It sounds like a good way of minimizing the cost caused by the defect of the raw material supply but it may be deceiving. Trying to use a defected or unplanned raw material in another application where its suitability is not tested by using scientific methods, can lead to extrusion problems, formation of scrap and cause other spill-over effects.

Also in some other areas the internal supplier and the case company need better integration with each other. There were a few problematic products which had been difficult to extrude for a few years already. One of these was a brown foam profile. The resin used in this product contained pigments and only foaming liquid was added during the feeding process. There were numerous problems; the resin got lumpy and needed sifting before feeding, it did not drain properly during feeding and also had extrusion problems like excessive swelling. Opinions about the reasons for this problematic behaviour varied a lot; lumps formed during transporting because of vibrations, material got lumpy due to pigments or the tool for that particular material was bad. However, the scrap percentage of the brown foam profile is more than planned in most of the runs. In addition, brown foam plastic scrap (like other coloured foam plastic scrap) ends up in the landfill. Attempts have been made to solve the problem but not in accordance with systematic and scientific enough methods or plans. Fast and effective actions are of paramount importance, rather than firefighting in the production line. Caused scrap, frustration, decreased customer satisfaction and disorder in production could be avoided with faster problem solving.

5.3.2 Facilities

The company has two main warehouse spaces; one in the second floor above production and a tent outside. The former is the main place where materials used in the near future are stored. From here raw materials drain by gravity to hoppers in the production, but with plasticized PVC raw material suction is used to convey material from a bag or an octabin box on the floor to a hopper. The outdoor storage has few problems in relation to material and employees. The temperature variation between summer and winter is huge and may affect the properties of the raw material. Also condensation of water especially in spring and autumn affect the raw material. Mostly only regrind and rarely used raw materials, packing materials and some finished products are stored in the outdoor storage. However, this does not facilitate the use of regrind. There is also a psychological effect - “out of sight, out of mind”. It is easy to store regrind out of sight but mentally and physically more difficult to pick it up from the outdoor storage.

One problem with the warehouse facilities is that there is no bar code system with the pallet places. Because of this, no exact information about certain material bags is available. There is a map showing the location of the materials, but the problem with this is the fact that when the amount of different materials grows, the conceptualization about their locations decreases. Also, because of limited pallet places materials have to be sometimes placed outside their own place. In the beginning of the research a too common problem was that material was lost. This has become much better due to a development project started in October. However, the real-time information, which tells where a certain material bag can be found and how much of which material is located in a certain pallet place would speed up the process of finding the raw materials and make the inventory and material management more reliable.

5.3.3 Calculation of Material Consumption

Theoretically the required material quantity is based on calculations about produced volume and added quantity of scrap. Bill of materials (BOM) tells “the recipe of product” and the amounts of raw materials needed. With most products a theoretical scrap percentage is 10 %, in other words a yield factor is 0.9. With new products the yield factor can be determined to be lower but the target for all products is to get it to the level of at least 0.9 and later in the future to the level of 0.925. During production information is written down, which is needed when calculating the actual quantity. This is based on three things: produced metres, a metre weight and formed scrap. Produced metres are shown in work order. Metre weights are written down during extrusion depending on the product once every two hours, once an hour or in the beginning and end of the run. With foams this is more critical due to bigger variety in metre weights. Scrap is weighed in the end of the run or with long runs during the run when the scrap cart is full. The person responsible for materials collects work orders, calculates consumption and reduces consumption from the balance.

Weighing metre weights correctly is extremely important. Because this is done manually on paper, the risk of incorrect balances is real due to human error and negligence. This occurred several times during the research. In the beginning of the research, also the weighing of the scrap pallets had a risk of being inaccurate. When people changed during a shift change, it was not always clear if a pallet had been weighed. The problem with this kind of material consumption calculation is that it does not happen in real-time.

Masterbatch bags used in a product are weighed before and after a run. The consumption is calculated by subtracting the end weight from the start weight. This is marked to a work order and the person responsible for the material subtracts the consumption from the balance. The problem here is that even though the procedure is very simple, there were continuously differences in the masterbatch balances. They are used in very small ratios (only a few percent) but their high kilo price makes this issue important. During the discussions I also heard that sometimes masterbatches were used more than necessary in order to produce a desired product (a general percentage is 2-3 %). It is a waste of money to produce over-quality and this habit should be eliminated.

It was possible to see symptoms of a broken material and inventory management. As already stated, sometimes material was lost but more often it ran out or was soon to run out during extrusion runs. It was observed that this was very frustrating for employees. Sometimes a tool was assembled to the extruder (which can take up to many hours) but afterwards it was noticed that there is not raw material even though, according to the balance, there should have been. If raw materials run out during a run, it generates extra shut-down and start-up scrap, wasted labour hours and causes extra work to find out the reason for the shortage. Also, laborious and frustrating regrind inventories once a month are signals for the same problem. I took part in one of them and there were relatively big variations between the real balance and the balance shown in ERP. Corrections cause a lot of extra work which is actually a waste of time and effort compared to a situation where material consumption would have been calculated correctly at the first time. There is of course a need for inventories but once a month is too high of a frequency because this time is taken away from everything else, such as from improving current processes (raw material and pigment inventories were done less often).

5.4 Production Process

All work in the production shall be highly specified as to content, sequence, timing and outcomes (Spear & Bowen 1999). Many symptoms of a broken process could be detected; the quality was not always as expected, some things took too long, processes had to be done many times (scrap), employees felt frustration (design flaws), output time and quality varied but it was difficult to react to it, there was a need for continuous reviews when production processes were not reliable and the management tried to solve the problems through firefighting, but the fires kept recurring (Madison 2005, p. 55-59). One source for a broken process is numerous variables. This makes systematic approaches even more important, because without them and controlled input also the output varies a lot.

5.4.1 Extrusion of Established Products

The interviewees stated that when planning investments, the company is sometimes focused on wrong things and the basic machines do not get enough attention. Calibrating, water cooling and air cooling were seen as too rough when trying to achieve high dimension accuracy. Small changes in the water cooling system may cause large changes to product dimensions and if changes cannot be done with a sufficient accuracy, meeting the specifications becomes difficult. If there is just an “on/off” options without measuring scales, calibrating becomes more or less a hand-feel operation.

An extrusion process starts when an operator looks up a Visual Planning & Production Follow-Up-program and picks up a corresponding work order, a product card and a sample. The product card is information input and should be the guide to how the extrusion of a certain product should be done. It was discovered through the interviews that too often the cards were not up-to-date, they were not clear enough or did not have all the necessary information. When the variety expands and people change from one line to another, the importance of reliable information is the key. A manual form is may not be the best one. Making corrections and adding extra information to the same card or folder, makes the reading of the product cards difficult. If there are even nine different paper versions in a folder, how is it possible to know which one is the right and the best one? Confusing and messy appearance does not make products cards attractive to read. This is alarming because too many times I heard in the production that some people do not read them. This problem came out also during some of the interviews. Unclear and partly outdated product cards had caused also a secondary phenomenon; some employees have had to make up their “own instructions” about extrusion conditions. This leads to a situation where extrusion output is person-related, not consistent.

Pre-printed work orders may not be the best option due to outdated information about material balances. During the work in the production it became obvious that employees have to always check the existence of material because the balances in the work orders are not up-to-date and can be even weeks old. Another reason is unreliable calculations of material consumption. A question arises here; what is the role of the balances in the work order if they are not up-to-date? It takes work and presence man hours to go the second floor or outdoor storage and check the material balance. Also, pre-printed work orders carry a risk of human errors; paper can be lost, forgotten to be printed or forgotten to be brought to the production. It is also an additional operational step and according to Lean-philosophy, it is a waste to carry printed papers over to the production, if printing can be done in the production.

Most of the extruders are manual but there are also computerized extruders. At least with those there should be ready temperature settings available from a menu. At the moment there are too many “hand-feel” searches for the right extrusion conditions, which lead to formation of scrap. It emerged during conversations that one reason why the available computer programs were not used properly in the lines where it would have been possible, is partly down to employees' uncertainty about computers. Every extrusion machine is unique but there should be at least a common starting point for the searches. This is also part of the systematization of the entire process. If there is a wide range of extrusion conditions, they could be optimized. The goal is to find the best possible conditions which are repeated in every case. This is the only way to maintain a similar output. It also helps to reduce products that are overweight especially with foam profiles because overweight is also a waste of money and materials.

There were not enough guidelines as to how materials with complicated processing properties, like ABS and PC, should be prepared. Drying these materials properly is very important to prevent previously mentioned product problems. The product cards included guides about drying temperatures but not about drying times or acceptable moisture contents. Completing actions blindfolded leads often to unwanted output. As time passes, things (such as drying time) have been learned through practice but before that it will cause a lot of scrap, frustration and wasted labour hours. This could be seen partly in other guidelines and operations as well. The common way to act was to try and see what happens rather than acting in accordance with instructions.

Large-sized scrap is extremely difficult to recycle and because of this there are critical steps to be taken at the start-up of extrusion. Care is of the essence during these operations and for instance people from R&D are talented enough to pull material through an extruder with minimal scrap. For others, there should be highly scripted approaches as to how it should be done. Every preparation must be done before material is fed in to the extruder and all attention should be focused to the line. Also, it is just a fact, that not everyone is good enough to start-up difficult product runs. If it is noted that a certain employee has too difficult a start-up for him/her, someone should be delegated to help with it.

New products get more priority than old ones. It was possible to see this and in some interviews it emerged that sometimes the process of turning a "new higher priority product" to an "established - we can handle this - product" was scattered. Because the cycle of new products was so fast, older products which still had problems during production or with their properties, did not get enough attention. Older products should be monitored as long as productability and properties are good enough. Production and R&D should solve problems together as long as the quality is good enough and it is advisable to do so from the start. I heard that there was a big variation in this matter and some R&D people cooperate better than others. Also in the interviews it was noted that difficult products were extruded too many times with high scrap percentage but not fixed properly. After the run everybody let out a sigh of relief until the same difficult product came to the working list the next time. This is repeated many times until the product is truly established.

Troubleshooting was often more blindfolded than organized. Shift leaders and some employees, who were more conscientious, took samples of the section where the problem occurred, analysed it openly and made corrective actions. But in addition to this, I saw “hand-feel” seeking and indiscriminate corrective actions with the mentality “let’s try and see what happens”. There was often a rush to intervene in the process when waiting would have been wiser. This may make the troubleshooting run in circles. Changes that were made (for instance changing nozzles) were sometimes hard to follow. Especially when there had been a long time between the previous and the following extrusion run, there was a risk of forgetting about the changes made. And when the number of changes without documentation increases, the overall picture may become blurry.

Haste in the production came out in every interview. It is not clear if this is due to badly directed resources, lack of resources or just a feeling. But there is one important point - Is the time really spent on valuable work? A feeling of rush can also be based on badly directed resources. However, if a lot of time is spent on firefighting, there are not enough resources for value-creating work. It was obvious from the observations that shift leaders and production officers had to use a lot of time in solving continuous and unexpected problems. This is tricky because problems of course have to be solved, but the shift leaders’ primary task is to improve the production process, to ensure that every task will be done and to support employees by their presence on the lines. Here the employees’ part becomes important, because if they can prevent problems occurring and solve simple issues by themselves, shift leaders have time to improve the process.

Secondary operations were not seen as a major source of scrap. Visiting the secondary operations unit showed that only a small stream of the manufactured products actually goes there and employees were mostly satisfied with the quality of prefabricated products that they get from the production.

Last but not least, reclamations tell also about the performance of the current production process. The appearance of the product was the reason for 28 % of all reclamations made in the year 2015 (surface quality, shape defects, etc.). This reveals insufficient quality control methods (how measurable and representational criterions are; pass/fail answers?) or lack of care (human errors due to tiredness or neglect). Statistically direct human-related reasons were 23 % of all reclamations, which is a relatively large amount. It should still be taken into account that these are statistical numbers and real root causes should have been studied in every case to be certain about the real reason for reclamation.

5.4.2 Extrusion of New Products

In a subcontracting environment, where extruded products are tailored to customer specifications, cooperation and strong integration between production and R&D is critical.

Generally “over-the-wall” mentality and detachment of R&D from other operations may be a big source of problems in the production. In addition to product properties, development projects have to focus on how products will be produced (and how they will be transported to customer). This is also the key for a fast and effective way to get new products to customers. (Heikkilä & Ketokivi 2005, p. 103.) It is important to get products to the market as quickly possible in the new economy. The companies that are early in the market have the opportunity to get a bigger market share, define higher prices for products and get a better net present value (NPV). In other words, the importance of time as a competitive advantage is significant. (Hayes 2002.)

There were done a protocol and a value chain-picture about putting into practice of new products from an offer request to deliver or finished product. This is a very good and systematic approach but not always followed. The tool department has a responsibility together with salespeople and a project manager to develop tools and products that are ready for production. In the interviews it came out that the development is sometimes only partial when a new difficult product is coming to the first production run after test runs. When the status of the product changes from “test” to “on-production”, sometimes the tool department withdraws from the project too early, because they have so many new product projects (here we come to a question, if the resources of R&D are sufficient). In some interviews it was said, that informing people from the production about test runs could be better organized. Especially a production planner needs more information about the stage of the development process to be able to promise delivery dates. On the other hand, employees should also take part in test runs to get useful information about future tools and products. This did not always happen due to fear of new products and the need for training or just because of a lack of motivation.

One could sense haste in the production to get new products out to the customer during the first or second production runs. The delivery date for the customer was promised by the sales and the production tried to respond to this. In many interviews it was noted, that there was often a misunderstanding that all important processing parameters were known, even if they were not. Of course it is necessary to get new products to the customer as soon as possible, but the lack of knowledge of suitable processing conditions usually causes trouble. These issues have an impact on everything. They cause frustration when there are design flaws or difficulties and a panic to get products finished. Working hastily increases the risk of mistakes and scrap. Again the rat race is about to start; scrap may cause a shortage of raw materials, eat resources from elsewhere, complicate production planning and material management and there is not enough time to improve the process. The sales have responsibility here to survey all important parameters from the customer.

5.4.3 Quality Control

Quality control differs a lot depending on the product. Dimensions, surface quality, appearance and a metre weight were common issues, to which attention should be paid. In addition, there were product specific issues like resistance to measure. Many products also have callipers. In general, this is the direction, in which the quality control should shift - to unambiguous (pass or fail) and fast. Mausers are very useful but some distances are tricky to measure because they are dependent on the measuring angle. However, callipers have to be very carefully designed. It should not be possible for them to indicate that product is passed if it in reality has not. For instance, in January there was a charging hose which passed the calliper test that measured the inner diameter, but in reality it failed. The outer diameter was measured at the beginning of the run but during production it was only assessed visually because the hose fitted to the calliper. Due to a human error it was not noticed that the pipe was not centralized properly. The lack of proper quality controls and passed defect products peaked in evening and night shifts, which indicates that quality control should be easier and free from human errors (like Poka Yoke).

The importance of unambiguous quality criteria is especially important in evening and night shifts when there are no managers available. In November there was a run for the biggest new profile of the range. There were not enough clear rules as to whether the profile was acceptable and the line was stopped even though the profile was acceptable. However, the decision was right because it is a risk to run a heavy profile for the whole evening and night just to realize in the morning that is was all scrap. But if there had been clear quality criteria in place, the line would not have been stopped and a lot of start-up scrap would have been saved (the profile was at first extremely difficult to pull through the extruder due to its large size and a slow pulling speed).

Colour and gloss are not sufficient for a visual assessment, if it is an important criteria for customer. This was more problematic in the beginning of the research but was improved later on. There should be measurable tolerances expressed in colour coordinates or gloss scale. When customer specifications about colour and gloss tighten, this becomes even more important. It was reported in interviews that a few customers have such tight colour specifications that it is difficult to respond to them within the current process and quality control. As long colour is visually assessed, it is not clear what the acceptable colour is (saturation, hue, brightness) because it depends on lighting, human eye and surface quality. The discussions and interviews revealed that if there are no clear rules about colour and gloss, it becomes tricky to even discuss it with the customer. It leads to confusion about the desired colour and how it will be achieved. At the end of research the measuring of colours with coordinates got more attention and training continued on the issue and so it improved.

At the moment, because of the variables in the equipment and raw material, extrusion process has to be monitored all the time. During work on the process, it became clear that half an hour's absence from the line could cause dozens of failed profiles. As long as there is no sensor (manual or automated) on the line, it just relies on luck that the extrusion succeeds (during the research a video camera was used on one line for quality control purposes). At the end of the research when the team work was implemented, this issue had become a little better due to the roles of a packer and a trimmer. The packer is usually less talented than the trimmer and can monitor the quality of the profiles during packing. However, sometimes the packer was not trained properly (temporary employee) and the performance of his/her quality control was insufficient. In these cases the trimmer or the shift leader has the responsibility to instruct the packer. On the other hand also the trimmer should monitor the process at the beginning of the line and not let own quality control suffer (defects are not allowed before moving to the next step).

5.4.4 Maintenance

Maintenance of machines is obviously a prerequisite for the production if you want to avoid unpleasant surprises. There was an excellent maintenance program for each line in the production. It included guides as to what should be done and when (once a week and once a month) also illustrated with pictures. Unfortunately this was not followed as it should have been. In some of the lines employees were extremely committed and followed the program, but there were also lines where this was done half a year ago. A simple maintenance done once a week can prevent many extrusion problems. Regular maintenance helps to discover if there is need for a more proper maintenance in the near future. For instance, if there are old granulates inside the machine, it can lead to quality rejects on the surface of the product.

It was discussed in the interviews what the reason was for the lack of basic maintenance in the lines and if it still was seen as important. The obvious and easiest reason was haste. As noted many times before, haste is partly caused by unexpected problems. Almost every other week the reason was that something small was broken in a machine or other equipment. Also unplanned repairs took often a long time to fix because first the root cause had to be found out. By performing weekly maintenance, many of the problems in the machines could be eliminated or at least find out about them early enough to include them in the production plan as planned repairs. Furthermore, this reduces the pressure and leaves more time for value-adding activities.

It emerged that time pressure is not the only reason for insufficient basic maintenance carried out by the employees. I heard that Friday's last shift before weekend often leaved earlier than planned and this tells about lack of control and commitment. The root cause can also be that maintenance is not seen as part of somebody's responsibility or its importance is not clear enough. Some employees expressed tiredness because of a heavy work load. So if something can be left undone, it is just human behaviour to leave it, when you do not feel it to be your personal responsibility.

5.5 Recycling

How should formed scrap be handled to keep it high quality with regards to recycling? How should regrind be made so that it can be re-used? How should regrind be used to ensure unproblematic extrusion and products which meet customer specifications even if they are partly recycled? Among other things, the current recycling procedures have been observed in view of these questions.

5.5.1 Facilities

The case company’s recycling facilities consist of one grinder for foam PVC, two grinders for different engineering plastics, four grinders for plasticized PVC and three grinders in a scrap room. One of these is mostly for white PVC, one for coloured PVC and one mostly for electric tubes. Cleaning a grinder is laborious and that is why collecting each scrap type as much as possible before grinding, makes it easier (but this decreases flow efficiency). Employees expressed some frustration about cleaning the grinders. At the moment there is a very conscientious person responsible for the grinder in the scrap room, but one possible reason for previously made mixed-colour-PVC scrap is the lack of motivation to clean the grinder between different coloured scrap runs. This mixed-colour regrind is the most difficult to use and at the moment mostly sold. Eliminating is a good starting point because of the careful and diligent person taking responsibility in the scrap room.

Formed scrap is collected in carts and ground after an extrusion run or during it (long extrusion runs). Start-up waste is collected in pails. After grinding, regrind is put in a small or big bag. The problem here is that there has to be a lot of regrind to fill a large bag. On the other hand, if the warehouse is full of small bags, their use becomes more difficult due to an increased number of collections and a blurred overall picture. During inventory it was noticed that small bags being placed all around the production hall, is a risk for making mistakes in balances. These materials “float” if they are deleted from the virgin material balance but not added to the regrind balance.

When it comes to recycling, there is one good exemplary model in the case company’s own production. Plasticized PVC is well re-used. There are enough grinders near to the lines, systematic storing of regrind in labelled garbage cans, the inventory turnover is fast and people have good a comprehension of what regrind type can be used in each product and what regrind ratios are suitable. The plasticized PVC unit was almost a closed-loop system, so it served as a benchmarking model during research. There were still some things that needed improving like welding strips which were not recycled and more space was needed to store made regrind but overall this unit worked very well.

5.5.2 Scrap and Made Regrind

Figure 23 below shows the actual scrap percentage, the planned scrap percentage, the Group's target and the most optimistic level. The data in the chart is from the year 2015 because there was not any available corresponding data from the year 2014 in the BI-program.

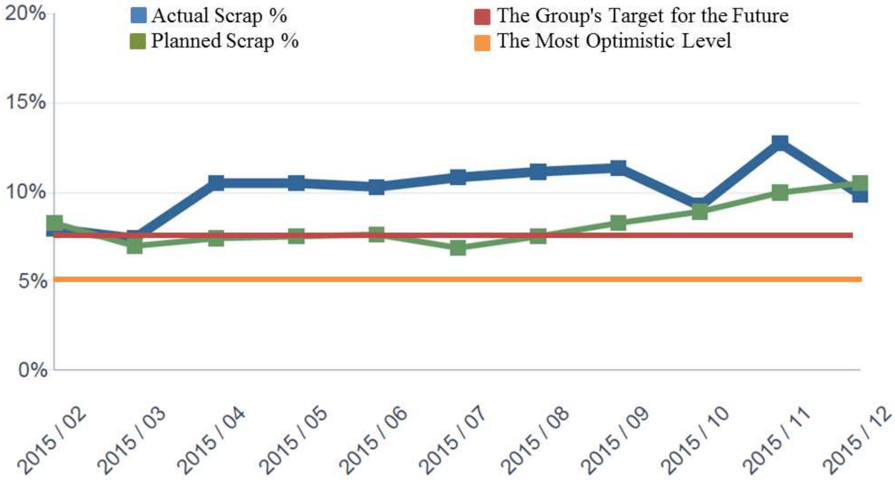


Figure 23 *Actual scrap percentage, planned scrap percentage, the Group's target for the future and the most optimistic level*

In March, October and December the actual scrap percentage was equal to what was planned and in March it was within the Group's target. In the other months and especially in the high season in summer it was much higher than target. The biggest difference between planned and made was in July. The peak in November is a result of many new products and their higher scrap percentage.

Collecting of formed scrap to carts needs some fine-tuning. Long and thin profiles were often dragged over the floor. Contaminations like dust may stick to the profile and be spread to the regrind and cause surface quality defects during re-processing. Carts also need a clearer location system that indicates from where they can be collected for grinding. Without a clear visual control system, there is a risk that the carts are collected from the production hall for grinding before the scrap is even marked to a work order, or if required, a sample taken. The carts also need a system which tells what plastic they include. Sometimes it is written down on one profile but if not, it becomes tricky for the person responsible for the scrap room to recognize the plastic type and mark it as correct regrind type.

Profiles with a combination of copper wire and plastic must be separated to be able to be recycled. Plastic profiles go to landfill due to possible metal contaminations but copper can be sold. At the beginning of the research, copper was separated mostly by one motivated employee only and adventitiously by other employees. The difference in selling price between combination of plastic and copper (circa 2.00 €/kg) and pure copper

(4.30 €/kg) is significant. That is why the lack of separation does not make sense from a financial perspective, especially now when the ownership of copper has been moved from customer to the case company.

It was noted during the observation that the marking system of regrind was too vague and not clear enough. Only the following information was marked on a bag: the date of grinding, who ground the regrind and the name of the plastic (not the code). Sometimes not even that information was marked. If there is not enough information on a bag, the employees cannot trust what is inside. For people who have not worked in the case company before (like me), the use of nicknames for different regrind types does not tell enough. This system has to be made so easy that even new people know immediately what is inside a bag. This is highlighted more when new temporary employees are needed to increase the flexibility of the production.

Also, the incomplete marking of a G-code, which tells the type of regrind, makes their use confusing. In addition, the G-code system is being updated but at the beginning of the research G-codes did not correspond to virgin material codes and not each virgin material code had its own G-code. If one G-code covers many different regrind types, their use becomes trickier when there is no clear link between the virgin material and the regrind. Figure 24 illustrates the old marking system of bags.

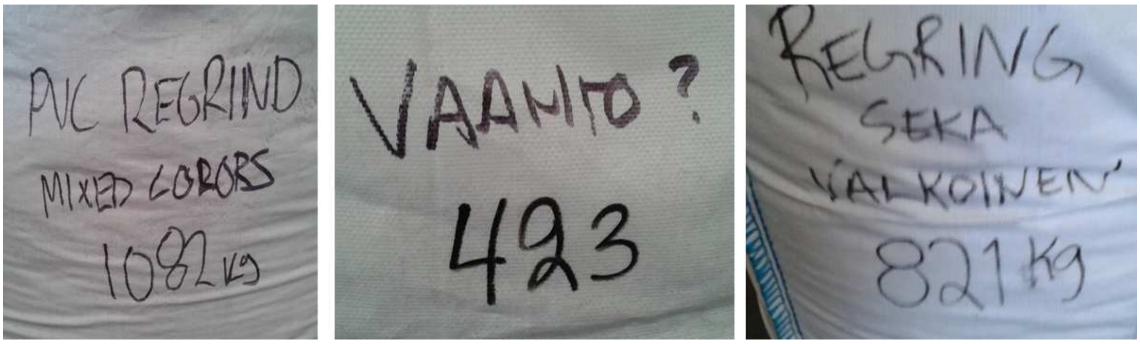


Figure 24 *An old marking system of regrind bags (photographs 7.9.2015)*

After grinding and marking the bag, the amount of each regrind was marked down on a form. At the beginning of the research, the person responsible for the material collected this paper once a week. The frequency has been increased but still the made regrind balance is not in real time and not efficient enough. The production control person's work becomes complicated when the balance of regrind drags.

5.5.3 Used Regrind

Appendix D shows charts of made and used regrind from the years 2014 and 2015. Figure 25 shows the distribution of regrind by material types in the year 2014. The data is from the ERP and BI-programs. It should be considered that some material codes have changed.

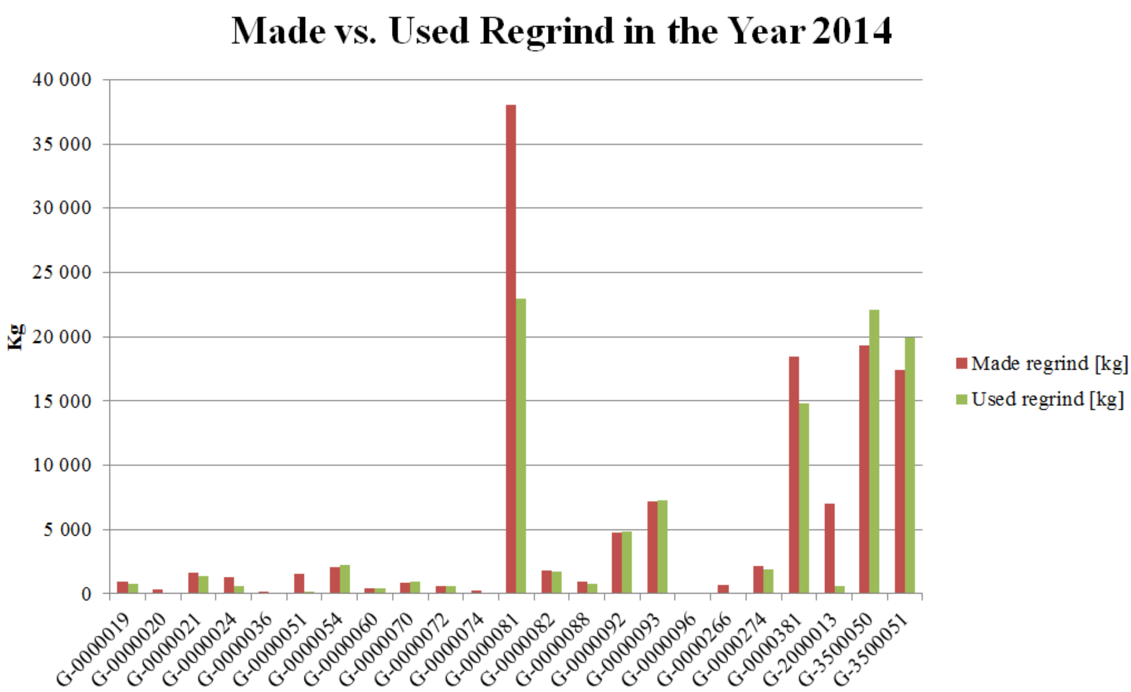


Figure 25 *Made and used regrind per material types (ERP, BI-program)*

G-8000081 is absolutely the most made and also the most used material type. This consists of rigid coloured PVC. The problem is that a large amount of made regrind remains unused and this is why the largest potential lies in this rigid mixed colour PVC regrind. G-0000381 white rigid PVC has a better situation in percentage terms. The poorest usage of made regrind is with G-2000013. That is coloured ABS. Code G-3500050 is not used anymore but G-3500051 is foam PVC. White foam PVC is mostly used but, as mentioned before, coloured foam PVC goes to landfill.

In general recycling of materials should be considered already in the beginning of the product development project. There were many raw materials which are not most suitable for recycling. PC and PS are tricky to re-use because they lose part of their optical properties during re-processing. Also glass fibre plastic, a blend of wood chips and plastic and a combination of plastic and copper are difficult to re-use. Furthermore the use of regrind is not systematic enough and suitable regrind ratios for certain products and materials have not really been studied by using scientific methods. The shift leaders have studied regrind ratios a few times but regrind ratio tests are still a grey area. The problem may be that the ball about using regrind has been thrown to the production, but it has not been planned and studied enough.

The use of regrind is not reliable and easy enough. One employee put it well; “If you use regrind, you just make your day more difficult.” Regrind ratios and products that are suitable for feeding recycled plastic are found by practical experience. A profile X is a good example. It has a large sales volume, it is big and heavy, has low specifications and can be made entirely of mixed white regrind. This is why it also has a big cost impact. Finding new products like that with low specifications will become important in the future. If regrind is used and problems occur during extrusion, the first thing done is usually to leave regrind out of the feeding. This is understandable because usually there is haste in the production, errors eat into valuable production time and new scrap is formed. The used ratios vary which also makes the output variable. This is not desirable because if the properties of a product also change and are not known, there is a risk that in reality the product does not meet a customer's expectations.

Planning the use of regrind happens mostly in a weekly meeting where the next week's runs are scheduled. In principle, this is a good idea because shift leaders, the production planner and the production manager are all in the same session. Coming together like this can give a better understanding of any limiting factors or issues to be taken into account. On the other hand this is a manual approach. In the case of regrind, if it is decided to use it in a certain product, at the top of the work order it should be written down for instance: "use scrap". This is not thorough enough and does not make production employee work unequivocal. Also, during a week meetings there are so many other things to remember that thinking about use of regrind may be forgotten.

The attitudes towards the use of regrind hinder its use. During interviews it emerged that many employees do not understand that regrind could be a valuable raw material or that reducing scrap and increasing the use of regrind could have a huge financial potential. Also the attitude "everything or nothing" is negative, because even if a small ratio of regrind is used systematically, at the same time formation of scrap is limited. Made scrap, made regrind and used regrind were not visible enough in production. After an extrusion run scrap and regrind was taken away from the eyes and at the same time maybe also away from the mind. In addition, most of the employees were not motivated enough to use regrind. At the same time there were some employees who were very motivated and frustrated because of the attitude "not even worth of try". The motivation and direction of people who are reluctant to change, is important in getting all of the organization to work towards a common goal.

5.6 Information Flows

Transparent and efficient exchange of information is necessary in extrusion production because currently it is largely manual and very dependent on the performance of the operator. Also information sharing and good integration between sales, R&D and production is important in a customer-orientated business environment where product development projects may take a long time in designing and producing suitable profiles for the customer and at the same time finding profitable and efficient production methods for the case company.

Overall, during observations, discussions and interviews it was noted that information sharing works well horizontally (especially in the day shift). It is direct and open but depends on one’s own activity. For instance, information sharing between production and maintenance was substantial and active.

Vertical information sharing was not as good as horizontal information exchange. A possible reason is the physical distance between the two floors. Employees from production did not take part, other than in morning meetings and responsibility for transmitting information forward to floor level is largely down to shift leaders and partly managers when they visit the production. It is human behaviour that when you have a lot of things to remember something may be forgotten. During the discussions it became clear that sometimes employees were informed of decisions taken relatively late. Especially when introducing new products with higher scrap percentage, it is important to plan the work together between managers and employees. One employee said “you should have a crystal ball to forecast what will happen in the production on the following day”. It should be remembered that this may not be the whole truth because often negative experiences are emphasized. People remember better events when they have an experience of being badly treated than events when they have been treated well. Also how questions are set is an important point and affects how people answer. (Baumeister et al. 2001.)

When shifts change, exchanging essential information between the previous and the next shift is important to avoid making the same mistakes again, to be prepared for possible extrusion problems and to know if something unusual has occurred. At the moment information sharing depends on if employees want to do it in their own time. Usually the next shift came in 15 minutes before their working time. Not all employees came earlier and that is understandable if they do not get monetary compensation for it. In these cases there is a risk that the next employee is not prepared enough and an extrusion problem could occur. However, because of expensive machine time, material costs and ripple effect of problems, 15 minutes of working hours pays for itself very fast.

After Lean-philosophy was introduced in the case company, many channels to convey ideas have been opened. Idea boards on the lines, a problem solving board and a repair request board in the maintenance room door are examples of great ways to express ideas. Another area where the activity of the employees needs improving is the use of the Visual Planning & Production Follow-Up program. The reasons for the lack of resources or a quality reject were not always written down. This is important especially after an evening and night shift when there are fewer people working and conveying information forward. Sometimes it was unknown what problems occurred in the night shift. Overall this issue has improved during the research but still needs attention.

Sometimes decision making took too long. Brown foam PVC window profile with high scrap percentage was a good example of this issue. The physical distance between the internal supplier and the case company complicates decision making when communication happens only by phone or computer or by visiting. It was observed that sometimes after making decisions on actions, tasks were left up in the air. Sometimes the progress of the project was delayed while waiting for someone’s answer. If decision making is concentrated on a few people, who are already very busy, they can become bottlenecks in the project.

5.7 Daily Managing and People

It was great to see that there was partly a real team spirit in the production between shift members. During difficulties employees combined forces to solve the problems. Of course, like in almost every organization, not all get along with each other, but mainly the teams worked very well together. In the beginning of the research when the production had not moved to teamwork, the employees expressed their eagerness to work together more as a team. And that, I think, is great and shows potential with reference to Lean-philosophy.

There were some really talented employees working in the production. I saw overwhelming commitment to the job and the company. At same time I heard during interviews that not all work is evenly distributed and highly motivated employees sometimes do also less motivated and less hard-working employees’ work. This is not fair and carries the risk that really deserving employees lose their motivation. Some employees expressed frustration because they felt that salaries are paid based on time rather than created value. Also some lack of discipline came out in every interview. Some interviewees felt that there will be no penalties even in the case of the outright neglect of tasks. In addition to discipline there has to be of course also support and encouragement. In this area employees were mostly satisfied and happy.

Working in the current extrusion process is challenging and sometimes hard. If employees are loaded with too much work, the risk of mistakes increases. This is why listening to the employees’ feelings and having empathy is important. During the work in production it was noted that a night shift is tough and prone to human errors. It was also observed that many of the problems occurred in the night shift. This is why design practices and the production plan should consider the performance level of night shift.

Because it appeared in many interviews that the most obvious reason for formed scrap are new unskilled employees, a longer familiarization time can help to reduce scrap. Some employees felt that it is not long enough and due to a wide product range and large raw material variety handling all details can be challenging.

5.8 Afterword Regarding the Current State

As previously discussed, previous chapters focus on development issues. This should not lead to a misunderstanding that *all things* in production were not well. Overall, the current state in the case company has great opportunities for recycling and there were more positive than negative issues in the production and other operations.

The first good point and a competitive advantage is their own internal raw material supplier. Communication between supplier and production is much easier and delivery times shorter than if the supplier was external. This gives a huge advantage when raw materials of products can be tailored to meet customer specifications. Recycling is also easier if raw materials that are difficult to recycle can be modified. These two units also pull well together.

Regarding inventory and material management has to be said, that buffers are decreased at a low level. Especially with the end-product warehouse buffers are extremely low. In the view of Lean-philosophy this is great when the need for inventory is minimal and only small capital is committed to inventory. Overall, the flow efficiency of virgin raw materials is good.

One could observe an innovative atmosphere about new products and tools in the company. Enthusiasm about new products was great to see and the mental threshold to try challenging profiles was at a low level. Success cannot be achieved without bravery and self-confidence and these are not problems in the case company. Sales, production and tool departments were all open-minded to new ideas and this was good to see.

During the observation and work in production I was amazed at how good practical skills the employees had picked up, because almost everything from tool assemblies to quality reviews is manual. Many things have to be learned through practise and I really take my hat off to the employees who are able to handle it because theoretical knowledge alone is not enough. Also office workers expressed good commitment to making processes and activities better. When a problem occurred, the root cause was found out and corrective actions were made. Many people including shift leaders worked long hours to fix problems and that shows commitment.

Many managers expressed great enthusiasm about recycling and this is the best possible opportunity for it. Using regrind was tried with many products and facilities for recycling were purchased. Also raising a question about how recycling could be done with higher ratios, is a good starting point because without the support of the managers and their eagerness to find solutions, it would be much more difficult or never even tried.

Overall, when I started the research I was positively amazed at how well everyone accepted me. Employees were open and helped me a lot when I was (with poor skills and lack of practical experience) working in the production and asking (also very simple) questions. No one refused to be interviewed and I am thankful about that. Also, already admitting their own weaknesses (which all organizations have) shows their openness and the eagerness to develop their own processes and operations. I am sure that improving the extrusion process towards a closed loop system shows great promise.

6. IMPROVING EXTRUSION PROCESS TOWARDS THE CLOSED-LOOP SYSTEM

The closed-loop system has to be a common goal for the entire organization. It starts with a vision and continues with making a strategy that supports the other targets of the company. (Wills 2009, p. xiii, 30.) As with every strategy, moving towards the closed-loop system is a choice between alternatives and it requires a long-term commitment from the entire organization. (Heikkilä & Ketokivi 2005, p. 29-33.) On the other hand, it can produce value and act as a competitive factor in the environment where green values have got more and more importance. The ability to be cost competitive, forces the company to use valuable resource as efficiently as possible.

In the previous chapter there was a list of development issues that cause scrap or hamper the use of regrind. In other words issues that prevents the closed-loop system from being realized. In this chapter those issues from the development areas (found through observation and interviews, see Figure 26) are attempted to be solved according to Lean-philosophy and especially using the four Lean-rules by Spear and Bowen (1999):

1. *All work shall be highly specified to content, sequence, timing and outcome.*
2. *Every customer-supplier connection must be direct and there must be an unambiguous yes-or-no way to send requests and receive responses.*
3. *The pathway for every product and service must be simple and direct.*
4. *Any improvement must be made in accordance with the scientific method, under the guidance of a teacher, at the lowest possible level in the organization.*

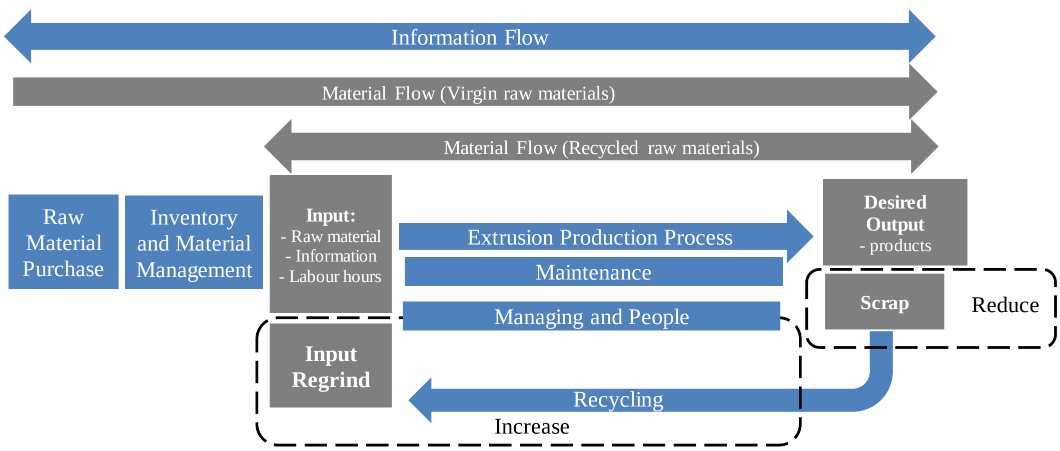


Figure 26 *Developing areas in the current process*

It should be noted that processes, not individual tasks, are under development. They are important but individual tasks cannot themselves achieve organizational goals and none of them matters if the overall process does not work. (Hammer & Champy 1993, p. 35; Gray & Starke 1984, p. 175.)

6.1 Raw Material Purchase

Overall, if a closed-loop system is desired in the case company, it has also to cover the internal supplier. Structural mechanisms, functional mechanisms and strategic mechanisms can all be used to integrate these units better together and to achieve the common goal (Heikkilä & Ketokivi 2005, p. 176). Processes of units have to be compatible with each other because the output of the internal supplier acts as input for the case company, so getting the desired output from the case company, requires also the desired output from the internal supplier. When the recipe of new raw material is planned, recyclability should be one criterion.

When decisions are made about another unit, it should be taken into account how it affects the other unit and if there is any effect the decision should be made together. A functional mechanism for integration is increasing frequency of meetings at different levels of employee of units. An interest for this was noticed also during interviews. It was great to hear that some employees from the case company wanted to visit the internal supplier more often to be able to improve the process for both parties. A strategic integration method could be turning a strategy of a closed-loop system into both units' language. (Heikkilä & Ketokivi 2005, p. 176-195.)

Integration becomes crucial when dealing with products with exact and difficult colours. In the internal supplier's production there is more knowledge about the materials and in the case company's production knowledge about the production process. Defining rules for new products together helps both parties' operations; the internal supplier knows what the end product requires from their operations and at the same time the case company knows how the raw material behaves in production and how it should operate to achieve agreed properties in the end product. It is important that agreed extrusion conditions are always followed because without the controlled input and process, the output varies. Both, the prepared raw material and the end product, should have agreed tolerances regarding colour. With products that are challenging in the view of raw materials BATCH-number used in a raw material bag and onward in a product, could help to keep track of used raw material if a complaint from the customer is received. Fast decision making is primary because every time when a raw material with insufficient processing properties is extruded, more scrap, lost labour hours and other problems increase the costs caused by the raw material.

Finding direct and unambiguous communication channels between the internal supplier and the case company is important for both. Employees in extrusion production are the customer of the raw material delivery process and their feedback is an important part of process control (Martinsuo & Blomqvist 2010, p. 6). In this context we can rely on Rule

2 (Spear & Bowen 1999); every connection must be standardized and direct (Spear & Bowen 1999). This rule is useful with reference to a couple of previously mentioned observations. The first issue where it can be used is the question of quality and homogeneity of raw material. When the number of handovers decreases, the opportunity for errors also decreases due to avoiding the broken-phone effect (Madison 2005, p. 264-265). There could be for instance a pre-designed form on paper or online. An example of a pre-designed report is given in Appendix F. By asking the employees directly what the symptoms of a problem were, the message is authentic and unchanging. In this way one could construct a timeline to deal with problematic raw materials and improve them to meet better the requirements of the case company's extrusion machines. For instance, if some raw materials get more feedback in relation to extrusion problems, it should get higher priority (if it is also produced in high amounts).

Another issue where Rule 2 (Spear & Bowen 1999) could be useful is reclamations. Under the current procedure the message does not come straight where the problem occurs if the employee him/herself does not make reclamation. Here a pre-designed form would be useful and it would require a sample of material and profile or at least photos (see appendix F). With sufficient documentation the problem solving and prevention at the internal supplier becomes easier. On the other hand, doing reclamations has to become more active. Without reporting problems, the process won't improve.

The third issue where direct and fast communication channels without wasted steps are needed are cases when a shortage of raw material suddenly happens (see Figure 27). The first priority is to make the calculation of material consumption reliable but if material runs out anyway, there has to be a specific way to act according to Rule 1 (Spear & Bowen 1999). When an employee notices a shortage of raw material, he/she should inform about it straight after noticing. A long chain and physical distances could be bypassed by a chat-software which connects the case company's production, the production planner and the internal supplier. After the notice about the shortage production planner could confirm the shortage and order more raw materials. At the same time the internal supplier is aware as soon as possible to be able to take note of a shortage in their raw material production.

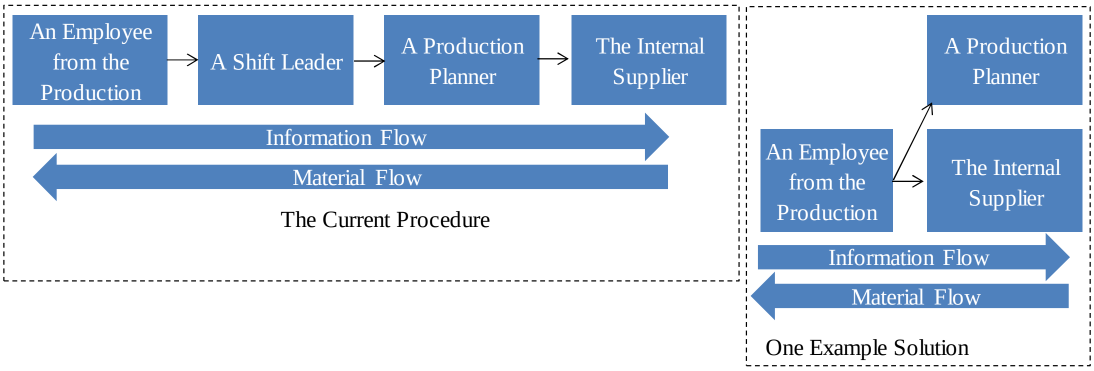


Figure 27 *The current procedures and the shorter communication channel between an employee from production, the production planner and the internal supplier*

Testing of raw materials should always happen before delivery. If something unusual is noticed in tests, it is not acceptable to deliver it to the case company. It takes more time to fix the problem, causes more shipping costs and delays delivery of replacement raw material, if it is noticed in the case company. Also, the mentality of “Let’s try a second raw material in another product rather than primary one” or “Let’s try if it works anyway” carry a risk that the raw material, which did not meet requirements, causes problems and costs more than the simple cost of a raw material bag would have been. An alternative but not so recommended method is to agree on products which are easy and possible to process with unplanned raw material (and that are possible to process with “secondary raw material”). This requires a risk assessment and estimating the extent of the problem at the internal supplier before shipping to the case company. The problem is that unusual raw materials usually have random reasons for as to why they do not meet with recommendations, so agreeing on products for every unusual property becomes difficult and there is a risk that products do not meet an external customer’s needs.

6.2 Inventory and Material Management

There are three things above all others; systematic (again), real-time and reliability. As previously mentioned Rules 1 and 3 serve as useful improvement platform (Spear & Bowen 1999). Because the devil is in the detail, all work has to be highly specified. Especially in the calculation of material consumption small details can have a huge effect. When responsibilities are well known, the outcome will be better because when something is everyone’s problem it becomes no one’s problem. (Spear & Bowen 1999.). Order and cleanliness of the second floor storage have been improved significantly after a dedicated responsible person was appointed.

6.2.1 Facilities

Current inventory system is somewhat insufficient. The biggest deficiency is in the inventory counting system with symptoms of missing raw material bags, high frequency of inventories and relatively big corrections. A universal product code (UPC) or a bar code with a visual control system could be one solution. It is fast, accurate, gives continuous information to managers, reduces the need for periodic reviews and gives simplified control. (Stevenson 2012, p. 560-561.) The system follows a strict protocol and a visual control which is shown in Appendix E. The use of the UPC system requires a few additions; scanners and small computers in forklifts, an additional program integrated to the ERP and the possibility of weighing a bag after an extrusion run. Overall, the raw materials have a simple and specified path which should not change unless the protocol is extremely redesigned (Spear & Bowen 1999).

The outdoor storage should be used only in the case of there not being space in the second floor storage. Regrind especially should be nearer to facilitate its usage. Shelves could help to store raw material bags in a more organized way because if they are in a large disorganized line, the first in - first out method (FIFO) does not work and raw materials stagnate. (Rosato et al. 2000, p. 562.)

Production has shifted to teamwork. This concept could be used to form better internal logistics because employees felt that the internal logistics coverage is sometimes inadequate. Employees who are good at getting products into shape and solving extrusion problems could focus on the runs and less skilled employees could operate the internal logistics. Because extrusion is vulnerable to external disorder, especially with difficult products and start-ups, the presence in the line is important. In these cases it would be helpful if packing and picking up packing materials could be done by an internal logistics person. For instance building pallets for foam PVC profiles takes labour hours that would be better used monitoring the process.

6.2.2 Calculation of Material Consumption

Calculation of actual material consumption needs a redesign. It should turn from manual to more automated due to continually reoccurring human errors and lack of accuracy. Small mistakes especially with foam PVC profiles made in the calculation of material consumption can during long runs cause errors in the balances due to changes in dimensions and/or density.

The solution for more reliable calculation of material consumption could be a measuring device connected to a feeding unit which calculates the amount of used material in kilograms. However, even if there was a measuring device which determines the total amount of used materials in kilograms, it is extremely important that information from a measuring device is written down at the end of a production run. This should be highlighted for employees because they have a huge responsibility in that. Also using discipline becomes topical for shift leaders. Overdue actual consumptions could improve in long production runs if the person responsible for materials, collects consumption from measuring devices once a day and compares it to what was planned. If actual quantity is much higher than planned (at that stage of the run), he/she could warn a production planner. Especially with foam PVC weighing metre weights does not lose its significance because it provides a good indicator about process performance.

6.3 Production Process

Recommendations for development areas in production process can be concentrated on two concepts; systematic organized approaches and good knowledge about the process. Rather than learning through trial and error, activities should be done more in accordance with the scientific methods (Spear & Bowen 1999). During observation it became clear that many times scrap, rush and problems could have been avoided if there had been clear and proven rules how to act. Due to the continuous nature of extrusion process, it should be operated very carefully to avoid unwanted surprises because extrusion problems can have huge financial impacts (Rauwendaal 2014, p. 763).

The extrusion production has been chosen as a pacemaker of the value stream because in the case company it is the major process where a product takes the final form to the customer (Rother & Harris 2008, p. 1-2). It is at the centre in developing recommendations and other support processes should be synchronized around it. However as noted, cooperation between production, R&D and maintenance will lead to better matches between new product and capabilities, reduced manufacturing costs, improved quality, shorter time to market and creates conditions for integrated knowledge-based approaches across these three functions (Olausson & Berggren 2012).

6.3.1 Extrusion of Established Products

Because the extrusion process in the hall starts with collecting work orders, product cards and samples, the input information should be reliable and up-to-date. Printing work orders and products cards with the latest information, when an extrusion run is about to start, is recommended. In this way also the risk could be eliminated, that product cards in the production hall would not be updated. Product cards should also have all the special information about what is needed to assemble a tool, set the line ready for production and use photos, if possible. Nothing should rely on supposition or talk, because it has been shown to be a source of errors.

Start-ups should have strictly controlled procedures. Set times for start-ups help to plan production and avoid situations where delivery dates are hard to achieve due to underestimated start-up times. Raw material should not be fed into the hopper until everything else is ready. These procedures were not sketched in this study, because rather than making rules from outside, they should be made by teams of employees because of their personal experience and ability to influence the rules (Laamanen 2002, p. 256.) After a specified pathway has been agreed on, it should not change (Spear & Bowen 1999).

Extrusion conditions should be tested and approved. If the range of the noted suitable conditions is wide, iterations may be required to find the best possible ones. Iteration process could be facilitated with the use of computers because they can monitor and save used temperatures (to the memory). In lines where integrated computers are not available, it is necessary to record all operating conditions on a pre-designed document until equilibrium is attained. Collected information can include: set point and extruder temperatures, melt pressure, melt temperature, extruder load, screw rpm, feed rates, dryer conditions, take-off speeds, take-off equipment temperature, pressure associated with take-off equipment, vacuum level, product quality and product dimensions. (Giles et al. 2005, p. 68.) Final data depends on the product.

It should be established if the rush in the production is real or is caused by bullwhip effect. Many times I heard that customers rush with the orders. Making transparent information routes across the supply chain and depending on the end customer's demand could help. This area was not included in scope of this master's thesis but did come to mind. However, reducing time pressure is important because it increases the risk for mistakes because careful actions are easily ignored. The problem with acting hastily is that new issues most likely occur, they increase the pressure again and the rat race starts again. Even if there is pressure, one should calm down and follow procedures to avoid undesired results because loss of control was observed, especially when there were a lot of orders for production.

If a problem occurs with an established product for one reason or another, making a written plan with a functional activity flowchart and clear responsibility areas could help to avoid grey areas, make the progress of the project easy to follow and speed up problem solving (Madison 2005, p. 23). It is important that all people who are responsible for a certain step of the project are specified and there are deadlines for all steps. Making a written plan and a chart can come across as laborious and slow, but proper documentation of the plan is a good opportunity to reduce the entire project's lead time when responsibilities are not left to float.

Analytical methods during troubleshooting are essential to avoid a guessing game at best. After employees have learned their own standardized work and know it thoroughly, troubleshooting with scientific methods and teaching people how to solve problems intelligently, is a way to create a learning organization. In the Appendices A, B and C there are some example tables that can be used as a structure as to how a problem could be solved. These tables are recommended to supplement employees' own notions. It is important that there is a pathway showing how troubleshooting is constantly done because any variations hide the link between the corrective action and the result. (Spear &

Bowen 1999.) With products that cannot be fixed during the same run, constructing a timeline could help with reducing delays in the next run, because it is easier to remember the last run and avoid making the same mistakes again (Rauwendaal 2014, p. 766). When identifying the potential cause and making corrective actions, following the Socrates fashion of iterative problem solving is one way to get employees to make changes to the extrusion process that are based on sense, not on guesswork (Spear & Bowen 1999).

6.3.2 Extrusion of New Products

The border between a new and an "established" product should be more dynamic and integration between production and R&D *somewhat* higher. This area produced different opinions during the interviews; partly it performed well but partly it needed fine-tuning. If a product passes the test runs well, but after turning it production ready, the "established product" signals problems, its priority should rise again, especially if its demand is expected to grow in the future. Extrusion problems are often so complex that solving them fast and efficiently requires input not only from production but also from R&D and maintenance. In cases where the problem is a raw material-related, input from the raw material producer is also needed. (Rauwendaal 2014, p. 765.) It is recommended to slow down and solve the problems correctly straight away, even if it required more resources, because the total amount of used resources will probably grow, if issue was left hanging (Liker 2006, p. 38).

In a process organization teams of employees should have the right to influence the issues that affect their work and according to Lean any improvements must be made at the lowest possible level in the organization (Nieminen 2007, p. 40). On the other hand, as mentioned many times before, they have a good knowledge of the reengineered environment, which can be valuable during improvement (Kurnik 2016). Involving employees more in test runs can have many advantages: they are more committed, transmission of important information about a new tool is more effective, they are more prepared for new tools and they might have useful information about manufacturability. Also, because in many interviews it was found out that too many times important parameters were missing before production, planning first production runs carefully together could reduce employee frustration and formed scrap. However, getting people to participate in test runs needs good leader skills. If an employee is afraid of new products, he/she should be encouraged but if it is all about the lack of motivation, discipline should also be used. A good time to delegate participants to test runs is the morning meetings when most of the people are together.

6.3.3 Quality Control

A prerequisite for quality control is a good knowledge of the product and customer specifications. New employees should have adequate training for quality control because extrusion is too expensive a process for guessing and learning through trial and error. The shift leaders carry the responsibility for this or one of the more experienced employees should be authorized (this must be agreed, not just assumed that someone will do it). You have to know your process and when employees change from a well-known line to an unfamiliar line, they need more support and guidance from shift leaders (Giles et al. 2005, p. 251). Without proper guidance about a product and what should be paid attention to, a packing person runs the risk of packing failed profiles.

Quality control has to be fool proof, unambiguous and there must be pass/fail answers to all questions. Working in a three-shift rota is a factor to be considered due to raised human error risk. Poka-Yoke is a useful way to prevent quality control indicating “pass” if it is in reality “fail” because of human error. Also, all products which have tight colour or gloss specifications should have measurable tolerances with pass/fail answers.

Team work helps in the quality control operations. Walking back and forth in the line is waste of time and hampers quality control. Also, when a problem occurs, according to Murphy’s Law, another problem occurs in another line. In these cases the team work shows its value. It helps to keep the extrusion process under control, if another person is at the other head of the line. The packing person can act as a sensor and visually measure the actual quality and standard. If she/he notices something unusual, a start-up-person is called to bring extrusion under control again. In the feeding head of the extruder, a start-up-person observes the melt flow and other equipment-related factors. Communication between these people intensifies continuous quality control but also requires good communication because “the left hand should know what the right hand is doing”. (Trade 1995, p. 8.)

6.3.4 Maintenance

Basic maintenance by following the set program exactly per line must be adopted as a weekly operation to avoid unexpected problems. If maintenance is done on Friday evening, it is easier for Sunday night’s shift to start runs. However, shift leaders are responsible that the program is being followed. They have to embrace the role of leader and the responsibility that the team performs all requisite tasks. The benefits of basic tool maintenance (cleaning) have also been shown in the practise.

When the line is empty for a long time someone from maintenance could be delegated to perform deeper maintenance like reading screw and barrel wears which have a significant effect on the output of the extruder (Steward 2015). Resources for deeper maintenance are also easier to allocate if simple weekly maintenance is done because then issues noticed (not critical or topical but considered for the future) could be written down. At the end of the research the frequency of planned repairs was increasing and it is positive to see this development.

6.4 Recycling

Recycling has to be organized and carried out in accordance with scientific methods (Spear & Bowen 1999). Ratios of regrind should be known and recycling should never compromise quality (Giles et al. 2005, p. 523). PVC especially is thermally sensitive material and its structure, mechanical properties and thermal properties may change during re-processing mostly due to ageing (Sadat-Shojai & Bakhshandeh 2010). To keep output consistent there should be the exact ratios of regrind which are always used when regrind is fed to the extruder. However, recycling within a factory has good prospects because many thermoplastics have a high potential to be mechanically recycled (Hopewell et al. 2009). At least small ratios could be processed without extrusion problems (Frankland 2013).

6.4.1 Facilities

Overall, the recycling facilities are a good starting point. There are many grinders available but they have the disadvantage that the noise in the production hall is high. The flow of rigid PVC scrap to regrind needs fine-tuning because there are many lines and employees, so the risk of confusion is real. Visual control is a good way to do it in practise. Figure 28 below shows one example solution. The target is to give a clear signal when scrap is available for recycling.

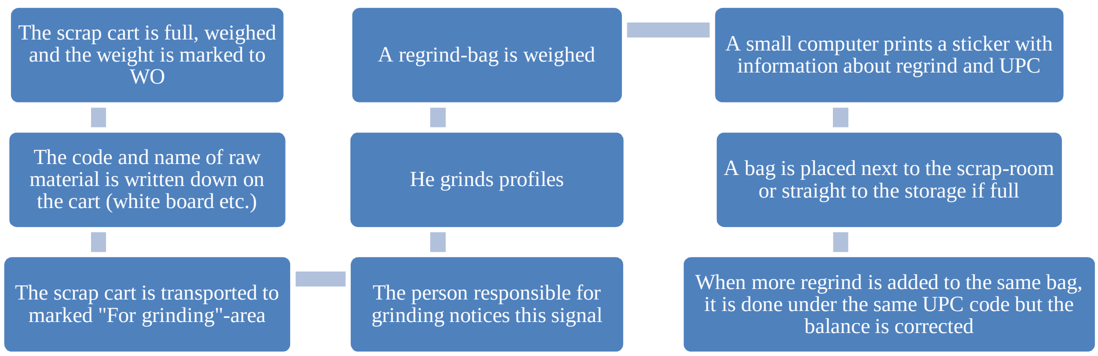


Figure 28 *An example solution regarding flow of rigid PVC profiles to regrind*

Marking the type of scrap raw material is important. It can be done for instance by checking the box on pre-printed paper or small white board in the cart, but anyway it is important that both name and code are marked down. “For grinding” area means a taped area which gives a signal to the grinder to pick-up a cart. It has to be near the grinding-room. After grinding, a small computer prints a sticker with UPC code and information about regrind; who was grinding, the date and the code of regrind and the name. It is important that most of the raw materials have the corresponding agreed G-codes. Only the letter in the beginning of the code should change if raw material is natural (no colour options) or already coloured. This forms a stronger and clearer link between the virgin raw material and the regrind. When printing a sticker, it is recommended that the ERP automatically adds regrind to balances, so that the production controller and the employees have real-time information. Without real-time information working and clever decision making inside a dynamic process becomes extremely difficult.

It is important that made regrind flows efficiently because it ties up capital like any other raw material (and even more). This is why placing it in the tent should only be done if there is no space in the second floor storage and this would make its usage easier.

Mainly there are enough grinders but if a solution for using coloured foam is found (this will be discussed later), then a grinder for them becomes topical. Also a small grinder for coloured PVC would help the work of the person responsible for grinding. This would also decrease the mental threshold to separate different colours because the biggest financial potential in PVC lies there and in the year 2014 over 15 000 kg of coloured PVC was unused. Recycling copper wires has also a huge financial potential because the difference between clean and unclean copper have double the difference in price. If manual recycling becomes too heavy for the employees, the acquisition of a machine should be considered.

6.4.2 Scrap and Made Regrind

Table 5 below shows two scenarios for reducing scrap percentage with data from 2015. Calculations are based on the data from the BI-program (from February-December).

Table 5 *Two scenarios for reducing scrap percentage, actual material scrap quantity [kg] and value [€]*

	Actual	**Scenario 1**	**Scenario 2**
Scrap %	10,02	7,50	5,00
Actual Scrap Quantity [kg]	159 397	119 309	79 539
Actual Material Scrap Value (Local Currency) [€]	288 677	216 076	144 050
Spared Material When Compared to Actual [kg]		40 088	79 857
Savings When Compared to Actual [€]		72 601	144 627
Actual - Material Usage Variance [kg]	33 441		

The actual scrap quantity and value is in column *Actual*. By using the same average kilo price (1.81 €/kg), it is easy to calculate what it would mean if scrap is reduced to level

7.50 % or 5.00 %. Reducing scrap percentage has a strong impact when it comes to reducing material costs. The total impact is even bigger, because when the quantity of scrap reduces, also landfill costs and the lost value due to sold regrind reduce. A 3rd Scenario can be built based on Scenario 2, where all formed scrap is used as a regrind in the company's own production;

- Value of regrind: 0,7 * 144 627 € = 100 835 €
- Lost value: 100 835 € - 144 627 € = -43 215 €

This model is very rough. Only the value of the material, not other costs, have been taken into account. But is a good indicator how big a positive change reducing scrap can cause.

Increasing the use of regrind has good premises because there usually is no need for washing or cleaning and there are no mobilization costs when comparing to post-consumer plastic waste. However, the purity of scrap is a demand (Hopewell et al. 2009). Long profiles should not be dragged on the floor. Profiles used with copper wire should be separated from other wires and not let to drop on the floor if the run breaks. It would be also interesting to study with a microscope if copper left behind so much metal contamination that it would prevent the use of scrap as regrind. With copper profiles fortunately the new video camera used for quality control informs fast if dimensions are not acceptable. Furthermore copper wire can be separated from the profile when trimming the extrusion run after a start or a problem.

With rigid PVC the only way to reduce mixed-colour waste is separating. Plasticized PVC unit should work as a role model. To prevent small bags being placed everywhere in the warehouse, the simplest solution is to use marked trash containers (with UPC). Colours that are difficult to use, but able to be dyed black, could be collected into their own container but the primary target is to use each colour separately (ensure that not all regrind is not collected to a mixed colour-container just because it is easy). This requires that all regrind placed in trash containers is high quality because otherwise all regrind in the trash container will be ruined. Because of the heat history of the materials is a major factor when determining recyclability and the quality of the regrind, profiles which are seemingly burned or defective should not be ground into regrind to ensure the highest quality. In addition to this, regrind should flow more efficiently so placing trash container inside would help that.

Re-granulating of regrind at the internal supplier is a topic that was not studied due to its large scope and the physical distance. It would help to reduce the range in bulk density and enable the addition of new stabilizers and lubricants. This is a large area to study and many things should be considered, for example how much re-processing really would cost and whether the benefits are big enough.

6.4.3 The Use of Regrind

A physical prerequisite for using regrind is the possibility to feed two materials. This should be available on every line. The second and the most important prerequisite is that the ratios of regrind are known and the use of regrind is as easy as the use of virgin raw materials singly. If using regrind is too complicated or causes problems during extrusion runs, most probably the employees will not use it and it is not profitable either if using regrind generates more scrap. The target is to make the use of regrind an automatic action during extrusion runs (if enough regrind is available), even using it in small ratios and getting the extrusion output more consistent because one must always ensure that the quality is as expected by the customer.

The range of materials and products is so large that finding best ratios of regrind and virgin material requires a project team with members from R&D (they have a deeper knowledge of the tools and materials), production officers (they know the boundary conditions of the production better) and most motivated and talented enough employees (practical experience). It is recommended that most of the activities are performed at the lowest possible level in the organization. The project team should exchange information with the sales to ensure that customer expectations are fulfilled. The project team’s internal customers are the employees from the production, so collecting feedback from them about processing and active information exchange with them is also essential. In view of product properties the customer is external.

The project would start with determining the materials with highest financial potential and where the study should start (see Figure 25). After that a sample functional activity flowchart and written targets would help to ensure that project progression is easy to follow and happens effectively enough. It is important that every activity is highly specified as to content, sequence, timing and outcome. Test runs should be planned for every week in the Visual Planning & Production Follow-Up program (also work orders about required materials should be done to avoid distorted material balances). It is recommended that test runs are done by an employee team member because it has a positive impact on the implementation of the regrind use and helps to achieve a learning organization where employees are able to solve problems themselves and improve their own work. (Spear & Bowen 1999.)

Test runs have to be based on scientific methods, include proper documentation and be under good control. Test runs should be short to limit the generation of scrap and start with low ratios of regrind. The impact on the properties should be studied properly (see Chapter 3.7.5 Common problems when using recycled plastic). The person performing the test runs has a reporting responsibility to the rest of the team. The project team analyses the results together and makes a decision whether the move to the next phase can be allowed. Here the studied regrind ratio could be tested in the product run to find out if it works in longer runs. The presence of at least one group representative is required. Also the results from the real product run should be documented and analysed.

After establishing a functional ratio to a certain product or material, the automation of the use of regrind starts. Everyone shall be made responsible for the use of regrind. (Mann 2010, p. 77.) One way of doing this, is to include the regrind (code, name and balance) to the work order under other required materials. If the balance of the regrind is bigger than required amount, there should be a clear pass mark (green box, a text: “Use regrind” or another visual signal). (Spear & Bowen 1999.) This is at the same time “a customer promise” that the regrind ratio marked to the work order is trouble-free. The shift leaders have the responsibility to monitor that the work order is being followed and on the other hand they should give support to employees in the beginning. The employees in the production are again “continuous sensors” and collecting feedback from them on pre-designed forms (online or paper form, see Appendix G) offer valuable information for improvement purposes (Trade 1995, p. 8).

At first, before the project team has got enough solutions, the best way to agree about the use of regrind is to decide together in weekly meetings, in which products regrind can be used (learned through practise). The person responsible, who writes down the use of regrind in work orders, has updated balances of each regrind type. The use of regrind has to be actively pursued and encouraged. And again, there have to be written ratios of regrind, which are always followed to ensure a uniform output from the extrusion process. (Spear & Bowen 1999.) This is sometimes done but should be done more often.

With special products that cannot be used again because of tight property specifications (like a charging hose) should get a very high priority during a run to limit formation of scrap. High frequency of quality controls and using more human resources are some things that can be done. Also finding secondary products for regrind could be done to reduce scrap. Plaster made of biodegradable plastic and wood chips are examples of these products.

Coloured foams which usually go to visible places and must have a good appearance, are more difficult to use as regrind than other plastics. This is also a tool- and line-related issue. One solution to this is to design a product with a core of regrind and a surface layer of virgin material because plastics usually have an excellent chemical adhesion to the same type of plastic. This offers a good looking surface but cheaper bulk price. In this area cooperation between sales, R&D and production is topical. Sales are responsible for identifying the customers’ desires and openness to receiving products made in this way. (Slack et al. 2001, p. 18.) On the other hand, green values are becoming more and more substantive and recycling part of the value proposition (Wills 2009, p. xvi).

The use of regrind should become more visible. Visual control (for instance charts, statistics on info TVs) are a good way to connect employees to processes around scrap formation and use of regrind. This shall be done in terms of both kilo and euro because using kilos only is misleading. The further the responsibility of reducing scrap and using regrind can be appointed, the better (for instance at the line level). Reviewing the biggest scrap sources, root causes and corrective actions in weekly meetings is great, but the disadvantage is that no employees are taking part in weekly meetings. If this was done in a meeting with employees, the impact would be greater because then no one can hide from the truth. It could make people take more responsibility when they face the results of the work directly. Changing the employees' set of values takes a long time, but is worth it because values are the biggest factor affecting human behaviour (Elo-Pärssinen 2007, p. 47). The role of reward systems in motivating people is indistinct, but building a reward system that encourages employees to perform desired activities may underpin the operations and long term strategy (Laamanen 2002, p. 140).

6.5 Information Flows

The daily information flood is huge so separating relevant issues from irrelevant is topical also when it comes to reducing scrap. If the right information is not available in the right place at the right time, mistakes or problems are probable. Transparency and availability are two key factors. One boundary condition is that not all employees work at daytime when most of the decisions by managers are made. Other boundary conditions are the physical distance between the production level and other floors and distance between the internal supplier and the case company because these limit daily casual communication.

When the amount of information increases, the risk that something will be forgotten grows. Especially shift leaders are in a critical role because they are the major messengers to the production floor about the decisions made in upper floors. At the same time they have probably the most things to remember. As mentioned in few sections already, in bigger projects making a functional activity flowchart where responsibilities about activities are recorded could help to avoid grey areas. In the everyday communication within production the use software where agreed tasks (for a certain person) are written down and after performing signed off, could help to avoid forgetting or misunderstanding. The employees themselves usually come up with the best solutions and the only requirements are that there is visual control that visualizes important decisions and show when an activity should be done, how, by whom and enable managers to focus on relevant things when it comes to discipline (Mann 2010, p. 53-74).

According Lean-philosophy information should move upstream and this should also be considered when planning vertical information routes. Routine and simple information can be collected from downstream with the help of forms but more complex information requires bringing an employee from downstream to upstream to participate in a redesign project (new products, necessary product changes, other new projects etc.). (Madison 2005, p. 264-265.) This does not mean that all employees from the production should take part in meetings, but one suitable employee for each project would create a feeling about being important. When rules and decisions about daily production issues are made together, it is harder for employees to target their frustration at supervisors because they have an opportunity to influence. On the other hand, when problems are solved at the lowest possible level, this could lead to a learning organization which does not all the time need controlling from outside because people are able to make intelligent decisions by themselves (Spear & Bowen 1999).

Horizontal information moves well in the organization but information exchange between shifts needs strengthening. Getting monetary compensation for the 15 minutes shift exchange would probably increase presence. Using for example a bonus which is paid for employee presence during shift changes, could be one solution but asking the employees themselves what they consider to be motivating is more recommended. The main thing is that they feel it is fair and encouraging.

A good knowledge of the customers and the products would create good basis for producing higher value to them and increase commitment. When people realize that the customers are paying their salaries, not the bosses, they too want to produce high quality products which meet the customer specifications. (Hammer & Champy 1993, p. 73-73.) Sales people often visit the customers and bringing shift leaders sometimes along to meet with the customer, would be one way of increasing knowledge about the customer. Improving your own operations is not the only benefit because at same time you show that the customer is important to you and you want to give the best possible value to him/her. This might deepen the customer relationship and increase the relative customer satisfaction.

6.6 Daily Managing and People

Due to the manual nature of the current extrusion process, involving, motivating and committing employees is extremely important. They are the operators of the process and the performance of extrusion is largely dependent on their capabilities. They are also familiar with the previous processes; information management (work orders, product cards), R&D (they design products and ensure that all required parameters are available in production) and raw material production (produced material should fulfil the case company's extrusion process needs) so listening to their feedback should be part of the development activities. (Trade 1995, p. 8.)

Discipline and motivation are two important issues when it comes to the daily floor level management. The former needs some strengthening because the leader's task is to ensure that every important task in the production will be completed and the work is divided equally (Laamanen 2002, p. 119-120). Visible controls (for instance made scrap per line-charts) makes focusing on discipline easier so this area has a good basis to develop (Mann 2010, p. 53-74). Motivation is one major factor in addition to competence when it comes to achieving high performance (Lawrence 2014). Motivating was considered to be sufficient and I observed the same. The only area where this could be done better is justifying as to why an employee's idea was not implemented. By showing empathy, negative feelings about being ignored, could be possibly avoided. Negative memories can stay in mind for a long time, affect to the attitude and also the actions.

Training and improving competence is a major factor when reducing scrap in extrusion because a good knowledge of the materials and equipment are a prerequisite to successful product runs (Giles 2005, p. 251). Also because, after all, every extrusion machine is unique having practical experience in the production is at least as important as theoretical knowledge. Temporary employees are a good way to increase the flexibility of production capability but they have also limitations due to the lack of practical experience of the process. Getting the good employees to commit is more recommended because even if their capability was partly unused, they can produce higher value with bigger output.

Currently many things in the production are still learned through the method of trial and even though this is not the most recommended way to learn because sometimes lot of scrap is formed a good analysis was almost always done after a problem had occurred. It is positive, that the leaders actively investigate the root cause and put actions in place to prevent the same thing from happening again. The company delivered also good training. When teams were built, many courses for employees were held. This was a positive discovery. In the end of the research also training on measuring colour was organized after there had been difficulties with certain products.

Due to the fact that there were very talented employees in production, whose labour input was high and valuable, the talent management comes topical. The desired skills and properties have to be tied to the closed-loop strategy in order to allow it to be effective (Lumme-Tuomala 2015). Giving the employees the possibility to grow and advance in their career is important in order to keep them satisfied and as part of the organization. In relation to the closed-loop system they can be role models to other employees.

The goal is that everyone working in the extrusion process becomes talented enough to be able to solve problems themselves and improve their own working environment (Spear and Bowen 1999). It is great that there is for instance one extrusion trimming person above the others, but this also makes the organization vulnerable. What happens if this person is not able /does not want to work anymore? Already now, when there are many difficult product-runs starting at the same time which can only be assembled and started by the most talented trimmer, product changes are delayed because not all runs can start at the same time. Decentralizing talent and keeping the most talented satisfied could be a good solution. The easiest solution is to hire very talented people but because practical experience in the process is always needed, another solution is to find few apprentices to work with talented employees.

The reward systems have been mentioned a few times before, but overall if possible, they could turn even more from time-based to value-based. This is already partly true in the case company. People who create more value than expected could earn some extra and on the other hand people who do not want to give their best and who create less value than expected could get the basic salary. This would turn the organization's value system from protective to productive. (Hammer & Champy 1993, p. 73.)

6.7 Summary of Results

When improving an organization and its physical flows towards a closed-loop system, in this case the plastic material flow, a few things are more important than others: thorough knowledge of internal core processes through which materials flow, and support processes that maintain that flow. According to Figure 26 the results are classified into three categories: factors that eliminate the formation of scrap, factors that facilitate the use of regrind and other issues that facilitate the closed-loop system. The results are collected in Table 6. All recommended issues are based on making the process highly specified, making the connections within the process direct and fast and following scientific methods. This was done because extrusion has so many variables that without systematic and organised operations it is impossible to achieve a closed-loop system.

Table 6 *Research results: things that eliminate scrap, things that facilitate the use of regrind and issues that facilitate the closed-loop system*

Area	**Things That Eliminate scrap**	**Things That Facilitate the Use of Regrind**	**Things That Facilitate the Closed-Loop System**
Raw material purchase	Improving raw materials together in cooperation	Recyclable raw materials	Better integration: cooperation with difficult products, direct and standardized communication channels, collecting feedback from employees
Inventory and Material Management	Reliable and real-time calculation of material consumption, real-time inventory management		
Extrusion of Established products	Controlled start-ups, systematic and always followed extrusion conditions, iterating towards better ones, systematic and analytical troubleshooting		Up-to-date and unambiguous input information about extrusion conditions, fast and effective decision making, cooperation with R&D
Extrusion of New Products	Determining all parameters before extrusion runs (test runs are more controlled)		Involving employees in projects and test runs, in depth interaction between production officers, employees and R&D
Quality Control	Unambiguous specifications and clear Pass/Fail answers, measurable tolerances for colour, appearance and gloss (if important)		
Maintenance	Following basic maintenance program		
Scrap and Made Regrind		Separating different colours and plastic types	
The Use of Regrind	Ratios found by following scientific methods	Automated use, “new profile X”, product with a regrind core	A project team, making the use of regrind more visible also in the production, understanding of employees that using regrind is valuable
Information Flows	Better vertical and between shifts information sharing		Information should move more to upstream
Managing & People	Discipline, better theoretical knowledge	Involving, motivating	Creating learning organization

The first improvement issue is to eliminate all factors that cause scrap. It has also the most significant financial effect and decreasing the scrap-percentage to 7.50 % from the current 10.06 %, means already over 70 000 € savings in material costs. When taking high waste taxes, poor returns from sold regrind and other direct and indirect costs to transform scrap to regrind (labour hours, energy, storage etc.) into account, it is clear that financial savings can be huge. Re-use of regrind can be difficult due to changes in MFI, different bulk-density than with pellets or powder and changes in mechanical properties. However, most thermoplastics can be recycled and used at least with low ratios. The use of regrind should be studied by following scientific methods to avoid extrusion problems and scrap caused by disorganized use. It also has to become more automated and the used ratios are recommended to be always the same. It is better to use regrind even with 5 % than not at all. Here also the role of employees is highlighted. It is possible to achieve a closed-loop system, but it takes effort from all departments. Everybody should share the same visible goal - reduce waste, increase the use of re-grind.

7. CONCLUSION

Recycling within the company is a potential way to affect material costs, especially in the extrusion process where material costs can cover half of the total product costs. At the same time changes in the legislative environment affect enterprise dramatically due to tightened enactments related to organic landfill waste. In this situation there are two options; acknowledge the changes and continue operations as before and pay a higher price for waste or turn changes into competitiveness. A closed-loop system is an outstanding solution to respond to changes in the external environment. It improves the internal use of resources, optimizes cost structures, exploits green values and helps to give higher value to customers. It is a strategy which requires a long-term commitment and participation from the entire organization. Before starting, a thorough knowledge of the value chain is required. Every material and information flow has to be sorted out from an overall level to a detailed level. Because the aim is to reduce waste-output and return formed scrap-output back to valuable input, also the concept of processes becomes topical. Without having a knowledge or control about own core and support processes improving comes impossible.

7.1 Research Process

The aim of the research was to find partly hidden and indirect sources of scrap, things that affect the use of regrind and plan new approaches that enable the improvement of the extrusion process towards a closed-loop system. All approaches should follow Lean-philosophy because it has already been introduced in the case company a few years ago. It also has a strong connection to the process-orientated nature of the extrusion and the closed-loop system. The research was mostly qualitative because the quantitative information was too limited.

In the beginning of the research the knowledge of internal operations, value chain or anything that affects the formation of scrap or the use of regrind were unknown to the researcher. This is why the research problems had to be solved step by step. At first the overall picture of the company and the main operations was gained through participant and non-participant observation, work in the production and finding numerical input and output of the extrusion process (in September). When working in the production the goal was to look at the process from “inside” with an employee’s eyes. According to Lean-philosophy information should move upstream so this method followed Lean principles. The numerical input and output data from the ERP and BI-reports gave information about the efficiency of the process, made waste, made regrind and used regrind. It told about the extent of the research problem. Observations continued during the research and were documented in a note book and some photographs were also taken. The BI- and ERP-programs were used to follow made and used regrind, scrap per item and scrap per tool figures. This information was documented in Excel files and if something unusual was noted, it was noted, solved, analysed and documented in the note book.

After establishing a rough picture about the research environment, the interviews started (from October to the beginning of November) in order to discover areas where attention should be paid to. The chosen interview method was theme interview because it was not always clear what forms scrap and affects the use of regrind. Interviews were recorded (bar one), transcribed and analysed. The preliminary topics in Chapter 5 are the result of the interviews. A visit to the internal supplier also took place in October. The results were analysed with the help of the literature and comparisons to the own observations (in November). The topics about the current state were established after the discovered development areas were accepted in the Executive Committee meeting in the middle of December. After that the search for solutions and recommendations started as to how the closed-loop state could be achieved (Chapter 6 in December and January). This was done by comparing all the collected information to the literature about processes, Lean-philosophy and extrusion. Ideally, at some future stage, no landfill or combustible plastic waste is formed, all scrap (no more than planned) is transformed to regrind and all regrind is used efficiently and fast. All operations would be controlled, communication channels would be direct and improvements would be done according to scientific methods.

Literature was used from the beginning until the end of the research. With the help of literature it was found out what a closed-loop system requires, what successful extrusion with low scrap level requires and how plastic can be recycled inside the factory. Re-use of regrind was studied only with the help of literature and previous studies. Literature about extrusion was important because the aim is to assemble a closed-loop system in the case process. Operating with low scrap level requires also thorough knowledge of extrusion equipment, materials and their relationship to each other.

7.2 Research Results

It was found out that the extrusion process is challenging due to its continuous nature, many variables and susceptibility to equipment or material related problems. Successful operations require highly specified methods and in order to keep high quality output consistent, the extrusion conditions should be studied by following scientific methods in every run (before better methods have been discovered). Restricting the formation of scrap in the process requires that all sources of extrusion problems and undesired variables have been discovered. Determining the optimal situation does not limit to equipment and material related suggestions. Due to the manual nature of the extrusion process its performance is largely dependent on the performance of the operators. This makes systematic methods primary when trying to achieve successful extrusion operations and a closed-loop system.

In addition to the primary target, reducing scrap by keeping the process under control, the secondary target was to increase the share of recycled plastic. It was found out that pre-consumer plastic waste has good properties for a mechanical recycling due to its high purity and non-existent mobilization and separation costs. Most thermoplastics have a high potential to be mechanically recycled and at least, when used in low ratios, extrusion problems can be mostly avoided. But, as when processing virgin materials, also the use of regrind has to be highly scripted, systematic and studied under control. In addition to the study of processing conditions, studies about the impact on properties are recommended due to the re-processing impact on rheological, morphological, thermal and mechanical properties. The most common problems, when using recycled plastics, are formation of micro cracks, changes in colour, surface defects, changes in MFI, widening of the molecular weight ratio, ageing which leads to weight reduction and brittle behaviour. The recommended ratio of regrind depends on the desired properties.

The research covered raw material purchase, inventory and material management, extrusion production process, recycling inside the factory, information flows and daily management and people. The main observed problem was that there were not enough systematic and organized approaches. Also documentation, control of the process and iterating towards optimal extrusion conditions need fine-tuning. Without proper documentation, process improvements become impossible. Grey areas, firefighting and other symptoms of broken processes showed that the process needs improving before it is possible to achieve a closed-loop system.

It was found out that due to a raw material is input to extrusion process, it has to be integrated to the process and a closed-loop strategy. Inventory and material management ensure that all required materials (input) are available when they are needed because without them the process will not run or it will break between the runs (new start-up and trimming scrap). Information flows are also in a major role because without the right information in the right place and at the right time, the desired product with high quality and planned features cannot be produced (products out of specifications are classified as scrap). The Lean-strategy was considered to be a valuable theory when observing the current process and outlining recommendations, because it has the same goal with the closed-loop system (eliminating waste and maintaining flow), it has a process-orientated nature and the Group had already implemented it a few years ago (recommendations have to comply with Lean-strategy).

The given recommendations for each area focus on how to reduce factors that act as a source of scrap and on the other hand, what approaches are required for turning scrap into high quality regrind and using it as effectively as possible. Recommendations (Appendix H) are classified into categories mainly based on processes and also responsibilities of each process are named. Still, a closed-loop system is not a project that covers just a part of the organization. It requires abandoning the traditional task-orientated functional organization (because none of the functions can themselves achieve organizational goals) and integration and cooperation of the whole organization.

The research about functional regrind ratios in each product is a large area to study. This is recommended also to be a starting point for the future developments. Forming a project team and cooperation between production officers, employees and R&D is suggested in order to achieve scientific results that work in practise. Here, as in every other development area, collecting feedback from the employees is important. The product improvement and changes should be done at the lowest possible level. However, leaders have the responsibility to implement control methods and approaches.

Overall, I see a lot work ahead but also a huge potential because of eagerness to develop and an open-minded atmosphere. Admitting that you have your own development areas is the first step on the way towards the perfection.

7.3 Discussion of the Results

Due to the mostly qualitative nature of the research, *the reliability* depends strongly on the objectivity of the researcher and the ability to filter emotions, attitudes and values out of the interviews. An attempt was made to do the research objectively and without taking anyone’s side but already the place for writing in the officers’ room led to a situation where I was more in their environment than at the production floor level. That also affects the reliability of the results. There is also a risk of having forgotten to note some significant issues in the interviews that would have been important to take into account. It can also affect the reliability of research if something has been given too much importance and something else has been overlooked.

Stability of the research is poor. Every day is different in the production and extrusion runs differ from each other a lot, which makes it difficult to find the optimal conditions. Product changes are normal, raw materials may change and customers may change their specifications. In a subcontracting environment this is normal but if the research would be done a year later, the results would be different. It is also impossible to forecast if there are some important things in the future (difficult products, material changes etc.) that should be taken into account. For this reason the results should be implemented with consideration of possible changes in the environment. Results may be also being short-lived. However, some rules, like the four Lean-rules by Spear and Bowen, are applicable to many environments.

Consistency depends strongly on who we ask about the research problem. Different departments may see the problem about scrap and regrind very differently. Because of this the interviews were completed with more than one party. Analysing observations, such as the discussions, was a balancing act but there is a risk that some party have got too much attention during the analysis. In order to be consistent it should be considered that measuring scrap or used regrind per line is not a fair method because engineering plastics are much more difficult to produce than some other lines. Also the amount of start-ups and lengths of extrusion runs strongly affect the amount of formed scrap. This is why the amount of formed scrap should be done per set line and be compared to its previous state, not to the numbers of other lines.

Validity depends largely on the theme interviews. The theme interviews pointed out topics what to pay attention to and also provided topics for Chapter 5 and 6. It can be concluded that the validity of the research was good because when the factors that cause scrap or affect the use of regrind were presented in the Executive Committee meeting, they accepted them. They also revealed that some of the issues were noticed before but the research highlighted their importance. Theme interviews were not highly structured which affected the validity in a positive way. People were also able to say things that were not included in the direct questions.

The *reliability of the literature* was somewhat affected by narrow extent of publications about recycling inside companies. It was also difficult to find literature about a closed-loop system in the enterprise field. Many more studies were done about environmental issues, sustainable development and post-consumer waste. Previous studies show partly opposite results about changes in plastics during recycling and re-processing. Used plastic raw materials also differ from each other a lot which affects the applicability and reliability when talking about raw materials in the case company. It is recommended to do tests on each plastic raw material to be sure about changes in a certain material type. Also exact regrind ratios are not directly available in the literature and should be tested.

Possible *sources of errors in quantitative areas* come from human error and limited available data from the BI-program and ERP. That is the reason why some calculations are based on data from the year 2014 and some on data from the year 2015. The outlined scenarios are very rough, only directive and should be treated with caution.

The research did not cover all the issues that I would have liked to. During it many unexpected things arose which would have needed more study. These include the possibility of making products with a regrind core and a virgin material surface, re-compounding at the internal supplier and solving exact regrind ratios for each of the main products. These should be studied further in the future because especially products with a regrind core but a virgin material surface could have a huge financial potential. Solving exact regrind ratios is an extremely important area of study and should start immediately in addition to eliminating factors. However, the research time was relatively short for getting deeper into these topics and they are only mentioned as interesting areas for study in the future.

REFERENCES

Abbas-Abadi, M. S., Haghighi, M. N. & Yeganeh, H. (2012). Effect of the Melt Flow Index and Melt Flow Rate on the Thermal Degradation Kinetics of Commercial Polyolefins, Journal of Applied Polymer Science, Vol. 126, pp. 1739–1745.

Baumeister, R. F., Bratslavsky, E., Finkenauer, C. & Vohns, C. (2001). Bad is Stronger than Good, Review of General Psychology, Vol. 5, No. 4, pp. 323-370.

Brown, K. A., Holland, M. R., Boyd, R. A., Thresh, S., Jones, H. & Ogilvie, S. M. (2000). Economic Evaluation of PVC Waste Management, A Report Produced for European Commission Environment Directorate, AEA Technology, 193 p.

Burton, T. T. & Boeder, S. M. (2003). The Lean Extended Enterprise - Moving Beyond the Four Walls to Value Stream Excellence, J. Ross Publishing, Co-Published with APICS, Florida, United States, 296 pp.

Chanda, M. & Roy S. K. (1998). Plastics Technology Handbook, Third edition, CRC Press, Taylor & Francis Group, Sweden, 1195 pp.

Elearn: Elearn Training Company. (2005). Quality and Operations Management: Management Extra, Pergamon Flexible Learning, 96 pp.

Elo-Pärssinen, K. (2007). Arvot ja yhteiskuntavastuullinen toiminta suurissa suomalaisissa perheyrityksissä, Doctoral dissertation, University of Jyväskylä, Faculty Economics, 188 pp.

Frankland, J. (2013). Regrind and Melt Pumps, Plastics Technology, No. 11. Available (referred 22.1.2016): http://www.ptonline.com/columns/regrind-and-melt-pumps.

Frankland, J. (2011). Extrusion: Start Up and Shut Down Properly, Plastics Technology, No. 1. Available (referred 1.1.2016): http://www.ptonline.com/columns/start-up-and-shut-down-properly.

Giles, H.F., Wagner, J.R. & Mount, E.M. (2005). Extrusion - The Definitive Processing Guide and Handbook, William Andrew Inc., Norwich, USA, 542 pp.

Valtioneuvoston asetus kaatopaikoista. (2013). 331/2013, 2.5.2013. Available (referred 2.12.2015): http://www.finlex.fi/fi/laki/alkup/2013/20130331#Pidp4387744.

Gray, J.L. & Starke, F.A. (1984). Organizational Behaviour: Concepts and Applications, third edition, Charles E. Merrill Publishing Company, Columbus, United States of America, 732 pp.

Hammer, M. & Champy, J. (1993). Reengineering the Corporation: A Manifesto for Business Revolution, Nicholas Brealey Publishing, London, 231 pp.

Hanhi, K., Mansikkamäki, P., Haukijärvi, M., Tervala, O., Lindgren, T., Järvelä, P. & Ihalainen, P. (1999). Fundamentals of Elastomers - Module 6, European Tyre School, HTML-based lecture material. Available (referred 27.12.2015): https://www.tut.fi/ms/muo/tyreschool/moduulit/moduuli_6/hypertext/3/3_2.html.

Hayes, R. H. (2002). Challenges Posed to Operations Management by the New Economy, Product and Operations Management, Vol. 11, No. 1, pp. 21-32.

Heikkilä, J. & Ketokivi, M. (2005). Tuotanto murroksessa – Startegisen johtamisen uusi haaste, Talentum Media Oy, Helsinki, 272 pp.

Hiltunen, L. (2009). Validiteetti ja reliabiliteetti, Jyväskylän yliopisto, 13 s. Available (referred 6.10.2015): http://www.mit.jyu.fi/ope/kurssit/Graduryhma/PDFt/validius_ja_reliabiliteetti.pdf.

Hirsjärvi, S., Remes, P. & Sajavaara, P. (1997). Tutki ja kirjoita, Tammer-Paino Oy, Tampere, 432 s.

Hopewell, J., Dvorak, R. & Kosior, E. (2009). Plastic Recycling: Challenges and Oppurtunities, Philosophical Transactions of the Royal Society, Vol. 364, Issue 1526, pp. 2115-2126.

Hunt, V.D. (1996). Process Mapping: How to Reengineering Your Business Processes, John Wiley & Sons, 272 pp.

Hutter, L., Capozucca, P. & Nayyar, S. (2010). A roadmap for Sustainable Consumption, Deloitte Review, Issue 7, pp. 45-59. Available (referred 31.12.2015): http://dupress.com/articles/a-roadmap-for-sustainable-consumption/.

Kartalis, C. N., Papaspyrides, C. D. & Pfaendner. (2002). Closed-Loop Recycling of Postused PP-Filled Garden Chairs Using the Restabilization Technique. Part 2: Material Performance during Accelerated Heat Aging, Journal of Applied Polymer Science, Vol. 88, pp. 3033-3044.

Kurnik, R. (2016). Process Improvement Teams Power Six Sigma Success, SixSigma. Available (referred 22.2.2016): http://www.isixsigma.com/implementation/teams/process-improvement-teams-power-six-sigma-success/.

Laamanen, K. (2002). Johda liiketoimintaa prosessien verkkona, 2. painos, Suomen Laatukeskus Oy, Helsinki, 300 s.

Lappalainen, E. (2015). Johtajasilakka opettaa parvea, Talouselämä, No. 33, pp. 30-34.

Lawrence, M. (2014). The Lean System of Motivation, Industry Week: Advancing the Business of Manufacturign. Available (referred 29.12.2015): http://www.industryweek.com/lean-six-sigma/lean-system-motivation.

Liker, J. K. (2006). Toyotan tapaan, Readme.fi, Helsinki, Finland, 323 pp.

Lumme-Tuomala, R. (2015). Talent Management - pelkkää sanahelinääkö?, Talouselämä, No. 34, pp. 61-62.

Madison, D. (2005). Process Mapping, Process Improvement and Process Management, Paton Press LLC, Chico, United States of America, 313 p.

Mann, D. (2010). Creating a Lean Culture: Tools to Sustain Lean Conversions, Second Edition, Taylor and Francis Group, LLC, New York, the United States of America, 269 pp.

Martinsuo, M. & Blomqvist, M. (2010). Prosessien mallintaminen osana toiminnan kehittämistä, Tampereen teknillinen yliopisto, Teknis-taloudellinen tiedekunta, Opetusmoniste 2. Available (referred 13.11.2015): https://dspace.cc.tut.fi/dpub/bitstream/handle/123456789/6825/prosessien_mallintaminen.pdf?sequence=1.

Meskanen, A & Järvelä, P. (2000). Muovien kierrätys ruiskuvaluyrityksessä, Tampere University of Technology, Department of Material Science, 32 s.

Modig, N. & Åhlström, P. (2013). Tätä on Lean: Ratkaisu tehokkuusparadoksiin, Rheologica AB, Stocksund, Sweden, 167 s.

Peltonen, A. (1998). Tuottava tehdas, Syventävä WWW-materiaali, Opetushallitus. Available (referred 6.10.2015): http://www03.edu.fi/oppimateriaalit/tuottavatehdas/index.html.

Poropudas, M. (2011). Polyvinyylikloridin (PVC) kierrätys ja uusiokäyttö, Master’s Thesis, Tampere University of Technology, Department of Material Science, 90 pp.

Rauwendaal, C. (2014). Polymer extrusion, Fifth edition, Hanser Publications, Cincinniti, Ohio, The United States of America, 934 pp.

Rauwendaal, C. (2010). Tips and Techniques: Boosting Extrusion Productivity - Part III of III: Trim Your Material & Energy Costs, Plastic Technology, Issue 11. Available (referred 1.1.2016): http://www.ptonline.com/articles/tips-and-techniques-boosting-extrusion-productivitypart-iii-of-iii-trim-your-material-energy-costs.

Rosato, D. V., Rosato, D. V. & Rosato, M. G. (2000). Injection Moulding Handbook, Springer Science & Business Media, Berlin, Germany, 1457 pp.

Rother, M. & Harris, R. (2008). Creating Continuous Flow an Action Guide for Managers, Engineers & Production Associates, Cambridge, Lean, Enterprise Institute, 104 p.

Rummler, G.A. & Brache, A.P. (2012). Improving Performance: How to Management the White Space on the Organization Chart, Jossey Bass, 288 pp.

Sadat-Shojai, M. & Bakhshandeh, G-H. (2010). Recycling of PVC wastes, Polymer Degradation and Stability, No. 96, pp. 404-415.

Slack, N., Chambers, S. & Johnston, R. (2001). Operations Management, Third Edition, Financial Times, Prentice Hall, Pearson Education, Essex, England, 765 pp.

Sombatsompop, N. & Thongsang, S. (2001). Rheology, Morphology and Mechanical and Thermal Properties of Recycled PVC Pipes, Journal of Applied Polymer Science, Vol. 82, pp. 2478-2486.

Spear, S. & Bowen, H.K. (1999). Decoding the DNA of the Toyota Production System, Harvard Business Review, No. September – October, p. 97-106.

Stevenson, W.J. (2012). Operations Management: Theory and Practice, Global Edition, Eleventh Edition, McGraw-Hill Irwin, United Kingdom, 878 pp.

Steward, E. (2015). The Effects of Screw and Barrel Wear on Extruder Performance, American Kuhne. Available (referred 27.1.2016): http://www.americankuhne.com/newstechtip/50-the-effects-of-screw-and-barrel-wear-on-extruder-performance.

Subramanian, M. N. (2011). Basics of Troubleshooting in Plastics Processing: An Introductory Practical Guide, Wiley-Scrivener, 242 pp.

Suomen Lääkäriliitto. (2005). Suomen Lääkäriliiton suositus: Yötyön ja pitkien työrupeamien aiheuttamien haittojen ehkäisty. 12 pp. Available (referred 25.12.2015): https://www.laakariliitto.fi/site/assets/files/2707/yotyo_opas.pdf.

Syrjälä, S. (2013). Polymeerien reologia, Lecture Slides, MOL-42060 Polymeerien reologia, Tampere University of Technology.

Tague, N. R. (2005). The Quality Toolbox, Second Edition, ASQ Quality Press, 584 pp.

The European Council of Vinyl Manufacturers. PVC-recycling technologies. Available (referred 7.1.2016): http://www.pvc.org/en/p/pvc-recycling-technologies.

Trade - Training Resources and Data Exchange, Performance-Based Management Special Interest Group. (1995). How to Measure Performance A Handbook of Techniques and Tools, Special Project Group, Assistant Secretary for Defence Programs, Office of Operating Experience, Analysis and Feedback Assistant Secretary for Environment, Safety and Health, U.S. Department of Energy, Handbook, 186 p. Available (referred 10.11.2015): http://www.orau.gov/pbm/handbook/handbook_all.pdf.

VinylPlus. (2015). Sustainable & Recyclable. Available (referred 28.12.2015): http://www.vinylplus.eu/recycling/a-smart-material/sustainable-recyclable.

Wills, B. (2009). Green Intentions: Creating a Green Value Stream to Compete and Win, Taylor & Francis Group, New York, the United States of America, 274 pp.

Xinyu, L. & Jian, L. (2009). Research on the Integration of the Methods of Enterprise Value Stream and Material Flow - Based on the Theory of Lean Production and Circular Economy, Industrial Engineering and Engineering Management IE&EM '09, 16th International Conference, Beijing, China, October 21-23 (09), pp. 243 - 247.

Yamagar, A. C. & Ravanan, P. M. (2010). Material Management by Using Lean Principles a Case Study, Proceedings of the 2nd International Conference on Manufacturing Engineering, Quality and Production Systems, pp. 104 - 112. Available (referred 26.12.2015): http://www.wseas.us/e-library/conferences/2010/Constantza/MEQAPS/MEQAPS-19.pdf .

APPENDIX A: POTENTIAL CAUSES AND CORRECTIVE ACTIONS TO COMMON MECHANICAL EXTRUSION PROBLEMS ACCORDING TO GILES ET AL. (2005)

Appendix A Table 1 *Potential causes and corrective actions to common mechanical extrusion problems (Giles et al. 2005, p.251-263)*

Mechanical extrusion problem	**Potential cause**	**Corrective action**
1. Extruder screw does not turn	Motor field voltage turned off	Check breakers
	Barrel temperatures too cold	Check temperatures and raise if necessary
	Gear box oil pump not on	Turn on
	Water cooling to gear box off	Turn on
	Foreign material in the feed throat	Clean feed throat
	Torque coupler in twin screw extruder disengaged	Reengage torque coupler and turn extruder screw on
	Extruder exceeds load limit	Reengage torque coupler
		Reset circuit breakers
2. DC Motor will not start	Low armature voltage	Check nameplate on motor to ensure proper motor voltage
	Weak field	Check for resistance in armature circuit
	Open circuit in armature field	Check for open circuit
	Worn brushes	Replace brushes
3. Drive train problems	Belt slippage	Worn belts
		Something prevents the extruder screw from turning
	Belt squeal	Motor and gearbox shafts are not parallel to each other
		Belts are not a matching set
		Belts are not properly tensioned
		Incorrect number of belts for the motor Hp
	Thrust bearing failure	Replace thrust bearing
	Bearings overheating	Improper belt tension
		Shafts not parallel to each other
4. Rupture disk in extruder barrel fails	Sudden major contamination blocks screen pack	Change screens
	Die or adapter too cold	Heat die or adapter
	Wrong rating on rupture disk	Install higher pressure rated rupture disk
	Gear pump is not running	Turn gear pump on
		Increase gear pump speed
5. Barrel/screw wear	Screw, barrel and drive alignment	Borescope extruder to ensure proper alignment
	Straightness of screw and barrel	Verify screw and barrel are straight
	Material being processed (including additives)	Use proper screw and barrel materials for abrasive ingredients
		Use proper screw and barrel materials for corrosive formulation
	Incompatibility of screw surface and barrel liner	Verify screw and barrel materials are both compatible to prevent adhesive wear
	Improper support of barrel	Ensure adequate barrel support that is properly aligned
	Excessive loads on barrel discharge	Ensure die is properly supported and not just

		hung on the end of the barrel
	Screw design	Run the correct screw design for the material being processed
6. Screw turns but no material or limited material exits the die	Feed throat plugged or bridged	Remove plug to create material flow
	No resin in feed hopper	Fill feed hopper
	Plug of polymer stuck on root of screw channel	Force rod of same material into extruder
		Feed chunks of same material into extruder
		Shut down extruder dean barrel and screw
		Raise temperature while turning screw at low rpm – If plug is degraded this may make the situation worse
	Feed throat cooling not working	Verify water is circulating around feed throat
	Zone 1 temperature too high	Lower temperature in the first zone
	Wrong screw design	Change screw
	Screw is broken	Remove broken screw and install new screw
7. Extruder shuts itself off	Back pressure too high – Back pressure control shuts line down	Change screen pack
		Blockage in die
		Melt temperature too low
		Die or adapter temperature too low
	Gear box temperature too high	Cool gear box
	Motor or drive problems	Check electrical breakers
	Screw locked up	Determine if something is caught in the feed throat
	Extruder drive pulling too many amps	Melt temperature too low
		Back pressure too high – Slow down extruder, change screens
		Wrong screw design
8. Melt flows out of barrel vent	Back pressure too high	Change or remove screens
	Wrong screw design	Change screw with single screw extruder
		Modify screw design with twin screw extruder
	Temperature profile incorrect	Raise melt temperature
9. Polymer leaking around breaker plate	Breaker plate not properly seated	Reposition breaker plate
	Damaged breaker plate	Machine breaker plate surface to make it smooth
		Replace breaker plate
	Screens plugged back pressure too high	Change screen pack
	Bolts on die head not tightened properly	Tighten bolts after heating to operating temperature
	Breaker plate slide not moved all the way across	Reposition breaker plate slide
10. Extruder throughput rate is lower than expected	Screw or feed throat partially blocked	Clean feed area of blockage
	Wrong polymer grade	Change polymer
	Die/barrel temperature too low	Raise temperatures
	Screw starve fed	Increase feed rate
	Wrong screw design	Change screw
	Worn screw	Measure screw dimensions – Replace if worn
	Screens blocked	Change screens
	Die needs adjustment	Adjust die opening
	Screw needs cleaning	Clean screw
	Drive belts slipping	Tighten or change belts
	Screen pack unsuitable	Change screens
11. Barrel temperature override	Barrel zones set too low	Raise set point temperature
		Raise set point temperature in previous zones
	Feed section is over-feeding	Slow screw speed in flood fed extruder
		Lower feed rate in starve fed extruder
	Transition section is too short	Use screw with longer transition section
	Screw is worn	Replace screw

	Mixing section is too tight	Use screw with different mixing section or screw with more clearance between barrel and mixing section
	Excessive work in twin screw extruder	Change screw design in sections with excessive heating
12. Extruder surging caused by equipment	Barrel temperatures not controlling properly	Check barrel controllers, verify they are working properly
		May need to replace screw
	Poor die design	Change die design
	Worn screw or barrel	Replace screw or barrel lining
	Die/barrel temperature fluctuations	Verify temperature controllers and cooling are working properly
	Extruder motor varying speed	Check drive control
13. Poor polymer mixing	Temperature too low	Raise barrel temperatures
	Back pressure too low	Add screens
	Improper screw or design	Change screw or modify design to provide the required distributive or dispersive mixing
	Mixing head on screw plugged	Clean screw
14. Product throughput variation over time	Screen pack contamination	Change screen pack
	Extruder is coming to equilibrium	Make sure system is at equilibrium before collecting product
	Reduced extruder output	Die blockage
		Feed blockage

APPENDIX B: POTENTIAL CAUSES AND CORRECTIVE ACTIONS TO COMMON EXTRUSION PRODUCT PROBLEMS ACCORDING TO GILES ET AL. (2005)

Appendix B Table 1 *Potential causes and corrective actions to common extrusion product problems (Giles et al. 2005, p. 265-279)*

Extrusion product problem	Potential cause	Corrective action
1. Product surging	Barrel temperature too low causing unmelted resin too far forward in the metering zone	Increase barrel temperature in transition and metering zones
	Screen pack unsuitable	Change screen pack
	Insufficient resin supply with starve fed extruder	Increase feed rate
	Partially bridged feed throat	Clean feed throat
	Irregular feed	Slippery additive - Starve or crammer feed
		Sticky additives - Starve or crammer feed
		Plugged screw channel - Change temperature profile
		Excessive fillers without enough polymer for fluxing - Change ratio
	Poor polymer quality	Change polymer
	Wrong grade of polymer	Change polymer
2. Variations in product occurring over time	Energy being put into the plastic has changed over time	Verify melt temperatures and pressures are correct
		Verify extruder temperature controls are cycling properly
		Check environment factors - Cold air flow
		Colder raw material
	Molecular weight of the polymer has changed	Check raw materials
		Increased regrind level
		Change in regrind type
3. Random product variations	Feed problems due to sticky material	Add small amount of talc
	Variation in plastic raw material	Check raw materials
	Combination of cyclic problems - Screw speed, pressure, temperature, etc.	Monitor all processing conditions
4. Streaks in extruder caused by poor mixing	Variation in product consistency	Generate more mixing
		Raise barrel temperature
		Raise die head pressure
		Change screw for more mixing
	Streaks appear during run	Raw material variation
		Colourant variation
		Change in plastic viscosity
		Screw damage
		Screw or die needs cleaning
	Unsuitable die	Determine if problem caused by die
		Die not assembled properly
		Die requires adjustment
5. Variation in product strength	Change in molecular orientation - Orientation in flow direction - Strength increases in flow direction	Reduce take-up speed
		Reduce draw ratio
		Slow cooling rate

	decreases in transverse direction	Reduce flow rate in die
	Resin degradation - Strength decreases in all directions	Lower melt temperatures
		Lower barrel temperatures
		Reduce shear heating - Change screw design
		Shorten residence time
	Change in crystal size - Smaller crystals produce tougher parts	Cool more quickly to reduce crystal size
		Add nucleating agent to promote smaller crystal growth
6. Degradation - Discolouration, Steaks, Dark/Black Specks, Loss of properties	Plastic temperature too high	Lower die/barrel temperatures
		Change screw design
		Change screw speed to generate less heat
	Exposed to high temperature too long	Reduce residence time
		Ensure no dead spaces exist in die or transition pipes
	Polymer reacts with other polymer or additives	Replace with other additives
		Verify polymers in formulation do not react
	Screw, die or adapter needs cleaning	Clean screw
		Clean adapter
		Clean die
	Unsuitable grade of polymer or poor polymer quality	Change polymer
		Reduce regrind
		Add thermal stabilizer to plastic
7. Dull streaks	Uneven plastic melt temperature	Increase barrel temperature
		Increase extruder head pressure
		Verify cold spots are not present in the die
	Non-uniform plastic cooling	Check and correct die for hot or cold spots
		Check uniformity of cooling after die
	Raw material variations	Formulation contamination
		Verify MFI of the resin is unchanged
	Sheet products	Die lips are not properly adjusted
8. Die lines/straight lines in extrusion direction	Surface defect in die	Machine die surface
	Carbon build up on die lip	Clean die
	Residue from blown screen pack	Clean die
	Sizing device	Determine origin of line and correct
	Take up unit	Remove interference causing scratch
9. Colour contamination	Extruder and die not properly purged from last material	Clean extruder and die
	Extruder blender or hopper not completely cleaned	Remove contamination
	Transfer lines not cleaned	Clean lines
	Inadequate premixing or feeding of colours	Remix original batch
		Check feed rate
10. Hole in extruded profile	Trapped air	Increase rear barrel temperature
		Increase restriction in screen pack
		Use vented extruder
		Increase plastic melt temperature
	Degradation of resin or additives	Lower melt temperature
	Resin contamination	Hole generated by previous resin or additive - Purge extruder and die
	Vacuum void	Cool profile slower
		Redesign extruded shape to minimize thick sections
	Moisture	Pre-dry material
		Use vented extruder
11. Gels or "fisheyes"	Polymer crosslinking in the die	Streamline die to prevent stagnation
	High molecular weight material	Raise melt temperature
		Increase screen pack mesh to filter out
12. Gauge	Poor melt mixing	Improve mixing

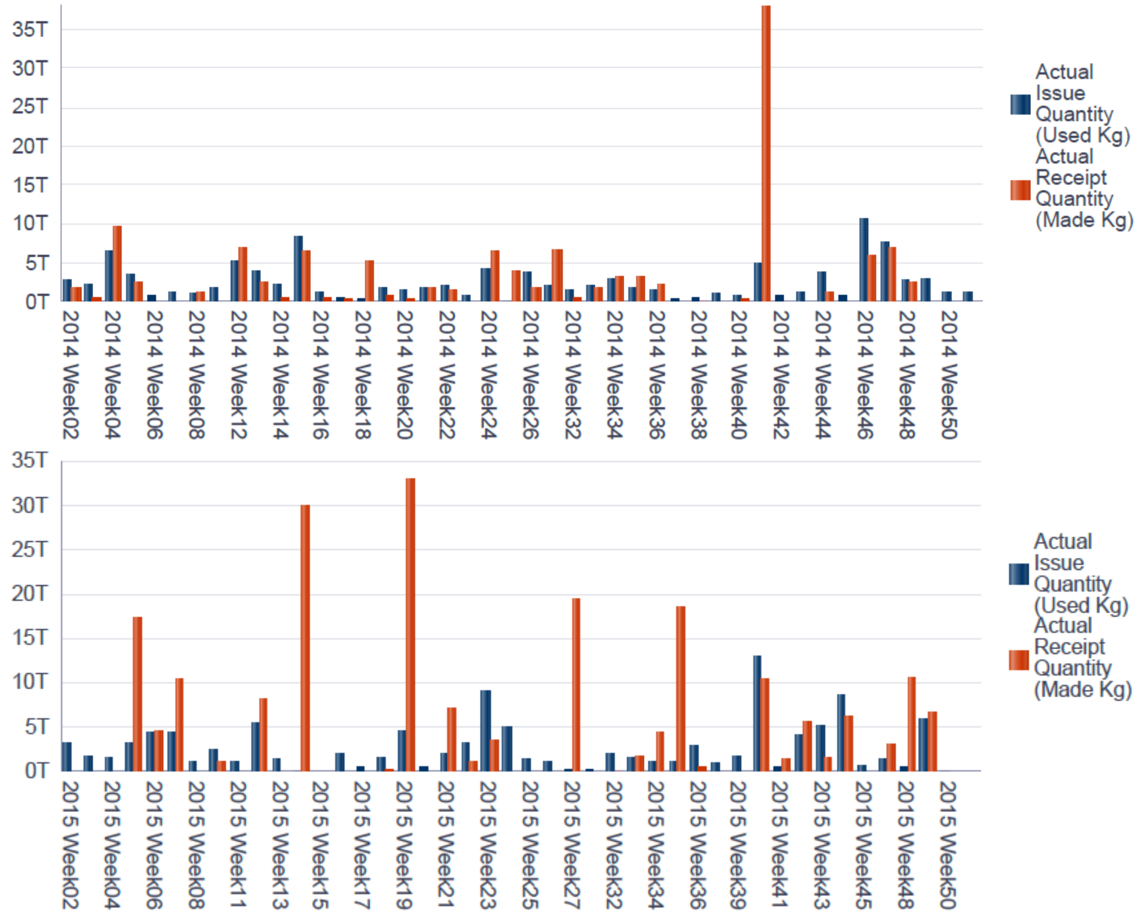
variations	Screen pack unevenly plugged	Replace screen pack
	Burned-out heaters in screen changer, adapter, or die	Replace heaters
	Heaters loose on adapter or die	Tighten heaters
13. Weld line	Polymer flow divided in die and not completely recombined	Increase molecular entanglement - Raise barrel temperature, extruder pressure and/or die temperature
		Increase length of flow path (extend die lips) to provide more time for molecular entanglement
		Increase pressure on molecules forcing them together, increase restriction in die past flow divider
		Mix plastics after divider - After die design
		Change plastic - Easier flowing, lower molecular weight
	Remove foreign material or contamination from the die	
14. Weak film or coating	Melt temperature too high	Lower melt temperature
	Wrong resin or blend	Check if using correct material
	Poor polymer melt mixing	Improve polymer mixing in the extruder

APPENDIX C: POTENTIAL CAUSES AND CORRECTIVE ACTIONS TO COMMON PIPE AND PROFILE PROBLEMS ACCORDING TO GILES ET AL. (2005)

Appendix C Table 1 *Potential causes and corrective actions to common pipe and profile problems (Giles et al. 2005, p. 307-310)*

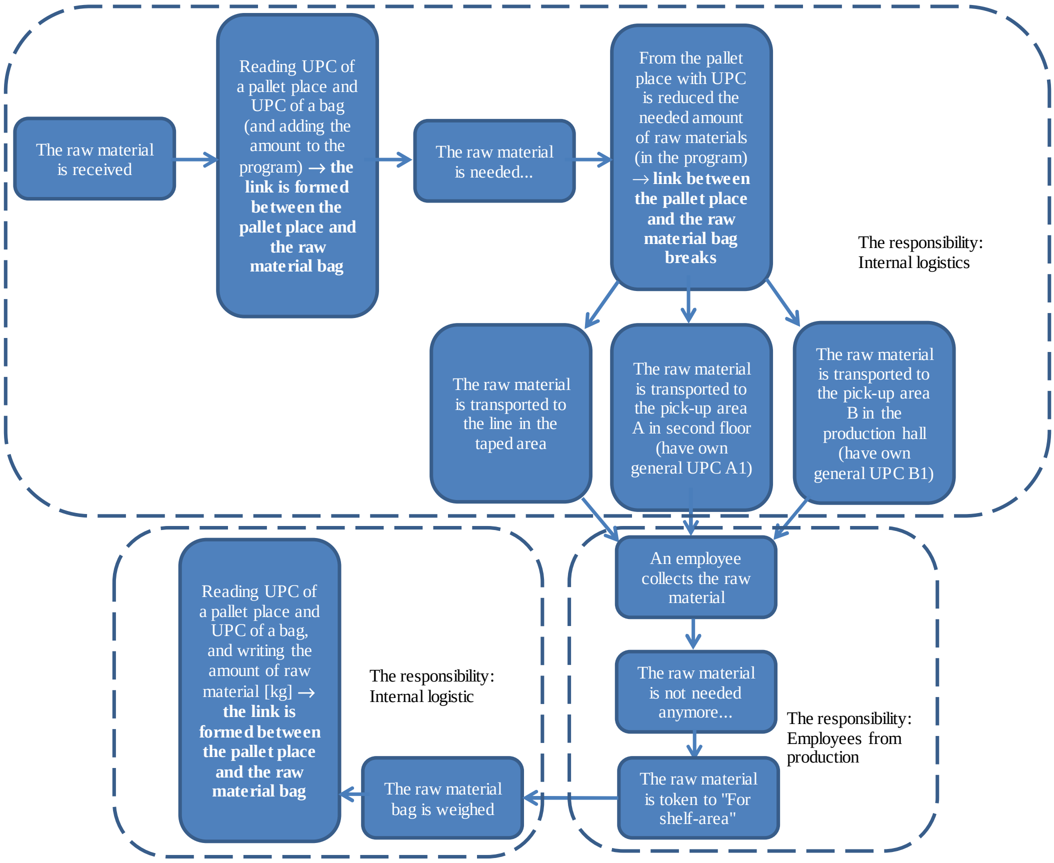
Pipe and profile problem	**Potential cause**	**Corrective action**
1. Excessive wall thickness or thinness	Improper die gap opening	Wall thickness high, decrease die gap opening
		Wall thickness low, increase die gap opening
		Pipe/tubing ensure die bushing in centred on mandrel
	Improper operation conditions	Verify puller speed is correct
		Verify screw speed is properly set
		Check extruder temperature, die and adapter set points
	Profile slippage at caterpillar	Check pulling force
		Ensure profile is dry before reaching caterpillar
2. Wavy surface inside pipe or tubing	Melt temperature too low	Increase set point temperatures in the last 2 zones, die and adapter
	Pulsating or non-uniform draw	Slippage is occurring in the caterpillar - verify correct pressure is being used and profile is dry
		Verify caterpillar belts are in good condition
	Resin formulation incorrect	Check formulation
		Add external or internal lubricant to formulation
3. Non-uniform flow or velocity out of different legs or sections of the die	Unbalanced die flow	Ensure taper prior to the die land area is the same providing uniform pressure
		Modify die land length
		Change die gap dimensions
	Dirty or contaminated die	Purge foreign material from die
		Disassemble and clean die of carbon deposits, degraded polymer, contamination
	Temperature fluctuations in die	Verify heaters and thermocouples are functioning properly
		Tighten any loose heater bands
		Check set point temperatures
		Insulate die
		Add additional heating

APPENDIX D: MADE AND USED REGRIND IN THE YEARS 2014 AND 2015



***Appendix D Figure 1** Made and used regrind in the year 2014 and 2015*

APPENDIX E: EXAMPLE PROTOCOL OF UPC SYSTEM



Appendix E Figure 1 *Proposed example of protocol of UPC system*

APPENDIX F: EXAMPLE OF A PRE-DESIGNED REPORT ON OBSERVED RAW MATERIAL RELATED PROBLEMS

Date: **Name:**

Line: **Product number:**

Material code: **Production date (and batch) of material:**

Screw turns: Screw loading:

Screw design:

Used zone temperatures:

Used tools, mixers, a breaker plate etc.:

Calibrating:

The amount of regrind (%):

The amount of colour (%):

Drying time and temperature:

Are set conditions same as in the product card (if not, describe why)?

Was there something visibly unusual in the raw material?

What were the symptoms of the extrusion problems (in the profile, melt flow etc.)?

What were the corrective actions?

Is there something else to be taken into account?

Required attachments: a photo of the symptoms of the problem & a sample of the raw material

APPENDIX G: EXAMPLE OF PRE-DESIGNED REPORT ON THE USE OF REGRIND

Date:	**Name:**
Line:	**Product number:**
Virgin material code:	**Production date (and batch) of virgin material:**
Regrind code:	**Grinding date and name:**
Screw turns:	Screw loading:

Screw design:

Used zone temperatures:

Used tools, mixers, a breaker plate etc.:

Calibrating:

The amount of virgin material (%):

The amount of regrind (%):

The amount of colour (%):

Drying time and temperature:

Are set conditions same as in the product card (if not, describe why)?

Was the appearance of regrind correct?

Was the melt flow of mix (regrind and virgin raw material) or regrind (if used singly) correct?

What were the symptoms of possible extrusion problems (in the profile, melt flow etc.)?

What were the corrective actions (if there were any problems)?

Is there something else to be taken into account?

Required attachments: A sample of the product and if there were significant problems also a sample of the problem area

APPENDIX H: RECOMMENDATIONS FOR OBSERVED ISSUES

Appendix H Table 1 *Recommendations for observed issues*

Area	**Observed issue**	**Potential corrective action**
1. Raw material purchase: The internal supplier and responsibility persons in the case company Chapters 5.2 & 6.1	In relation to recycling good integration between the internal supplier and the case company is required	Input for extrusion process (raw material from the internal supplier) has to be recycled and reprocessed → Recyclability could be one criterion when new raw material is designed
	Certain products had such tight specifications that it was hard to fulfil them, at the same time a raw material was in a major role	More active cooperation, planning, documentation and analysis from the beginning of the project → Common rules and a plan with the customer and the value chain how the goal is going to be achieved and how the performance is measured
	Faster problem solving with tricky raw materials (like brown foam PVC) which also generate scrap more than planned	Proper documentation of the mentioned problems, making a written plan with shared responsibilities and deadlines for each activity (for example with a functional-activity flowchart)
	Some employees found that raw materials are partly heterogeneous, which complicates the extrusion process and generates scrap	Employees in the extrusion process are customers of the raw material supply process → Collecting feedback directly from the employees (pre-designed forms etc.) and improving the process if necessary
	Reclamation procedures were not systematic and comprehensive enough	Written and mutually agreed approaches; Collecting feedback directly from the source, taking samples or at least photos each time → For instance pre-designed paper/online forms and required appendices
	In the case where an employee noticed a shortage of raw material, the message chain was relatively long (employee-shift leader-production planner-internal supplier)	By using agreed and standardized software employee is able to inform a production planner and the internal supplier straight after a shortage is noted (also in the evening and night shift)
	Raw material tests were partly done after transmission. If something unusual was noted, the information came too late	Clarifying the supplier-customer relationship; In principle, only the primary raw material needed should be sent , However, it can be agreed together what the products are where secondary raw materials can be used (has to be sure)
2. Inventory and Material Management: A person responsible	There was no exact real-time (online) information about where a certain raw material bag is → As a consequence raw material bags were sometimes missing	UPC for each bag, pallet places (or at least shelf rows) and other areas → A clear link between the raw material and its location, Real-time information where certain material is located
	The outdoor storage (tent) is not well	It is hard to tackle this issue at the moment

for material management, Internal logistics, A production planner, All employees from production Chapters 5.3 & 6.2	organized and it is not easy to collect materials from there, "A mental landfill for regrind"	(the space in the second floor storage is limited), Keep things flowing
	Some employees felt that internal logistics are insufficiently covered (too much to do in addition to extrusion processing)	Sharing part of the internal logistics work with less talented extrusion trimmers and letting more talented employees to focus on the lines (less scrap with quicker fixes) - This is already partly done
	Calculation of actual material consumption based on metre weights (and scrap) but it is not fully accurate (not enough measuring points in the arithmetic average) and it updates relatively late	Measuring devices integrated to extrusion machines → Exact consumption in the end of the run, The person responsible for the material could monitor consumption during long runs and warn the production planner if consumption is much higher than planned
3. Extrusion process: All people under production department, R&D, Chapters 5.4.1-5.4.2 & 6.3.1-6.3.2	Overall; Learning through trial and error	Overall; Activities should be completed more in accordance with scientific methods
	Work orders are pre-printed and material balances in the work orders are outdated	Work-orders should be printed just before a run starts (according to the Visual Planning & Production Follow-Up programs) and employees should get more IT training
	Product cards were partly confusing (many versions in the same folder), outdated and difficult to read	Also product cards should be printable with work orders (for instance as an attached appendix to the work order) → Always the latest version is printed
	Work orders did not include all information about required packing materials → There were no ERP-codes for some tapes and films (order was relying on verbal information)	Work orders should include all materials and amounts required to perform a certain product run, All packing materials should also have their own ERP-code to help ordering
	There was no strictly controlled protocol in place for start-ups; Some employees did it with less scrap but not all	There should be a protocol that all possible steps are taken before materials are fed to the extruder
	Used extrusion conditions vary and depend on the operator, Not all of the potential of the available integrated computers was used	There should be set temperature programs (which all should always be followed) in computers in the lines, where possible. Also other conditions should be standardized → Automated or manual collection of extrusion conditions and iterating towards the optimum
	Pressure in the production led often to rushed work → This often led to mistakes, problems and increased pressure	Even in the case of pressure, calm down and follow procedures to avoid mistakes and prolonged lead times
	If a more complex problem occurred which could not be solved by one or two people, decisions and responsibilities were sometimes left up in the air → Problem solving took too long	Making a functional activity flowchart; Who is responsible for each activity? What is the deadline for each activity? → Following the progress of the project becomes easier
	Troubleshooting was sometimes "let's try	Turning from doing things blindfolded to

	and look what happens" → Without controlled process changes generation of waste is possible	making changes according to analytical scientific methods, troubleshooting tables and using the Socrates method of iterative questioning and problem solving
	In some interviews it came across that the process of introducing new products was partly followed with a "Over-the-wall"-mentality (there was a large deviation between interviewees)	A dynamic limit between new and established product → If product shows problems during first test runs, cooperation with R&D
	Some people felt that they were not prepared early enough for first production runs	If possible, involving employees already in the design phase → Better commitment, exchange of important information and maybe new issues that should be taken care of (practical experience)
	Important parameters were missing too often before first production runs → Frustration among employees, scrap	Determining important parameters under controlled test runs can also shorten total lead time because you do not have to work hastily if a problem occurs (leads probably to new problems and increased pressure)
	Not all employees participated actively in test runs	Delegation, motivating, discipline → Information exchange
4. Quality control All employees, Shift leaders Chapters 5.4.3 & 6.3.3	New employees were not always properly trained for quality control and main operations → Quality control becomes difficult if you do not know the product	Good trained of all core tasks in the extrusion line and of all the things to pay attention to during production and quality control
	Some quality meters were too generic such as "good surface"	All meters should be measurable and every question should have a direct pass/fail answer → Tolerances for colour and gloss if needed, Pass/Fail answers
	Walking back and forth in the line and monitoring several lines at the same time makes active quality control difficult	Team work; Packers in the end of the line could be continuously on guard→ Inform if something unusual happens
5. Maintenance: All employees, Shift leaders, Maintenance Chapters 5.4.4 & 6.3.4	A great basic maintenance program was created for each line but it was not always followed actively, For instance clean tools have been shown to reduce scrap and shorten running-in time	Follow the maintenance program → Discipline!
6. Recycling: All people under production department, The person responsible for material	Handling of scrap was mostly satisfactory but long profiles should not be trailed on the floor → Contaminations like dust may decrease the quality of regrind	Cutting long profiles into small pieces to avoid trailing on the floor and contaminations
	Coloured regrind should not be mixed! → Mixed colour regrind is currently difficult to use, Sold to an external company	Separation of colours and placing for instance in trash containers like with PVC-P
	The study about functional regrind ratios	A project team is needed to study this area,

management, The production planner Chapters 5.5 & 6.4	was a grey area → Ratios were mostly found through trial methods, Shift leaders had also done some studies but this took time away from daily management duties	see the Chapter 6.4.3
	Coloured foam profiles cannot be used mostly because of the tight appearance specifications	Finding “a green product” which consists of a regrind core and a virgin material surface?
	The use of regrind was not emphasized enough, Monitoring of regrind is not visible enough to employees	Using visual controls (charts and calculations on info TVs etc.) for demonstrating the significance of the generation of scrap and the use of regrind (€,kg)→ Connecting people to the recycling process, Making people aware of the importance and their role → No one can hide from the truth
	The role of a reward system as a motivator is unclear and has been tried without success, Still at the moment there is no motivator	Finding a way to motivate people to use regrind
7. Information flows: All Chapters 5.6 & 6.5	Some employees felt that they are not informed enough, Vertical information partly breaks in the floor level	Involving employees more in changes and projects, improvements to be made at the lowest possible level
	Some interviews and discussions revealed that employees would like to be heard more and affect the operations they face daily	Involving employees more in changes and projects, improvements to be made at the lowest possible level, Collecting routine and simple information on forms
	Daily information flood is huge → Sometimes decisions made are forgotten	Writing down decisions and plans made and using for instance software for that purpose (with monitor in the production) → Next small and bigger projects would become easier
	Information exchange between shifts is critical but is done outside working time and not everybody comes in early enough	A system that employees feel to be fair, For instance “a presence-extra”
	Most people in production would like to know more about customers and products, Some felt the customer knowledge is insufficient	Taking shift leaders to customer visits → Creating better value to the customer, Creating commitment and the feel that the customers are paying the salaries
7. Daily managing and People: Shift leaders, Employees from production, Other managers Chapters 5.7 & 6.6	Employees felt that the discipline was insufficient; Work was not always evenly spread	Paying attention to this more in the future
	There were very talented people in the production who could be given bigger responsibilities	Talent management but at the same time take care of that all employees have a possibility to progress
	Production work is heavy but human errors are possible sources of scrap	Implementing procedures that are easy to follow also in the night shift, Listening to production employees feelings regularly
	Reward systems were not considered to be fully motivating	Turning reward systems from time-based to value-based