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Sustainable Supply Chain in the Textile Industry

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"Master of Science"

supervised by
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Affidavit

I, **SOPHIE SURINDER**, hereby declare

1. that I am the sole author of the present Master's Thesis, "SUSTAINABLE SUPPLY CHAIN IN THE TEXTILE INDUSTRY", 92 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Abstract

In the last decades the textile industry has been criticised for exploiting and polluting the environment. Particularly, the production of mainstream textiles such as cotton, has been found to create a great environmental burden.

To overcome these environmental issues, sustainable textile options have emerged on the market. This thesis compares and discusses two case studies: the supply chains of conventional cotton, and the supply chain of lyocell, a man-made regenerated cellulose fabric, which is praised for its sustainability. With material flow analyses, both supply chains are investigated in order to evaluate and analyse their direct and indirect impact on the environment.

The findings in this thesis show, that the cotton supply chain has an extremely high water demand, but a lower demand in chemicals compared to the lyocell supply chain.

In total, about 95 MJ/kg with non-renewable energy, 21400 litres of water and 3kg of chemicals are needed to produce 1kg of finished cotton fabric in this case study.

The production of 1kg of finished lyocell fabric has an energy demand of 72 MJ/kg with non-renewable energy, 94 MJ/kg with renewable energy, a water demand of about 1500 litres and a chemical demand of about 19kg. Out of these chemicals 17.5 kg are reused and recycled within the supply chain.

When energy sources are switched to renewable energy and partially self-produced energy, the lyocell supply chain produces 1.5 kg CO_2 eq/kg of finished lyocell fabric. In contrast, the cotton supply chain in this case study produces 3.5 CO_2 eq/kg of finished cotton fabric and thus releases more greenhouse gases and has a greater global warming potential.

Despite the fact that natural resources are exploited for commercial purposes in both case studies, the lyocell case study is the more sustainable supply chain due to the conversion of waste into energy and due to the recovery and recycling of chemicals and wastewater in certain production processes. These sustainable actions lead to a minimum waste accumulation and therefore to reduced emission.

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1. Introduction

The aim of this thesis is to compare a traditional cotton supply chain, which is known for having a negative environmental impact, with the supply chain of a man-made cellulose fibre called lyocell, which is praised for providing an environmentally friendly impact. The supply chains for both textiles will be presented in the form of a material flow analysis in order to evaluate and analyse their direct and indirect impact on the environment.

It is well known that the international textile industry has been under tough criticism in the last decades, due to its unethical working practises, violation of human rights and because of its contribution to environmental pollution (EJF, 2007). This thesis focuses on the environmental impact of the textile industry. The problems that come with environmentally unfriendly production lead to soil-, air- and water pollution due to the use of toxic substances during the sourcing processes of materials in the primary sector, as well as the use of toxic and polluting substances during the production phase in the secondary sector (Soth et al, 1999).

In the international textile industry there are little to no air or water pollution control systems and few legal guidelines on environmental protection, as these laws are usually established domestically. Today, sourcing and production for the majority of the textile industry take place in developing countries, where strict environmental laws especially for the industrial sector do not exist (Chavan, 2001). In addition, there are hardly any safety measures for workers in the sourcing and production phase of the textile industry, who are exposed to toxic chemicals on a daily basis (EJF, 2007).

The traditional textile industry and its supply chain greatly endanger the environment and ecosystem of people and animals living close to farming and industrial sides, and causes great problems. Moreover, there is a constant thirst for new fashion trends, created by fashion houses with their extraordinary marketing and branding techniques. This leads to conspicuous consumption and an oversupply of clothes. This consumerism generates an accumulation of unnecessary toxic waste. Aside from that, chemicals used in the production of clothes are often, in its end-product form, harmful to the skin of the consumer (Parry, 2014). Despite the fact that textile end-retailers have introduced recycling schemes, this is not enough to make this industry more sustainable, as it has to be done from the beginning of a supply chain. The supply chain of the textile industry has to become more sustainable (Muthu, 2014).

As a response to a raising demand in sustainable clothes, many manufacturers have taken the opportunity to produce and present greener clothing options, which are said to be higher in quality than for instance cotton and are said to have a low impact on the environment. The most well known sustainable fabrics, apart from organic fabrics, are regenerated cellulose fibres and especially lyocell. Lyocell clothes are said to be the future of the textile industry (Engelhardt, 2012). Justified with their low environmental impact and ethical production methods, these sustainable fabrics are praised to be able to satisfy the never-ending demand in fashionable clothes.

Therefore, this thesis examines whether regenerated cellulose fibres are indeed as sustainable as they are claimed to be. The approach is to compare the material flow analysis of a mainstream product, a conventionally produced cotton T-shirt, to the material flow analysis of a sustainable product, a lyocell T-shirt. The material flow analyses present the water and chemical demand of both supply chains from cradle-to-gate, so from the sourcing stage to the fabrication of a finished T-shirt. Both material flow analyses allow evaluating the supply chains' environmental impact and drawing conclusion on what distinguishes a sustainable textile from a non-sustainable textile.

The hypothesis in this thesis is that lyocell is in every aspect the more sustainable option compared to conventional cotton. The thorough evaluation and analysis of both supply chains with a material flow analysis and its direct and indirect ecological impact will demonstrate if this hypothesis is supportable.

Research Methodology

This thesis is based on quantitative research collected from books, academic and scientific journals, market reports and official statistics, which can be found in the bibliography. The thesis examines two case studies: firstly, a cotton supply chain and secondly, a lyocell supply chain. Furthermore, their environmental impact is compared after the creation and discussion of material flow analyses and the resulting data.

Primarily, the first case study is discussed. Literature research is conducted and summarised in order to find the most important information on how a cotton supply chain is structured. The research for this chapter is based on books and official statistics on cotton production. In this thesis the supply chain is cradle-to-gate, and starts from raw material sourcing and ends with the final textile garment, which is ready for retail. The supply chain is explained according to its production stages: raw material sourcing, fibre production, fabric production, fabric finishing and apparel production. For every production stage all relevant manufacturing processes are explained in order to fully comprehend further evaluations.

After the theoretic discussion of the cotton supply chain, a material flow analysis for the production of 1kg of finished cotton fabric is presented. The material flow analysis allows framing the theoretic findings. The material flow analysis incorporates the relevant data and explains in detail, the quantity of water and chemicals, which are necessary for each manufacturing process, as well as in what quantity these materials leave the production process as output. The data of each production process in the MFA is individually researched and based on textile production and chemical processing books, scientific journals, company reports and online lectures. If not already specified, the data is calculated for 1kg of cotton fabric. The material flow analysis allows the quantitative evaluation and analysis of how a cotton supply chain is constructed.

Afterwards, the environmental impact of the cotton supply chain is examined by discussing the direct and indirect consequences in regards to air pollution, water exploitation and pollution, soil erosion and pollution and the accumulative solid waste. The research in this chapter is based on environmental books, scientific journals and environmental reports published by NGOs.

Secondly, the same method is applied to the lyocell case study. Literature research is conducted and summarised in order to find the most important information on how a lyocell supply chain is structured. The research for this chapter is based on books, company reports, scientific journals and official statistics on lyocell production. Also for the second case study, the lyocell supply chain is cradle-to-gate, and starts from raw material sourcing and ends with the final textile garment, which is ready for retail. The supply chain is explained according to its production stages: raw material sourcing, fibre production, fabric production, fabric finishing and apparel production. For every production stage all relevant production processes are explained in order to fully comprehend further evaluations.

After the theoretic discussion of the lyocell supply chain, a material flow analysis for the production of 1kg of finished lyocell fabric is presented. The material flow analysis allows framing the theoretic findings. The material flow analysis incorporates the relevant data and explains in detail, the quantity of water and chemicals, which are necessary for each production process, as well as in what quantity these materials leave the production process as output. The data of each production process in the MFA is individually researched and based on textile production and chemical processing books, scientific journals, company reports and online lectures. If not already specified, the data is calculated for 1kg of cotton fabric. The material flow analysis allows the quantitative evaluation and analysis of how a lyocell supply chain is constructed.

Afterwards, the environmental impact of the lyocell supply chain is examined by discussing the direct and indirect consequences in regards to air pollution, water exploitation and pollution, soil erosion and pollution and the accumulative solid waste.

Finally, the outcomes and environmental impact of both case studies are compared and examined. What is more, it is reviewed whether the hypothesis in this thesis is confirmed and to what extent.

Limitations and System Boundaries

The presented material flow analyses are limited to the system boundary cradle-to-factory gate and thus exclude the retail stage, use phase, including domestic washing and drying of the products, as well as the disposal or potential recycling of the products. Despite the fact that the inclusion of usage and disposal would change the results of the environmental impact analysis, the diverse impacts of the production technologies within both supply chains would remain unchanged. Further, the conclusion on the degree of sustainability of both supply chains would also remain unchanged.

The lifetime for the cotton supply chain is 8 months and for the lyocell supply chain 10 years and 1 month. The reason for this discrepancy is that the cultivation and harvesting of cotton takes about 6-7 months and the cultivation and harvesting of the tree, which is later fabricated into cellulose, takes 10 years in this case study.

There are also uncertainties included in both case studies and material flow analyses, as different production methods and technologies can be used to produce cotton and lyocell. Moreover, input and output data can vary, depending on where it is produced, and which regulations have to be abided.

2. Conventional Cotton

Introduction

Cotton has become the most popular fabric in the world due to its characteristics such as comfort, versatility, durability, visual appeal and value. Due to mass production and economies of scale it has also become a relatively cheap fabric to produce.

In 2014, the biggest cotton producer was China, followed by India, the United States, Pakistan, Brazil, Uzbekistan, Australia, Turkey, Turkmenistan and Greece among, many other cotton producing countries (Statista, 2015).

The most typical cotton plant in southern parts of North America, Central America and the Caribbean is called Gossypium hirsutum. Cotton plants grown in South America are called Gossypium barbadense. Cotton, which is grown in China, India and Pakistan is called Gossypium arboreum. Cotton grown in Africa and Arabian countries is called Gossypium herbaceum. However, today different cotton types are grown globally and are not restricted to their country of origin. Sometimes cotton plant types are mixed and hybridised on cotton farms (New England Mercantile Group, 2015).

How a cotton T-shirt is made

1) Raw material sourcing

Cotton Cultivation

A successful cultivation and farming of cotton requires loose soil, preferably loose alluvial soil as well as offering the cotton plant warmth and sunshine during its cultivation phase. Early springs and long summers offer the ideal warm temperature day and night with an average temperature of 18 to 26 degrees Celsius. Equally as important is precipitation, as cotton farming requires a great amount of irrigation.

In the first development phase the plants need enough humidity, through fog and rain for instance, in order to grow well. Later, during the ripping phase and the harvest time, rain is harmful to the plants.

In subtropical regions with low rainfall, such as Egypt and the Central Asian countries of the Commonwealth of Independent States, artificial irrigation is therefore necessary.

An ideal climate indicates six to seven frost-free months between spring and autumn and a mean temperature in winter, which doesn't sink below 10 degrees Celsius.

Cotton cultivation requires the use of pure cottonseeds, which are imported from the country of their origin continuously, if cotton farming doesn't take place where the cottonseeds are from. In addition, fertilisation is a key factor and necessity in order to guarantee maximum yield of the cotton plant. Most important fertilisers required for cotton plants have been phosphate, nitrogen containing substances, ammonium sulphates, cottonseed meal and a few potassium salts. In addition, waste of sugar refineries, molasses and calcium cyanamide had been introduced as fertilisers.

Cotton seeds can either be sown by hand or by machine. When the plants reach a height of approximately 12 cm, the weaker and smaller cotton plants are removed (Pietsch, 1920).

Cotton Growth

On one hectare between 13000 and 26000 plants are grown with a gap of 30 to 60 cm between the plants. The reason for these gaps is so that the plants can absorb the maximum amount of light, warmth and air and to reduce shadows. This means that cotton farming needs a huge amount of soil.

During the growth time the cotton fields are cleared of weeds. Traditionally and in old times weed control was carried out by a two-horse cultivator, whose shovels removed the weeds thoroughly and fast. Nowadays, machines take care of weed control with a similar procedure. Additionally, during the growth phase pests, such as weevils, caterpillars but also fungus, infest cotton fields. Unfavourable natural conditions or poor control over the cultivation of cotton farms increase the existence of pests on cotton fields. In this case pesticides are applied in order to protect the cotton plants from such pests.

Nevertheless, plants are especially damaged through bad weathering with heavy rainfall and no sunshine, which harms the growth and impairs the seed and fibre forming of cotton plants. Also bad cultivation of the soil with little fertilisation leads to degeneration (Pietsch, 1920).

Cotton Harvesting

The ripening of the capsules lasts between one and three months. Between sowing and harvesting four to five months pass.

In Northern India the cultivation is less developed than in the United States or in Egypt. Indian cotton farmers often focus on companion planting. Due to poor farming operations, lack of control and interrupted harvesting, as well as due to unreliable weather conditions a maximum yield cannot be achieved. Sowing is depending on the occurrence of the rainy season, which takes place between June and August, followed by the cotton harvesting in October and March.

In most areas harvesting predominantly involves manual labour and has to happen very fast as ripe cotton on their capsules lose quality and quantity, as it is very sensitive to rainfall and heavy wind. Therefore, handpicking of cotton demands a large number of workers, who need to work on the cotton fields until all ripe cotton is harvested. In more developed countries cotton-picker machines take over the manual work.

However, the disadvantage of old cotton-picker machines is that they often pick ripe and unripe capsules. More sensitive machines in more advanced regions are able to differentiate between ripe and unripe capsules. These machines vacuum the ripe cotton-wool out of the capsules. Unwanted capsules and twigs, which are accidently caught up in the machines, are filtered out trough a ventilator in the machine. Whereas one human worker is able to pick about 45 kg of cotton per day, such machines have been able to pick a minimum of about 1130 kg of cotton per day. Besides, investing in such machines is, in the long run, is more cost effective than employing manual labour.

The picked raw cotton boll consists of cottonseeds and seed hair, where the latter is further on used to create cotton fibre. The raw cotton bolls are collected and dried in harvesting storehouses. Traditionally, the raw cotton is stored there for a minimum of 30 days as the picked cotton is usually not fully ripe yet. Ripening and collecting cotton wool in storehouses increase the market value of the cotton, as during this period the unripe fibres soak up the oil of the seeds and then become smoother, well proportioned and get a better colour (Pietsch, 1920).

Ginning

After storing the cotton, ginning takes place. Through ginning the cottonseeds in the cotton bolls are separated from the cotton fibre. Afterwards raw cotton wool becomes one third of its original amount. The cotton seeds are, afterwards, used either to plant new cotton, then pressed to make cotton oil or processed as cotton meal, which is used in fast-moving consumer goods. The seed free cotton, the cotton fibre, is also called cotton lint. The fibre of lint cotton is almost pure cellulose (about 84%) and is used to produce cotton fabrics.

Usually ginning is achieved by one of two methods. Cotton varieties with longer staples or longer fibre length are ginned with so called “roller-gins”. A roller gin uses a rough roller, which grabs the fibre and pulls it under a rotating bar with gaps that are too small for the seed to pass through. Roller-gins protect longer cotton fibre and treat them with more care. They can separate 150 to 200 kg of seed cotton wool daily, which results in 60 kg lint cotton.

Cotton varieties with shorter staples or fibre length are ginned with so called “saw-gins”. This process involves the use of circular saw that grips the fibres and pulls them through narrow slots. The seeds are too large to pass through these narrow slots, which means that the fibres are pulled away from the seeds. Saw-gins can separate 2500kg seed cotton wool daily, which results in 700 kg lint cotton. Saw-gins are more efficient and achieve a higher yield of cotton fibre ready to be used.

Commercial cotton is priced by quality, which roughly relates to the average length of the staple and the variety of the plant. Longer staple cotton (6.3 to 3 cm) is called Egyptian cotton, medium staple (3 to 2 cm) is called American upland cotton and short staple (less than 2 cm) is called Indian cotton.

Another method for cotton ginning is the so-called churka, which is operated manually and is well known in less advanced regions such as in East India. Here, the cotton bolls (still including the seeds) are pressed between wooden rollers and when the cotton boll turns the seeds fall off and the fibres remain. Nevertheless, this method is more labour-intensive and achieves a small yield in cotton lint ready to be used for further fabric production.

Nowadays, in modern industrial cotton production, mass cotton harvesting is carried out by smart machines that pick cotton bolls of the ideal ripeness, and, if they happen to pick unripe cotton bolls, separate wanted from unwanted material and have ginning machines that take over the drying and a more comprehensive separation process.

Here the cotton is processed in industrial cotton gins either in trailers or in compressed modules, which weigh up to 10 tons individually. The cotton in the trailers is drawn into the gin via a pipe, which is about 40 cm in diameter. There it is swung over the cotton. Conventionally, the pipes are operated manually but are now automated in modern cotton plants. Through the introduction of these modules, the need to drag the cotton from the trailers to the gin has been reduced.

Afterwards the cotton enters a dryer, which removes excess moisture. The cylinder cleaner has about seven rotating spiked cylinders to open up large bulks of cotton. If ginning does not take place on the same site as cotton harvesting, the delivered cotton modules are broken apart using spiked rollers, which also remove the largest pieces of unwanted material. Finer unwanted material, such as leaves and soil, passes through screens and rods in order to be removed. A stick machine uses centrifugal force, to remove larger foreign material, such as sticks and burrs, while the cotton stays in the machines by the quickly rotating saw cylinders.

Later the cotton bolls are separated again into seeds and cotton lint by ginning ribs. After the initial ginning the cotton lint is pressed through further pipes and is compressed into bales for storage and shipping.

Modern gins can compress about 15 tons of cotton per hour. Despite the fact that industrial methods to source, process and gin cotton fibre are more efficient and have an effect equal to economies of scale, it can lead to exploitation of the cotton soil and reduces the quality of cotton; compared to when all these steps would happen individually with more manual control (Anthony and Mayfield, 1994).

2) Fibre production

Cotton yarn preparation

If the fibre manufacture does not take place where raw material was processed, cotton is shipped in large bales. Even though the cotton has been separated from unwanted material, when cotton bales are opened they still contain vegetable matter. In order to fluff up the cotton and further remove unwanted material and impurities, the cotton is sent through a picker. There, the cotton is beaten with a beater bar and fed through various rollers, which further clean the cotton. The cotton is then collected on a screen and is fed through a number of rollers until it appears as a continuous soft fleecy sheet, the so-called lap.

Sometimes lint from several bales are mixed and blended together to provide a uniform blend of fibre properties. In order to guarantee efficiency of automated feeding equipment and the accurate consistency of the fibre properties, computers group the bales for production or feeding according to fibre properties. Afterwards the cotton fibres are cleaned further from impurities with a process called scutching.

In carding machines the cotton fibres are processed and separated into loose rope-like strands, also called slivers. During a so-called drawing process, fibres are strained and slivers are combined in order to balance out inconsistencies between thick and thin spots and to create an ideal size. After the slivers are combined, they appear as a thick rope of cotton fibres. Therefore they are separated into rovings, which are used in the spinning process (Collier, 1980).

Cotton yarn manufacture

Roving frames draft the slivers out more thinly and add a slight twist as the first step in the ring spinning of yarn. Several mechanical twisting processes are used in order to spin the yarn. For instance, ring spinning machines tighten and thin the yarn until the thickness needed for weaving or knitting fabric is achieved. Ring spinning machines are traditionally used for yarn manufacture. In technologically more advanced regions, open-end spinning is used, where robots are applied who spin almost six times faster than ring spinning machines. With open-end spinning, yarn is produced directly from sliver and the roving process is eliminated.

There are even more technologically advanced systems, which eliminate in-between steps during yarn production, such as roving, ring and open-end spinning. These faster systems are called air jet and Vortex and use compressed air currents to stabilize the yarn.

When spinning is finished, the yarns are wound around tubes or spindles and are ready to be formed into fabric. During the folding and twisting process ply yarn is produced, which are two or more single yarns twisted together. When ply yarns are twisted again they are called cord. Whether cotton is plied or not depends on the weight that is desired.

Sometimes when manufacturing high quality cotton, newly spun yarn goes through a process called gassing, where the yarn is passed through a flame to remove the loose fibre ends, make the thread round and smooth. After gassing, the yarn loses about 8% of its weight (Collier, 1980).

3) Fabric production

After the preparation of the yarn, there are two methods on how to produce cotton fabric. One is called weaving and the other one is called knitting.

Woven cotton fabric

The cotton weaving process uses a loom. On the loom, lengthwise yarns who are called warp, form the base of the fabric. The crossway threads are called weft. Warps require a higher amount of twist than the filling yarns that are interlaced width wise. The strong warp needs to loom on a warp beam. The weft passes across the loom in a shuttle, which carries the yarn on a pirn. The loom mechanically changes these pirns. This means, that the yarn needs to be wrapped onto a beam, and onto pirns before weaving can begin.

Originally, cotton fabric was woven by a wooden shuttle moving horizontally back and forth across the loom while interlacing the filling yarn with the warp yarn. Today, modern mills use high-speed weaving machines that perform at high rates and produce various forms of fabrics.

Weaving consists of various preparatory processes, including winding, warping, sizing, drawing in looms, processing the weft and finally weaving.

The rapier-type or metal-type weaving machines have metal arms that pick up the filling thread and carry it halfway across the loom where another rapier picks it up and pulls it in the rest of the way. Other weaving types use small projectiles that pick up the filling thread and carry it all the way across the loom. Another type employs compressed air to insert the filling yarn across the warp. The advantages of modern weaving machines are versatility, speed and reduced noise during operation.

Weaving machines can produce three types of weaves with a number of variations.

There is the plain weave, where the filling is alternately passed over one warp yarn and under the next. Plain weaves produce fabric types such as chambray, gingham and batistes.

Then there is the twill weave, where the yarns are interlaced in order to form diagonal ridges across the fabric. The twill weave is used for durable fabric types such as denim, gabardine and herringbone.

The last one is the satin weave, which produces a smooth fabric with high sheen. Satin weave is used for cotton sateen and is produced with fewer yarn interlacings and with either the warp or filling yarn, which dominate the surface of the fabric (National Cotton Council of America, 2015).

Knitted cotton fabric

The other method to manufacture cotton fabric with cotton yarns is knitting. Knitting constructs fabric by using a series of needles to interlock loops of yarns. Also knitting is done by two different ways namely warp and weft.

Weft knitting is comparable to hand knitting with stiches all joined to each other horizontally.

During warp knitting many pieces of yarn are zigzagged together by crossing the yarn. Warp knits are not as stretchable as weft knits and are more run-resistant.

The average T-shirt is a weft knit. With weft knits spools of spandex are processed from separate spool containers and interwoven through the cylinder with cotton yarn, which gives the finished good more flexibility and it does not wear out as fast.

Most cotton is knit on circular machineries, which have needles fixed to the rim of a rotating cylinder. When the cylinder turns, the needles proceed from stich to stich and produce a tube-shaped fabric. The width of this fabric is regulated by the size of the cylinder, which normally ranges from 22 to 152 cm in a diameter. In contrast, a hand knitter uses two needles, which forms one stitch at a time.

It depends on the width of the desired fabric how many needles are used in knitting machines. In modern knitting machines of over 2500 needles are common.

A knitting machine may have up to four cones per centimetre of fabric width.

Another basic cotton knitting type is the flat knitting machine. This type is designed with a flat bed and needles arranged in a straight line, which produce flat knitted fabric, comparable to woven fabric. It has the capability to make over one million stitches per minute and can be programmed to increase or decrease stitches automatically in order to widen or narrow the fabric at certain areas, which adds shape to the fabric. Also knitting machines can be set to produce a large variety of fabrics in different shapes (National Cotton Council of America, 2015).

4) Cotton fabric finishing

Cotton fabrics that come from the loom to the unfinished stage are known as greige goods or grey cotton fabric. In order for the cotton fabric to use its full textile potential finishing processes are applied, which provide an added value to the fabric. Usually, grey fabric undergoes finishing processes to meet the correct shape, size, colour and specific end-use requirements. When the supply chain happens at one factory, mills also dye or print their fabrics in addition to spinning and weaving. Other mills sell grey cotton fabric to converters who finish and reprocess the unfinished grey cotton at their plants. Due to today's high demand in divers and versatile textile goods and due fast moving fashion trends, there are endless ways in which grey cotton can be processed. Therefore finishing processes are complex, including a vast range and combination of colours, textures and unique qualities (National Cotton Council of America, 2015).

Overall, grey fabric is cleaned, prepared for the cloth, dyed or printed on, usually bleached or softened or treated in other ways to enhance performance quality.

Singeing

Singeing is the same process as gassing cotton yarn. Unwanted surface fibres from the fabric are heated by gas flames and burnt off in order to achieve smoothness.

Desizing

In order to desize the cloth, it is soaked in a dilute acid and then rinsed. Alternatively, enzymes may be used to downsize the fabric.

Scouring

Afterwards the cotton fabric is chemically washed, in order to remove non-fibrous impurities, natural wax, remaining soil or dirt from the fibres. This process is called scouring. The fabric is boiled in an alkali in an iron vessel called kiers, which forms soap with free fatty acids. The kier is closed so that the solution of sodium hydroxide can be boiled under pressure, leaving out oxygen, which could devaluate the cellulose in fibre. When desizing and scouring are, happenening in one process, the appropriate reagents are used to desize the fabric.

Bleaching

Given that, at this stage most cotton fabrics are naturally white, but for commercial purposes, still considered yellowish, the cotton fabrics are bleached. The process of textile bleaching enhances whiteness and removes natural coloration and remaining colour impurities from cotton. To which extend the cotton fabric is bleached depends on the required whiteness and absorbency of the processed cotton fabric. As cotton is a vegetable fibre mainly consisting of cellulose oxidising agents are used such as dilute hydrogen peroxide or dilute sodium hypochlorite. If the finished textile is supposed to be darker in shade less bleaching is necessary. For white T-shirts the highest level of whiteness and absorbency are important which indicates a high degree of bleaching to be applied.

Mercerising

If a more lustrous cloth is desired, the textiles are dunked under tension in a caustic soda solution, which causes swelling of the fibres and is then neutralised. The other characteristic benefit is strength, silken sheen and dye affinity of the cotton fabric. Before the fabric is mercerised, all alkali must be washed out or shrinkage will take place. Mercerising can be carried out at the yarn stage, directly on grey fabric or after bleaching.

Singeing

Singeing is the same process as gassing. Unwanted surface fibres from the fabric are heated by gas flames and burnt off in order to achieve smoothness.

Calendering

Another relevant mechanical finishing process is calendaring, where the fabric is passed between heated rollers to generate a smooth, polished or embossed effect depending on roller surface properties and their speed.

Sanforizing

After calendaring the cotton fabric, it is shrunk mechanically. This process is called sanforization, where the cotton fabric is stretched, shrunk and fixed lengthwise and widthwise before cutting, in order to reduce the shrinkage, which would otherwise occur after washing. Afterwards the cloth is fed into a sanforizing machine, where it is moistened with water or steam. A rotating cylinder presses a rubber sleeve against another cylinder, which is heated and also rotating. There the sleeve gets compressed and briefly expanded, followed by relaxing to its normal thickness afterwards. The greater the pressure that is applied to the rubber sleeve, the less shrinkage it will have later on. After all these fabric manufacturing steps a wash cycle takes place, which is sometimes followed by steaming the fabric (Muthu, 2014).

5) Apparel production

Dyeing

After the sanforization process, the cotton fabric can be dyed. The most common dyeing processes are piece dyeing and yarn dyeing.

Piece dyeing is for fabrics, which are supposed to be dyed in a solid colour. Here a continuous length of dry cloth is placed full-width through a trough of hot dye solution. Between padded rollers the desired colour is squeezed evenly into the fabric and then excess liquid is removed. Another option is that the fabric, which is prepared in a rope-like twist, is processed on a reel that dunks in and out of a dye beck or vat. For technologically or economically less advanced regions that produce and dye cotton fabric, cloth is commonly dyed by, fully immersing the fabric in an aqueous dye-bath according to a prescribed technique. For enhanced stronghold to washing, rubbing and light, other dyes like vats and reactives are utilised, which however require more complex chemicals during processing and are more cost-intensive.

Yarn dyeing takes place before the cloth is woven or knitted and is usually used to manufacture plaids, woven stripes, ginghams and other special patterned cotton fabrics. For instance in denim manufacture, blue dyed warp yarns are combined with white filling yarns.

A typical method for yarn dyeing is package dyeing. Here the yarn is coiled on perforated cylinders and placed on vertical spindles in a round dyeing machine. Those who are technically more advanced use computers in the dyeing process to formulate and match colours accordingly to the type of cotton fabric with high speed and accuracy (Babu et al, 2007).

Printing

Another way to colour cotton fabric is to print a paste or ink to the surface of the fabric in a prearranged pattern. Printing is sometimes also substitutes localised dyeing. What is more printing design on already dyed fabric is also an option.

To print on fabric, long runs of the same fabric design are manufactured on a roller print machine, which operates at a pace of fifty to a hundred meters per minute. Approximately ten different colours can be printed one fabric simultaneously.

A printing machine has a large padded cylinder, which is surrounded by a number of copper rollers, each with their own dye drain and a blade that removes excess dye. The number of copper rollers depends on the number of dyes that are desired. The cloth moves between the rotating cylinders and rollers under high pressure and picks up colour from the engraved area of each roller in an arrangement. The printed textile is dried and then put in an oven that sets the dye.

Another option is automatic screen-printing, where coloured designs are imparted to the cotton textile. Even though this method is slower than roller printing, it can manufacture larger and more elaborate designs, shadings and handcrafted effects.

A further option is flat bed screen-printing, where one design for each colour is reproduced on fine mesh screens. The areas on the screen, which are not supposed to be tinted with colour are covered with lacquer or other dye-resistant coating. The screens are then coated with dye on the back and placed in the sequence above the flat bed. While a belt carries the textile from one screen to the other, a roller presses or prints the dye through the open area of the screen onto the fabric. Modern flat bed printing machines are more advanced in regards to speed as they have the capability to print a large amount of design prints on long fabrics within a short period.

Another innovation is rotary screen printing machines, which have the highest production speed so far. Rotary screen printers combine screen and roller printing, by using pierced cylinders in place of flat screens. Rotary screen printers can print 16 colours. The colour dye is placed inside the cylinders and small metal rollers push the colour through the pores of the cylinder on the textile, which is in constant movement under the cylinder. Moreover, rotary screen printers are cheaper than roller printers (Clarke, 1974).

In recent years digital printing of textiles, which are marketed as premium goods, has become popular (Uiije, 2006).

Tailoring

The final stage of the cotton supply chain is the manufacturing of the actual textile good. For this case study the production of cotton T-shirt is chosen. Design and tailoring of the cotton apparel either takes place onsite, where the cotton has been turned into the fabric, or is shipped to clothes manufacturers.

After the design and pattern has been chosen, the required shape is cut out of the cotton fabric. Usually the shape is cut out very generously, which creates cotton fabric waste. Afterwards the cut out cotton fabric is tailored into a T-shirt either by hand or by a sewing machine. When the cotton fabric has transformed into the T-shirt it is ironed or steamed. Sometimes cotton T-shirts are printed on after they have been tailored.

When the cotton T-shirt is finished it is packaged and sometimes stored or immediately shipped to retailers, who distribute and sell the goods to their customers (MacIntyre and Tilton, 2009).

3. Cotton Material Flow Analysis

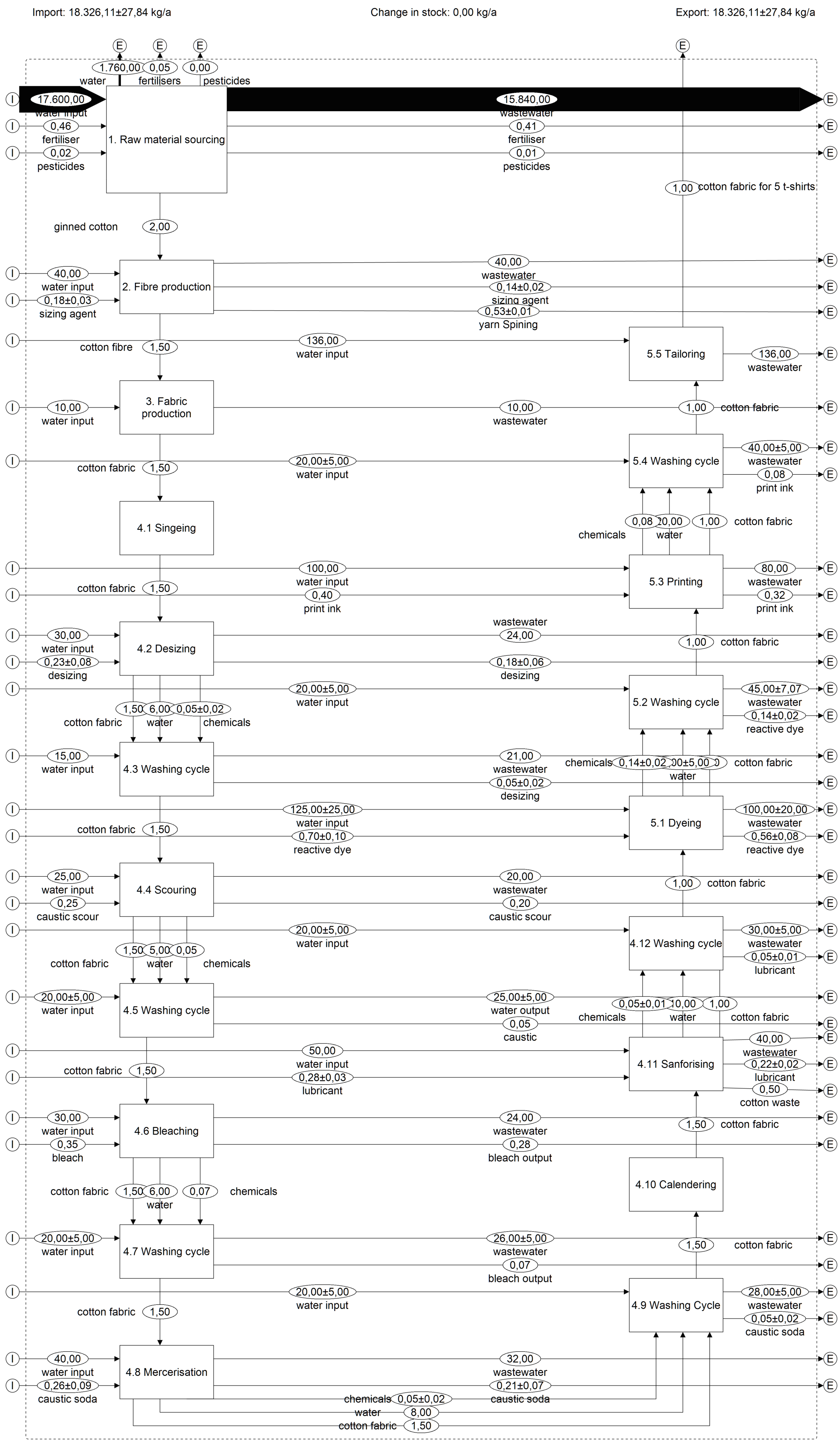
The material flow analysis (MFA) for 1kg of finished cotton fabric is calculated with a program called STAN 2.5, which was created by the Vienna University of Technology.

The MFA demonstrates which substances or goods are used in the entire supply chain of the cotton T-shirt. The steps of the supply chain include the entire textile process from cradle to gate, namely the sourcing of the raw cotton, the fabrication of the cotton fibre, the fabric production, the finishing process of the cotton fabric and the final apparel production of a cotton T-shirt.

Depending on the area, producers, supplier and processes applied, the exact order of the processes within the supply chain of cotton fabric can vary. The MFA demonstrated in this thesis is, therefore a, case study.
The numbers used in this MFA were conducted from research papers, books, journals and official statistics and are calculated for the amount of exactly 1kg of finished cotton fabric. On average, a cotton T-shirt weighs about 200 grams; so if each input and output process is divided by 5 the numbers for 1 T-shirt are given (Gogerly, 2013).
Regardless the fact that this is a case study the versatile nature of cotton textile processes create input and output related uncertainties, which are included in this MFA.

All measurements in the MFA indicate how much is needed for the production of 1kg of finished cotton fabric. It is assumed that the entire production process takes place in India.

The cotton MFA can be viewed on the following page as figure 1.



Flows [kg/a]

a = 1kg of finished cotton fabric produced within 8 months

Figure 1: Cotton Supply Chain

Cotton MFA Input

Energy demand of cotton MFA

The total amount of energy needed in this case study is about 95 MJ/kg produced by non-renewable energy. 55 MJ are required for raw cotton sourcing, fibre and fabric production (Muthu, 2014). 40 MJ are required for the finishing of the cotton fabric and apparel production (Luiken, 2012).

1. Raw cotton sourcing

The first process in the MFA is the raw material stage of the cotton supply chain.
The first process includes cotton cultivation, growth, harvesting and the ginning process of picked cotton bales. For the production of 1kg finished cotton fabric, 5 kg of raw cotton are required.

Water

The total amount of water in this case study to produce 1kg of finished cotton fabric is about 21 400 l/kg. 33% out of the total water demand comes from artificially irrigated water. 21 400 l/kg includes the water needed in order to dilute the wastewater (Chapagain et al, 2006). The total amount of water needed to dilute the wastewater of 1 kg of finished cotton fabric is about 3000 l/kg in this case study (Muthu, 2014).

The water input for the total raw cotton sourcing process equals 17600 l/kg for 1kg of cotton. The water output is about 40%, which is 7040 l/kg. The wastewater is then diluted. 50% with 8800 l/kg remain as stock in the soil of the cotton farm. The remaining 10% of 1760 l/kg water are evaporated into the air.

Fertilisers

During the cotton cultivation and growth stage fertilisers are used. For 1kg of finished cotton fabric, about 457 g/kg fertilisers have been applied during the raw sourcing process. On average on cotton farms, a mixture of 92% nitrogen, 67% of phosphate, 52% of potash and 42% of sulphur have been found in pesticides and fertilisers (Muthu, 2014). According to statistics, fertilisers applied on Indian cotton farms consist of a mix of 66kg/ha N, 28 kg/ha P_2O_5, 6kg/ha K_2O (Chapagain et al, 2005).

Pesticides

For 1kg of finished cotton fabric 16g/kg of pesticides are needed in order to keep vermin and weeds away from the cotton plants (Luiken, 2012). Pesticides are categorised according to pesticide groups. Out of these 16g/kg of pesticides, 67% are insecticides, 22% are herbicides, 5% are fungicides and 6% are applied for other pesticides (Soth et al, 1999).

2. Fibre production

Research suggests that during the production of cotton fibre some cotton mills wash the cotton before or after the spinning process, in order to clean the cotton from impurities. However, the amount of water applied here is very limited.

Water

As spinning is a relatively dry process the use of water is only required for the maintenance of humidity in the spinning of the cotton. After the spinning process, the cotton yarn is cooked in water and starch mixed solution in a process called sizing. Afterwards the cooked cotton is washed in water in order to get rid of remaining chemicals. Therefore the total water input for the fibre production process is about 40 l/kg (Patwardhan, 2008).

Sizing agent

After the spinning process, cotton sizing takes place. Cotton sizing is carried for many reasons. The main reasons for sizing are to improve loom efficiency, reduce sized dropping and warp breakage and to strengthen the cotton yarn. Thus a medium heavy sizing agent is used, which is mixed with water. The cotton yarn is cooked in this solution. For 1kg of cotton, about 150-200 g/kg sizing agent is applied, which consists of a mixture of starch, carboxymethyl cellulose (CMC) and polyvinyl alcohol (PVA) (Patwardhan, 2008).

3. Fabric production

Despite the fact that during cotton weaving or cotton knitting detergents and lubricants may be used, it was decided against the inclusion of heavy chemicals in this step in this case study. This is due to the fact that before the yarn enters the weaving or knitting machines it was lubricated in the sizing process and because in this case study, further straightening, softening and further enhancements of the quality of the cotton fabric take place during later finishing processes of the cotton fabric. For the cotton weaving or knitting stage a very light lubricant of 1.5% based on fatty acid esters and other chemicals per 1kg may be applied, but is not applied in this case study as finishing processes later in the supply chain treat the cotton fabric to achieve similar results (Showell, 2006).

Water

Similar to the spinning method, water is only required in order to maintain the humidity of the processed cotton fabric. The water input in this stage is 10l/kg.

4. Fabric finishing

4.1 Singeing

During singeing loose fibres sticking out of the cotton textile are burned off. Singeing increases the wettability and the affinity of dyeing, while improving the reflection and creating a smoother surface of the cotton fabric. In addition, it decreases cotton lint waste in further finishing processes (Chaudhury, 2006).

4.2 Desizing

Water

Desizing is the process of fully removing the size material from the warp yarns in woven fabrics. For desizing, a water input of about 30l/kg is required.

Desizing agent

During desizing the cotton fabric is treated, with a solution consisting of 150-300 g/kg sulphuric acid H_2SO_4. If a higher concentration of sulphuric acid is used it can damage the cellulose in the cotton fibre (Periyasamy, 2013).

4.3 Washing cycle

In order to get rid of the chemicals a washing cycle takes place. During the fabric finishing process a washing cycle takes place after each finishing procedure (Muthu, 2015). The water applied for the washing cycle is about 15-25 l/kg.

4.4 Scouring

Water

During scouring about 25 l/kg of water are used.

Caustic scour agent

As the woven or knitted fabric is still grey fabric, further finishing techniques are applied in order to raise the quality of the fabric. During scouring, where harsh alkaline chemicals are used the cotton fabric becomes whiter, softer, while natural impurities are removed. These chemicals include a mix of alkali NaOH, soda ash Na2CO3, wetting agents and sequestering agents. In total about 250 g/kg of this caustic scour agent is used (Hasan, 2014).

4.5 Washing cycle

In order to get rid of the caustic scour another washing cycle takes place. The water applied for the washing cycle is about 15-25 l/kg.

4.6 Bleaching

Water

The water requirement for bleaching 1kg of is about 30l/kg (Chapagain et al, 2005).

Bleach

As the cotton fabric is still not white enough to be sold to suppliers or in stores it is bleached. Bleaching can take place at the yarn spinning stage or afterwards during the finishing process. Sometimes the cotton yarn as well as the woven cotton fabric is bleached. To bleach 1kg of cotton 350g/kg of hydrogen peroxide are used (Karmakar, 1999).

4.7 Washing cycle

Again a washing cycle takes place to fully wash out the hydrogen peroxide which was used to bleach the cotton fabric. The water applied for the washing cycle is about 15-25 l/kg.

4.8 Mercerisation

Water

The water demand to mercerise cotton is about 40 l/kg. After the treated cotton is removed from the caustic soda, the remaining water, which will be weak lye can be concentrated by evaporation for recycling in other processes if all fabric finishing processes take place at one mill (Lacasse and Baumann, 2004). However, this does not happen in this case study.

Caustic soda

Cotton is treated with caustic soda NaOH, which leads to a swelling of the cotton. Cotton yarn can be mercerised or already woven fabric can be mercerised. It is argued that mercerisation of woven cotton fabric is not as effective as yarn mercerisation would be. Nevertheless mercerisation is often a part of the finishing process of cotton fabric.

During mercerisation cotton fabric is treated under tension in a solution of concentrated caustic soda. For 1kg of cotton fabric 170-350 g/kg NaOH are used (Lacasse and Baumann, 2004).

4.9 Washing cycle

After the cotton fabric has been treated in the NaOH solution during mercerisation it is washed. The water applied for the washing cycle is about 15-25 l/kg.

4.10 Calendering

Calendering is another finishing process, which increases the smoothness and lustre of the cotton fabric and makes it thinner. Here the fabric is folded and passed under rollers at high temperatures and pressure. The rollers polish the surface and increase the appearance and value of the cotton fabric. As this is a purely mechanical process no chemicals or water are added in the process of calendaring (Lawler and Wilson, 2002).

4.11 Sanforizing

After the calendaring step, sanforization takes place. As the cotton fabric is under constant tension during spinning, weaving, bleaching and other finishing processes the cotton fabric tends to shrink. In order to prevent shrinkage, the cotton fabric is sanforized.

Water

The cotton fabric is fed into the sanforizing machine, where it is moistened with water or steam, while a rotating cylinder presses a rubber sleeve against another heated and rotating cylinder. The cloth is put in between the rubber sleeve and the heated cylinder where it is forced into compression, expansion and relaxation. The greater the pressure applied, the less shrunk the cotton fabric is. The water demand of this process is about 50 l/kg.

Sanforizing lubrication

In order to facilitate the movement of the cotton fabric, which is treated in the sanforization machine, lubricants may be applied. Here about 250-300g/kg of non-ionic fatty acid softeners based on stearic acid ester of glycerol may be applied (Slade, 1997).

4.12 Washing cycle

After sanforization another washing cycle takes place to guarantee that the lubricant is fully washed out. The water applied for the washing cycle is about 15-25 l/kg.

5. Apparel production

During apparel production the final transition of the cotton fabric to the cotton garment takes place. 1 kg of finished cotton fabric is ready to be transformed into cotton T-shirts. As one T-shirt weighs about 200g, 5 cotton T-shirts can be made out of 1kg cotton textile. Given that they are all sold to the same retailer and are supposed to be the exact same in size and style 1kg of cotton fabric can be treated, dyed and printed on and can be finally cut and tailored.

5.1 Dyeing

Water

The water input to dye 1kg of cotton is between 100 - 150 l/kg (Chapagain et al, 2005).

Reactive Dye

There are several methods to dye cotton textiles but the most cotton fabrics are dyed with reactive dye NaCl. In order to dye cotton with a blue dye between 600-800 g/kg of NaCl are used for 1kg of cotton fabric (Luiken, 2012).

5.2 Washing cycle

After 1kg of cotton has been dyed blue it is washed. This washing cycle is very important as it prevents rapid washing out of the colour. It also removes residue colour, which is left on the already dyed cotton fabric. The water applied for the washing cycle is about 15-25 l/kg.

5.3 Printing

Water

The water demand of 1kg printed cotton is about 100 l/kg (Chapagain et al, 2005).

Print ink

Just like dyeing, printing is optional but the T-shirts in this case study have prints. The most conventional type of printing is screen printing. Also during printing, reactive dyes are used, which are mixed with urea, thickeners, resist salt, soda ash and water.

In order to print a modern motive on 1kg of cotton 400g/kg of this print ink is used during screen printing (Choudhury, 2006).

5.4 Washing cycle

After printing another washing cycle takes please to set the ink and wash out what is not required. The water applied for the washing cycle is about 15-25 l/kg.

5.5 Tailoring

This is the final stage of the supply chain. After 1kg of cotton fabric is woven, treated, finished, dyed and printed is it ready to be cut and sewn into 5 T-shirts.

After these 5 T-shirts are sewn they are ironed, steamed and washed again. Sometimes during these washing cycles, special detergents, which finally set the finished cotton T-shirt can be used. However, many retailers who sell conventional cotton clothing do not use these setting agents, which explains why coloured T-shirts are often discoloured after a few washes. Therefore this process it not included in this case study.

Water

Nevertheless, the water input during this final tailoring step is relatively high with 136 l/kg of 1kg of cotton or about 27 l per cotton T-shirt (Chapagain et al, 2005). The reason for this high amount of water consumption might be that outdated ironing, steaming and washing technologies are used in this production step and that a maximum removal of residual applied chemicals is desired after the final washing cycles. When the T-shirt is finished it is packed and ready to be sent to its suppliers and retailers.

Cotton MFA Output

During each production process the material input is used to alter and progress the cotton good. After the input material is used it turns into output material as it leaves the production process again. The estimated output of each production category, summarising all included production processes, is explained in this section.

It is estimated that 80% of the water used during production leaves the production site as wastewater. The wastewater is not as clean as it was, when it had entered the production processes as it is then mixed with chemicals during manufacturing processes as well as during washing cycles to wash out residual chemicals in the cotton fabric. It is estimated that 20% of the water and chemicals used during each process remains in the cotton. After the washing cycle, the remaining 20% of chemicals are washed out and the cotton product is dried and the water evaporates.

Total water and chemicals output

Total water output

For 1kg of cotton produced about 18400 l of contaminated wastewater are released into the environment. This water is then diluted with 3000 l fresh water before or while it is released into the environment.

Total chemicals released

For 1kg of cotton produced about 3 kg of chemicals are released into the environment and can be found in the wastewater and causes the contamination of it.

Water Output

1. Raw cotton sourcing

During cotton farming, it is estimated that 10% of the water input with 1760 l/kg evaporates immediately. The remaining 90% with 15840 l/kg of water remain in the soil and is washed out in the course of the 8 months period, which is the time frame of the cotton supply chain.

2. Fibre production

After cotton has been manufactured into cotton fibre 100% of the water input with 40 l/kg of finished cotton fabric leave the production site as wastewater and as evaporated water when the cotton fibre is dried.

3. Fabric production

After the cotton fibres are woven or knitted into cotton fabric, 100% of the water input with 10 l/kg of finished cotton fabric leave the production site as wastewater and as evaporated water, when the fabric is dried.

4. Fabric finishing

Also after every fabric finishing process 80% of the water input leaves the production site. During each subsequent washing cycle the remaining 20% from the previous process leave the production site. Additionally, 100% of the water entering each water cycle leave the production site or evaporates as the fabric is dried.

The total amount of wastewater, which is caused by fabric finishing, is therefore about 260 l/kg of finished cotton fabric.

5. Apparel production

For apparel production also 80% of the water input leaves the production site. The remaining 20% are washed out after each washing cycle. After the washing cycle 100% of the water input leave the production site as wastewater or evaporated water as the cotton fabric is dried.

The total amount of wastewater, which is caused at the final apparel production site, which turns the cotton fabric into customised T-shirts is about 430 l/kg of finished cotton fabric.

Dilution of wastewater

The total water needed to dilute the wastewater is 3000 l/k (Muthu, 2014). 2000 l/kg are needed to dilute waste water from the first raw cotton sourcing stage and the amount of water which is released after the fibre and fabric production stage about 1000 l/kg are required to dilute the waste water which comes out of process 4 and 5, the fabric finishing stage and the apparel production stage respectively.

Chemicals Output

It is estimated that about 80% chemicals entering the production processes leave as output mostly in the water they are treated and washed with. Every washing cycle removes further 20% of chemicals from the cotton fabric. Even though a very small amount of chemicals remains in the cotton fabric that was treated, in this case study it is assumed that 100% leaves as output.

1. Raw material cotton sourcing

It is assumed that after the application, 10% of the fertilisers with 45.7 g/kg and 10% of pesticides with 1.6 g/kg, are evaporated into the air together in the water they are mixed with.

Further, for 1kg of finished cotton fabric, 10% with 1.6 g/kg of pesticides applied on the cotton farm are evaporated into the air together with the water they are mixed with.

The fertilisers and pesticides applied during cotton farming remains in the soil for a while but are washed out during the timeframe of this case study, which is 8 months. Therefore, 90% of fertilisers and pesticides with 411.3 g/kg and 14.4 g/kg respectively, leave the soil together with the irrigation water as wastewater.

The total chemical output after raw cotton sourcing is 473 g per 1kg of finished cotton fabric.

2. Fibre production

After fibre production 80% with 140 g/kg of the sizing agent leaves the production site together with the wastewater. 20% of the sizing agent remains in the cotton fibre. Furthermore, out of the 2 kg of ginned cotton about 500g get lost as cotton waste during yarn spinning.

3. Fabric production

As there is no input of chemicals during fabric production, where the cotton fibres are woven or knitted into cotton fabric, there is also no output.

4. Fabric finishing

After each finishing process 80% of the chemical input leave the production site together with the water they are treated in. Each finishing process is followed by a washing cycle, which washes out 20% of the chemicals that are used. Even though it is assumed that chemical residues remain in the cotton fabric, in this case study 100% of the input leaves as output.

During 4.11 Sanforising, the cotton weight of 1.5 kg is reduced to 1 kg, as 500 g of cotton fabric are lost during sanforisation.

The total output of chemicals, which leave the cotton fabric finishing is about 1.5 kg per 1kg of finished cotton fabric.

5. Apparel production

For apparel production the same assumption applies as for the previous production categories. After each production cycle 80% of the chemicals used leave the production site as output. The washing cycles, which are carried out subsequently after the finishing process wash out further 20% of the chemicals applied.

The total output of chemicals during apparel production is 1.2 kg per 1kg of finished cotton fabric.

4. Environmental Impact Analysis of the Cotton Supply Chain

This segment discusses the direct, short-term, indirect and long-term impacts of the supply chain within its environment. The environmental impact of the cotton supply chain is not restricted to its system boundaries and time-span. Instead, the objective is to understand in a comprehensive way, which environmental impact the cotton supply chain has on its ecosystem.

1. Air Pollution

Energy for production

The total amount of energy needed to produce 1 cotton T-shirt is 20 MJ/kg. The energy source is non-renewable energy.
Non-renewable energy such as natural gas, oil and coal are burned and add to greenhouse gas emissions.

Coal is the most common source of non-renewable energy consumed globally and comes with a number of environmental problems, from mining to transporting to burning it. In India, where the cotton in this case study is produced, has been the world's third largest coal consumer in recent years. Therefore it is assumed that coal is used as an energy source in this case study (EIA, 2013).

When coal is burned to provide energy to the production of cotton fabric, including ginning, yarn production, cotton weaving or knitting and all cotton fabric finishing steps, it releases pollutants to the air. Air pollutants from coal are sulphur dioxide, (SO_2), nitrogen oxides (NO_x) and carbon dioxide (CO_2). Additionally, mercury is released when coal is burned, which can cause neurological and developmental problems when humans are exposed to it.
Further air pollutants are by-products, which are produced when coal is burned. These by-products are fly ash and bottom ash.
Apart from that, mining of coal leads to mountaintop removal and the death of many humans who work in mines (Gibson, 1981).

Energy for transportation

Further, oil is used to fuel harvesting machines, vehicles, ships and aircrafts for the transportation of goods across the cotton supply chain. The raw cotton, fibres, yarns, fabric and finished T-shirt are transported from mills to the supplier to the retailer. In addition to carbon dioxide CO_2, other pollutants are emitted when petroleum products are combusted. These include methane, mercury compounds, carbon monoxide CO and sulphur dioxide SO_2. When SO_2 is not filtered it can cause acid rain and harm plants and animals. As these emitters also travel, they do not only harm the direct but also proximate ecosystems. The amount of SO_2 and mercury compounds may fluctuate greatly depending on the sulphur and mercury content of the oil that is burned.

Additionally, nitrogen oxides (NO_x) and volatile organic compounds (VOCs) are emitted to the air during fuel combustion, which contribute to smog and ground level ozone. Also particulate matter PM is emitted, which contributes to lung diseases and asthma in humans. Moreover, lead and other air toxins including formaldehyde, acetaldehyde and benzene may be emitted when certain types of petroleum are burned, which all have crucial impacts on living beings. Apart from that, sourcing and drilling for oil can disturb and endanger natural habitats (EPA, 2015).

Cotton in the air

During cotton production, cotton dust is produced, which is a type of solid waste. The mass production of cotton often leads to a mass accumulation of cotton dust, and an increase in particulate matter in the air. As the cotton harvested on cotton farms is treated with pesticides and fertilisers, which contain toxic chemicals, also the cotton dust, which has entered the air contains these toxic chemicals. As a result, workers on cotton farms and locals living nearby the cotton farms are exposed to hazardous lung diseases and have to suffer from breathing problems.

Moreover, cotton waste and cotton dust, is also caused during mid production processes such as ginning, fibre production and yarn spinning, is rarely effectively collected in order to be disposed. Instead, solid cotton dust flows in the air, accumulates on the floor and other surfaces, which pollutes the air the cotton mill workers breath in. The human toxicity factor of cotton dust is therefore very high. (Kumar, 2008)

Chemicals in the air

Pesticide and fertiliser sprays can directly hit non-target vegetation and can drift or volatilise from the treated area and contaminate the air. Often pesticide and fertiliser drifts occur during every application and can spread over many kilometres. Fertilisers and pesticides can be detected in the air, rain, fog or even snow during different times of the year.

In India, where one third of all cotton farms are located, cotton accounts for 54% of all pesticides used yearly, despite of occupying only 5% of land. In an observation period of five months, it was reported that about 100 cotton farmers experienced over 300 separate incidents of diseases. 6% of these incidents were associated with severe poisoning, 38% with moderate poisoning and 39% with mild poisoning. Chronic effects of long-term exposure to pesticide involve impaired memory and concentration, disorientation, confusion and severe depression. Acute symptoms of pesticide poisoning include headaches, nausea, sickness, tremors, lack of coordination, breathing difficulty and respiratory depression, loss of consciousness, seizures and death. As the contaminated air travels, not only cotton farmers, but also people living in villages close to the cotton farms are exposed to this pollution (EJF, 2007).

2. Water exploitation and pollution

Exploitation of water sources

According to statistics, 97% of the water in the Indus River, which is located in Northern India, where our case study takes place, loses its quantity towards producing crops like cotton (WWF, 2015).

The reason for this is that cotton farming requires large amounts of water. In our case study, 17 600 litres of water are needed just for the agricultural aspect of this supply chain and to produce 5kg of raw cotton, which are later manufactured into 1kg of finished cotton fabric. During the later manufacturing processes about 740 litres are used. In addition to using water during most production processes, where chemicals are applied to the cotton fabric in order to generate a certain finish, these processes are followed by washing cycles, where chemical residues are washed out. Mismanaged irrigation practises and impractical fabric manufacturing processes leads to an overconsumption of water. In most countries, where cotton is produced, these amounts of water are naturally not accessible, which means that artificial irrigation is required. Water sources are shortened and rivers and lakes nearby shrink due to industrial exploitation, which causes droughts in areas where heavy irrigation of cotton farms and heavy water usage in the factories are necessary. This causes a depletion of water sources (Chapagain et al, 2005).

In regions where evapotranspiration exceeds precipitation and the amount of freshwater used for irrigation, a salinization of soil is unavoidable. Consequently, freshwater withdrawal for irrigation purposes lead to the depletion of lakes and rivers. When rivers are over-used for producing cotton, and when water inlets are redirected and used for irrigation and production purposes, rivers and lakes can dry out and fish species become extinct. There have been several cases, where high salt content of some exploited lakes or rivers have caused salt desserts. The high concentration of salt in the lakes and the high burden of toxins from the agricultural and production sites released back to the rivers have also destroyed the fishing industry in these regions. Additionally to salinization, winds can transport the salty and toxic sediments of the dry riverbed, which can travel in the air and cause health problems to humans and animals (EJF, 2012).

Further, often dams are constructed for a facilitated irrigation of cotton farms. This leads to a reduced water flow, which affects freshwater ecosystems lying downstream of the dam. As freshwater ecosystems are accustomed to specific water flows, any changes in water quantity or temporal distribution have the potential to affect whole freshwater ecosystems (Soth et al, 1999).

Pollution of water sources

Apart from the fact that enormous amounts of water are used during the production process, which are not as abundantly available in Northern India, as for instance in European countries, the water is hardly ever cleaned, recycled and then reused within the factory.

Large amounts of clean water are used in the production process and disposed as wastewater containing harsh chemicals. Wastewater is usually emitted to nearby water sources, which are often local rivers and lakes. Locals are dependent on these water sites, but when these sources become polluted they cannot make use of them anymore. Instead locals are often required to acquire their water demand per capita elsewhere. Water is often purchased from expensive water delivery services, due to the pollution of their domestic water sources (Soth et al, 1999).

The polluting substances in the wastewater depend on the production process. During the sourcing of raw cotton, fertilisers and pesticides are applied. In this case study these materials drain away into local rivers or local lakes. Due to inappropriate water management and irrigation technology, water runs off from fields to proximate lakes, rivers and wetlands. This run-off contains soil sediment including pesticide and fertilisers residues. These pesticides have a direct toxic effect on wildlife. Pesticides also have an indirect effect by accumulating in the biosphere. This leads to a decline in animal fertility and affects long-term freshwater biodiversity.

It has been observed that even when pesticides are properly applied with the correct technical instructions, there were still impacts on freshwater and ecosystems. This means that when highly toxic chemicals are applied, contaminated run-off from these fields results in extinction of fish in rivers surrounding the treated cotton farms. In comparison to pesticides, fertilisers are not directly toxic, but change the nutrient system and consequently the species composition of certain freshwater ecosystems. The most visible effect is eutrophication of freshwater bodies, where the growth of algae leads to interference of the biological equilibrium including exterminating aquatic life.

Apart from the water used to irrigate the cotton farms the fields are irrigated additionally with freshwater to remove the salt from the soil. This is done to prevent salinity of soils and water logging. However, when this water is returned to the rivers, the salt, pesticides and fertiliser residues containing drainage has a negative impact when they enter and pollute the rivers and lakes directly (Soth et al, 1999).

In addition to the high amounts of agricultural chemical and waste left in the wastewater that re-enter local water supplies, further down the supply chain, also the harsh chemicals used for bleaching, dyeing, detergents, the large amounts of caustic soda and all other finishing processes leave the production sites with the wastewater. For 740 of litres used to prepare the ginned cotton into 1kg of cotton fabric, about 2.9 kg of chemicals are used, which leave the production site as wastewater.

Industrial wastes and effluents are the biggest pollutants of most Indian rivers and other sources of fresh water. The majority of chemicals found in the industrial waste and used in this case study during the finishing processes, are toxic to life forms that consume this water. According to statistics, the cotton textile industry is the third highest generator of wastewater and water pollutant in India (Chand, 2015).

The outsourcing of primary, secondary and tertiary industrial production to India and other developing countries has lead to a number of environmental problems, including water supply, wastewater generation and its collection treatment and disposal. Production sights, which came up on the banks of rivers have not implemented a sound management of wastewater and sewerage management. In industrial areas in India, water is tapped for industrial use from rivers streams, lakes, ponds and wells and almost 80% of the water supplied passes out as wastewater, which is often left untreated and causes large scale pollution of the surface water. Likewise as in this case study, in about 26% of the cases the wastewater is treated and diluted with freshwater in order to minimise the concentration of chemical waste. In this case study 3000 l of freshwater are used per 1kg of finished cotton fabric in order to dilute the wastewater. The remaining wastewater is disposed untreated. The treated and untreated wastewater is disposed into natural drains, which flow into rivers or lakes and are often re-used on land for irrigation and cultivation (Chand, 2015).

This practice creates a very hazardous water cycle and a dirty industry, which endangers the environment, the workers engaged with the daily routines of the cotton textile industry and all other living beings exposed to this pollution. Furthermore, it has been reported that lakes and rivers located close to industrial sites in India have occasionally caught fire as a result of pollutants being dumped inside them for decades. A lake close to South India has been rich in ammonia, phosphate and low in oxygen, which formed severely toxic froth that caught fire due to the oil, grease and detergents that are in it. It is assumed that chemical reactions caused the foam to combust, while the fire was caused due to methane building up on the surface of the water. When this water is spilled out onto surrounding roads and areas it can cause even more dangerous incidents (O'Callaghan, 2015).

3. Soil depletion and pollution

The uninterrupted cultivation, growth and harvest of cotton have led to the degradation of soil quality. The natural landscapes including wetlands and floodplains, which are ideal areas for cotton cultivation due to their flat shape and fertile soil, have been transformed into arable land. The arable land is less able to soak up water, making flooding more common. In addition, due to the drainage of the soil and the mon-ocultural cultivation of cotton, the arable land no longer provides a habitat for its original plants and animals.

Despite the fact that the areas where cotton is grown have remained almost constant for the last decade, cotton production has depleted and degraded the soil in many areas. Another reason for this change is the salinization of soil, taking place through inappropriate irrigation and water logging. Therefore, even though cotton is grown on deeply ingrained fields the widespread exhaustion has also affected new areas and has caused destruction of habitat for living beings. Many practises used in growing cotton crops have lead to the loss of topsoil and destruction of soil characteristics that make agriculture possible (WWF, 2015).

Today, cotton is the world's most important non-food agricultural commodity. Since the 1980s the global consumption of cotton has risen radically, with demands now in excess of 25 million tonnes annually. While the bulk of global cotton production occurs in developing countries, the majority of cotton products are sold to consumers in developed and emerging economies (EJF, 2007).

Due to the high demand in cotton worldwide, cotton farming has grown en masse in many countries worldwide. Despite the fact that many of these countries do not have favourable weather conditions and water resources to grow cotton of high quality, cotton is still produced in these countries due to economic advantages. Further, many cotton producing regions lack state-of-the-art technology to produce cotton efficiently and sustainably (Smith and Cothren, 1999).

In order to compensate these lacks, large amounts of pesticides and fertilisers are applied on cotton farms, which help cotton plans to grow according to the commercially desired quality. In this case study about 460g of fertilisers and 20g of pesticides are applied on the soil per 5kg of cotton bolls. The land on which these crops are grown cannot be used for the growth of other agricultural commodities, as small input irregularities or disturbances on cotton farms can alter or damage the cultivation of cotton crops. Furthermore, cotton requires vast amounts of space and needs to be monitored regularly (Pietsche, 1920).

In this case study fertilisers and pesticides applied remain in the soil for a while before it leaves the fields as wastewater. The effects of inorganic fertilisers and pesticides on the soil are variable. Some products can have positive or negative impacts. The effects of fertilisers and pesticides on soil can either be direct or indirect. Direct impacts can be short-term or long-term and cause harm to the organisms that get in contact with the chemicals. Indirect impacts are long-term and cause changes in the environment and food sources of organisms. Both impacts affect nutrient availability and crop productivity in the soil.

Fertilisers

The direct effects of fertilisers on soil can be short-term, during the first stages or cotton farming after the application of fertilisers, and long-term, when the soil and crops need to be fertilised continuously. Indirect and long-term effects are due to changes in pH or changes in productivity, residue inputs and soil organic matter levels. This means that nutrient availability to plants and crop productivity are changed due to large amounts of fertilisers applied like in this case study.

Another relevant aspect is the potential damage to soil microorganisms from high concentrations of ammonia fertilisers applied. Studies have shown that total microbial activity in the area of applications were reduced for a short term and returned to normal after the application of fertilisers was stopped. However, when large amount of fertilisers were applied the recovery was stagnated (Seymour, 2015).

Pesticides

Insecticides are the most toxic class of pesticides, and herbicides pose great risk to non-target organisms. The positive impacts of pesticides on soil are increased cotton production due to reducing insects and weeds on the cotton farms. The negative impacts are that herbicide will decrease organic matter inputs from weeds, while other organisms such as birds and beneficial insects, and often non-target soils are hit. Certain pesticides also affect short-life cycle organism like bacteria, which however recover quickly. Nevertheless, longer-lived organisms such as nematodes and earthworms take longer to recover from damage (Seymour, 2015).

Heavy treatment of soil with pesticides can endanger and destroy beneficial soil microorganisms. If bacteria and fungi are lost, then soil degrades. Further, the overuse of chemical fertilisers and pesticides work for a few years. After a while there are not enough beneficial soil organisms to hold onto the nutrients. Another aspect is that plants depend on a variety of soil microorganisms to transform atmospheric nitrogen into nitrates, which the cotton crops can use. Herbicides disrupt this process, as certain chemicals applied reduce the growth and activity of nitrogen fixation by bacteria, including inhibiting the transformation of ammonia into nitrite and nitrate. Further, certain fungi aid the nutrient uptake of cotton plants but are damaged by herbicides in the soil (Aktar et al, 2009).

4. Solid waste

Throughout the entire cotton supply chain solid waste accumulates. This includes the by-products of the energy providing coal combustion, which is bottom as that contains metal oxides and alkali.
Other forms of solid waste are unripe cotton bolls, which were picked during harvesting and cannot be manufactured industrially. If cotton farms are not controlled and monitored regularly, if weather conditions in this season were not ideal for cotton plants to grow properly and if not enough fertilisers or pesticides were applied, unripe or pest-infected cotton bolls will be picked during harvesting. Throughout the entire supply chain cotton weight is reduced from 5kg of raw cotton bolls to 1kg of finished cotton fabric. The remaining 3kg are cottonseeds and plant waste. About 5% of the cottonseeds are used for sowing the next cotton crop and the rest is processed into cottonseed oil and feed for animals. The remaining 2kg of cotton lint are processed into cotton fibre, cotton yarn and cotton fabric, where 1kg of cotton fibre and cotton fabric waste accumulates.

This waste cannot be reused or reprocessed into commercial products and is rarely used in waste-to-energy technologies. Instead it is disposed of at landfills, together with every other type, of waste, which are produced in the cotton supply chain. In India, the most common type of waste disposal is unplanned open dumping. Apart from its strong odour and being aesthetically unpleasant, open dumping leads to tremendously unsanitary conditions and causes severe environmental degradation problems. Chemicals and other contaminants found in solid waste can seep into the groundwater and can be carried by rainwater to rivers and lakes. This further pollutes local water sites and destroys the water sources of humans and the habitat of wildlife. Waste is dumped in low-lying areas that are within or outside the cities and are designated as dumping grounds. Often waste is also disposed in unauthorised areas on the outskirts of urban regions. Occasionally, waste that has been dumped openly has been found on roads to rural areas, which do not have own space for the disposal of waste. Often hazardous industrial waste, which is neither spread nor compacted, is deposited at dumpsites that are designated for domestic waste. Instead, it is left uncovered and eventually degrades under natural conditions. As a result, the mixed waste dumped at open sites generates leachate and pollutes adjacent water sites, while contaminating the air with methane emissions and uncontrolled burning. Therefore, open dumping especially of industrial waste creates severe health and environmental issues for the urban and rural areas, especially for the people living in the proximity of the dumping sites (Sharholy et al, 2008).

In the year 2000, a solid waste policy was framed in India under the Supreme Court, under which municipality solid waste rules were created. The aim is to stop the unplanned open dumping of waste outside city limits, identify clear landfill sites and the prohibition of littering and open dumping on roads. Moreover, 50% of India's waste contains organic matter, which should be kept out of landfills in order to avoid the build up of methane. While there are only a few options to incinerate organic matter in India, it was suggested to potentially treat and convert it into stabilised degraded organic matter or compost. The compost can be used to improve soil quality by increasing its moisture and porosity and by delivering nutrients for enhanced structure of soil and a better agricultural yield. Moreover, if more organic waste is reused it could reduce the burden on landfills so that less waste ends on open dumped landfills (Zhu et al, 2008).

In the year 2013, pollution and environmental degradation was shown to have cost India 80 billion US dollars a year, according to the World Bank. Further, it is well known that the exploitation of child labour is quite common in the textile industry in developing regions; also well-known is the fact that children are more sensitive to the exposure of harsh chemicals. According to the World Bank, the impact of environmental damage in India is mostly caused by air pollution and contaminated water, which also leads to a high number of deaths especially in children. By switching to green technologies and implementing organic and ethical production methods, these severe environmental problems and human tragedies can be stopped (AFP, 2013).

5. Lyocell

Introduction

Viscose, rayon, modal, lyocell and other fibres of cellulose origin are made of cellulose from tree wood using different fibre manufacturing processes. This kind of fibre has been manufactured since the late 19th century and has been called art silk or artificial silk due to its smooth and soft texture. In the early 20th century the textile industry adopted the term rayon. Fibres of cellulose origin have also been called natural synthetic fibres or reconstructed fibres (Lackman, 2008). There are many different types of rayon and for this thesis the production of lyocell fibres is chosen. There are different ways to produce lyocell fibres as the production process of the most commonly traded lyocell type is legally protected with a patent. The supply chain of the lyocell fabric in this thesis is therefore a theory-based case study build on findings in scientific journals, books and company reports.

Lyocell producers

In the 1970s, an American fibre producer called Enka invented Lyocell and gave it the operation name Newcell. In the 1980s, a UK based fibre producer called Courtaulds Fibres further developed the technology to produce lyocell under the brand name Tencel. Courtaulds was the first producer to make lyocell fibre commercial available, but reduced to small outputs due to its limited output capabilities of its production plant in the UK. After Courtaulds bought a US production site, lyocell production and its market potential was highly expanded. In the 1990s, Austrian viscose producer Lenzing AG has also been producing lyocell fibres under the brand name Lenzing Lyocell. In the late 1990s, Dutch fibre producer Akzo Nobel Fibres merged with its newly acquired Courtauld Fibres and categorised it under the name the brand division Acordis Courtaulds Fibres. Acordis further developed and commercialised Tencel. In 1999, Akzo Nobel sold Acordis to CVC Capital Partners, a European private equity firm with its headquarters in Luxembourg (Woodings, 2001).

In the year 2001, CVC wanted to buy 80% stake in Austrian Lenzing AG but this acquisition was blocked by the European Union commission in order to prevent the creation of a regenerated cellulose producing monopoly (Smith, 2001).

Nevertheless, in 2004 CVC sold its Tencel division to Lenzing AG, after an intervention of the Austrian regional appeal court referring to cartel law. Lenzing adopted the brand name Tencel and aimed at improving the production of Tencel in order to make it more eco-friendly and reduce emissions (Fellhuber, 2004).

As of 2004, Lenzing AG had lyocell production sites in the UK, the United States and in Austria. In 2010, it was reported that Tencel had become one of the most expensive regenerated cellulose fibres, strictly protected by many patents owned by Lenzing AG, which entails the production technology of lyocell and prevents other lyocell producers form using the same technologies (Sen, 2012).

Today, Lenzing AG is the major commercial producer of lyocell fibres, with the exception of a few small companies producing enhanced deviations of lyocell fibres (Woodward, 2015). One of these producers is German fibre manufacturer Zimmer AG with its lyocell fibre called Seacell.

The main use of lyocell remains in the fashion industry, where it is applied in the production of lingerie, underwear, jackets, coats, blouses and an advanced version of denim. In addition, lyocell is also used in the production of work wear, household textiles and medical textiles. Lyocell can be manufactured into 100% lyocell garments or can be blended with other textiles (Smith, 2001).

Properties of Lyocell

Lyocell is a man-made textile, based on cellulose and prepared in a chemical procedure. Most commonly lyocell is made from beech, eucalyptus, oak and birch wood, which means that it comes from a purely natural resource. Due to the purely natural source of lyocell, it is claimed an organic, environmentally justifiable and eco-friendly textile, according to the principles of sustainability. Regarding lyocell's chemical procedure it is similar to viscose. The difference between both textiles is that lyocell fibres are produced in a different dissolvent solution and different spinning procedure than viscose fibre. This different production method of lyocell is known to be environmentally friendlier than the production of viscose as it uses fewer chemicals. As lyocell is a fairly new textile it is also known as an advanced version of viscose. In comparison to viscose, lyocell has the potential to fibrillate. This means that the wet fibre can develop micro-fibrils by manipulating or controlling fibrillation, which can

create a large assortment of fabric finishes. The texture of lyocell can, therefore, be from soft and suede-like to silky and smooth. Furthermore, lyocell is sturdier, smoother, more absorbent, less sensitive to heat and more boil-proof.
In comparison with cotton, lyocell is more elastic, sturdier, more resistant to deformation, easier to wrap, less sensitive to heat, firmer, less prone to wrinkle and easier to iron.

Due to lyocell's composition the fibres and lyocell fabric absorbs more humidity, which increases the wearing comfort for the consumer. Even after many washes, lyocell textiles remain soft and smooth and keep their gloss similar to silk. Further, lyocell textiles are very breathable, dermatologically friendly and therefore even suitable for very sensitive skin. Additionally, the advantages of lyocell fabric give the lyocell clothes a perfect fit, which does not change after washing them.
Due to its advanced characteristics lyocell is often mixed with other textiles such as silk, linen, wool, cotton and polyester (Sinclair, 2014).

Whereas the production of viscose and other regenerated cellulose fibres need the application of harsh chemicals in their production, the production of lyocell is less environmentally demanding. During the production of textiles such as viscose, rayon and modal the pulp is cooked in sodium hydroxide, sodium sulphide and carbon disulphide. Later viscose is spun in solutions mixtures of zinc sulphate and acid sulphur. This has lead to the conclusion that even though viscose has been seen as a solution to conventional textiles it creates a negative impact equally as strong as its competing textiles. Therefore, production of viscose has been reduced, adapted to use less chemicals or has been blended in with other textiles. Nevertheless, cooking in harsh chemicals is still necessary in order to achieve the consistency that viscose or lyocell has.

As a result more environmentally friendly production methods from wood pulp have been sought and lyocell was created. Apart from using fewer chemicals than viscose, modal and conventional cotton in its production the manufacturing of lyocell uses a closed-loop process (Shen and Patel, 2010).

How a lyocell T-shirt is made

1) Raw material sourcing

Wood production

Despite the fact that the wood production is rarely included in the life cycle analyses of viscose in many research papers or journals, it is mentioned in this thesis.

Depending on whether forests are protected from being used for industrial purposes, often managed tree farms are used instead as sources for industrial pulp produces. For the tree farming small amounts of fertilisers are applied based on nitrogen and phosphate. Sometimes viscose and lyocell producers use the trees, which have been grown in forests for years without using specific cultivation or growing techniques. The burden of rayon, viscose, lyocell and all other textiles, which are all sourced from trees is for this reason deforestation.

The pulp of hardwood trees, which later turn into lyocell is usually from a mix of trees chosen for their cellulosic properties including their colour and mount of contaminants. Hardwood trees are harvested by loggers and cut into 6 meters lengths and then debarked by highly pressurised jets of water. Afterwards the logs are placed in a chipper, which is a machine that cuts the wood into squares, which are between 3cm and 15mm in size (Lackman, 2008).

Preparing wood pulp

Before the wood turns into pulp the cellulose content is about 42%. Then lignin (27%), hemicelluloses (28%) and extractives, which are sugars in the wood, are removed from the pulp and cellulose remains inside the wood. To achieve this, the wood is cooked for about 7 hours in a solution of magnesium bisulphite, washed, bleached and dried. The end product of this raw material sourcing is pure cellulose pulp with the same chemical properties as cotton (Issakainen and Kettunen, 2015).

The magnesium bisulphite process removes the lignin and hemicellulose from the cellulose. The base can be split into magnesium oxide and sulphur dioxide and can therefore be used for chemical recovery. This means that the waste product of the solution, in which the pulp is cooked, in can be used as an energy source and for chemical recycling in the same or further process (Lenzing, 2015).

During the magnesium bisulphite process the cut-up 3cm – 15mm, wood chips are put into a vessel or a so-called chemical digester. Inside this digester the wood pulp is softened and cooked under high temperature in a magnesium bisulphite solution, which turns it into wet pulp. Then the pulp is washed with water in order to remove the chemicals. The softened pulp can be bleached to lighten up and get a uniform colour. The wood pulp is then dried into sheets that are rolled into large spools, which have a functional similarity to the purified cellulose sheets in the conventional viscose production process. The consistency of the cellulose sheets is similar to thick poster board paper. The cellulose roll weighs about 230 kg at this point.

Dissolving cellulose

At the lyocell mill, where the rolled cellulose spools are delivered to and further processed into lyocell fibres, the spools are unrolled and broken into small squared pieces. These squares are then cooked again in a large enclosed vessel under high temperature and pressure in a solution filled with amine oxide or N-methylmorpholine-N-oxide (NMMO) and water. NMMO is a strong hygroscopic substance, which quickly absorbs water in air up to an equilibrium concentration of about 60%. With NMMO contents of more than 65% aqueous NMMO, solutions can change easy into supersaturated solutions, while spontaneously crystalizing. These two properties are the reason for the commonly available concentration of 60% aquaeous NMMO solutions (Maron, 1994).

To dissolve cellulose, a solution of 60% aqueous NMMO, 30% and 10% pulp is required (Shand, 2006). After a brief period of soaking and cooking in the solvent, the broken up cellulose pulp sheets dissolve into a liquid solution. The liquid solution is then pumped out through a filter, to insure that all chips are dissolved and to remove any undissolved pulp chips (Woodings, 2011).

2) Fibre production

Cellulose NMMO spinning solution

During the spinning process the solution is pumped through spinneret heads into a diluted NMMO solution, which cause the cellulose strands to set and align. This procedure and spinnerets are used with a variety of manmade fibres. Similar to a showerhead, the spinneret is pierced with tiny holes, and when the liquid cellulose is forced through it, long strands of fibre are pushed out. This NMMO solution, which sets and aligns the cellulose strands, is diluted this time. The cellulose fibres are then washed with a de-mineralised water solution.

Afterwards the lyocell fibres are dried, through evaporation of their water content. In order to untangle the filaments easily they are coated with a lubricant such as soap, silicone or another drying agent, depending on the future use of the fibre. At this point the fibres are called tow.

The fibres are then carded for them to lay in the same direction and crimped to give the fibres texture and bulk. The crimper, which compresses the fibres, is carded by mechanical carders that comb the fibre to separate and order the strands. Next, the fibre is cut to a uniform length and baled together. The manufacturing process including unrolling the raw cellulose to bailing the fibres takes approximately two hours in total. Subsequently the lyocell may be processed in different ways such as be spun with other fibres like cotton or wool or be woven or knitted into pure lyocell fabric. For the latter product, the baled fibres are sent to fibre mills, where they are twisted into yarns and woven or knitted into lyocell fabric (Woodings, 2001).

Reuse of solvent NMMO

The amine oxide used to dissolve the cellulose and set the fibre after the spinning process is recovered and reused in this part of the manufacturing process. The dilute solution is evaporated, where water is removed, and the NMMO is routed for re-use in the pressurized vessel where the cellulose is dissolved (see 1. Dissolving wood pulp). The recovery process is said to reclaim 98 - 99% of the NMMO in the typical lyocell manufacturing process and unrecovered NMMO is decomposed in the wastewater processing (Woodward, 2015).

Lyocell yarn spinning

During yarn production, lyocell fibres undergo several mechanical processes that combine, align and spin them. In recent years, spinning technology has advanced so far that the improvement of textile quality while lowering the cost of yarn production could be achieved. The most commonly used spinning technologies are ring and open-end rotor spinning, the latter one also called rotor spinning, and air jet spinning. Despite the fact that ring spinning is relatively slow compared to air jet spinning, it is said to produce yarns of the highest quality in comparison to the other spinning technologies (Terinte et al, 2014).

Ring spinners can spin 20 meters per minute and air jet spinning produces 450 meters per minute. Moreover, ring spinning produces less waste compared to cotton spinning. Nevertheless, companies that use air jet spinning claim that their applied spinning technique guarantees the highest productivity, best product performance, lower hairiness and that air jet spinning is ultimately perfect for cellulose fibres (Eichinger, 2012).

As lyocell spinning is a dry process, there are no issues regarding the wastewater for this procedure and emissions are solely related to energy used. The amount of electricity used in lyocell spinning depends on the thickness of the yarn (Terinte et al, 2014).

3) Fabric production

Knitting

After the lyocell yarns have been produced they are knitted into a fabric. Knitting is a mechanical procedure, which involves knotting yarn together with needles. There are two ways to produce knits, namely flat and circular knitting. The most commonly applied knitting technology is circular knitting. During knitting often lubricant oils such as mineral oils are used for the needles and further parts of the machine in order to reduce friction. These lubricating oils are washed out during a washing cycle. Regarding the environmental impact of knitting, energy use is most relevant, as well as air emission depending on how much mineral oil based lubricant is used (Terinte et al, 2014).

4) Lyocell fabric finishing

Scouring

Also lyocell fabric is scoured during its finishing treatment. For the lyocell case study, the fabric is washed with bio-scouring agents. Lyocell is scoured to remove impurities in the raw lyocell fabric such as residual sulphur or auxiliaries used in knitting lubricant oils and to better prepare the lyocell fabric for dyeing and other finishing processes. Sulphur residues could potentially destroy or change the shade of dyes.

Bio-scouring agents are often a blend of pectinase and cellulose enzyme. It does not use harsh chemicals such as caustic scour agents such as NaOH and Na2CO3. Additionally, strong alkaline processes reduce the fabric weight by 6-8%. Bio-scours break down the pectin in fabrics and assist the removal of waxes, oils and other impurities. It is an environmentally friendly and gentle way of fabric processing and saves water and energy. This cellulose enzyme and pectinase treatment also improves the softness, pilling tendencies, drape ability and post-laundry appearance. Further lyocell does not require a large amount of bio-souring agent.

Scouring can be done individually or together with bleaching or desizing either at the yarn or the fabric stage of the lyocell textile. After scouring there is a washing process, which gets rid of the residue scour agents (Tao, 2001).

Dyeing

Dyeing can be performed either at the yarn production stage or when the fibre is already woven or knitted into a fabric. These two ways are called piece or yarn dyeing. The advantage of yarn dyeing is that during the dyeing process no pigments are lost. In the end the finished garment would not be dyed on the surface but in-depth. Lyocell, just like cotton and all other cellulose fibres, can be dyed with a large range of dyes such as reactive, direct, vat, sulphur and azoic dyes. Today, one third of dyes are reactive dyes, so this method is used in both, the cotton and the lyocell case study. Whereas reactive dyes offer a good balance between fastness and shade range, other dyes are faster but limited in shade and can be complex in their procedure.

Usually every fibre or fabric needs its own dyeing system and a certain combination of chemicals with process parameters such as temperature profile, time and pH value. In addition steam for heating requirements are required. In order to fully remove the residue dyes the dyeing process is followed by six washing cycle (Babu et al, 2007).

Softening

After dyeing and washing, the lyocell fabric undergoes another finishing treatment, which is softening. Fabric softeners have lubricant properties that are electrically conductive, which makes the fabric smoother and prevents the fabric to be electrostatic. Thus, softening improves the presentation, performance and feel of lyocell. The fatty acid softeners, which are used for softening the lyocell fabric, also improve the fabrics ability to be sewn better and can be used to guarantee hydrophobicity, stain release and anti-bacterial properties (Terinte et al, 2014).

Centrifugation and drying

The final step of the lyocell fabric finishing includes centrifugation, which is a mechanical dewatering using a centrifuge. After centrifugation drying of the textiles takes place. In the drying process the textiles are heating in order to remove the remaining water by evaporation. This step is necessary to remove and reduce the water content of lyocell fabrics after wet processing. Knitted lyocell fibres are dried using a stenter, which is a gas fired oven where the fabric passes through a chain drive that is held together by pins or clips. Before the air is exhausted to the atmosphere, it circulates below and above the lyocell textile. The stenter is also used to pull the fabric to the desired width, during chemical finishing and heat curing and heat setting (Terinte et al, 2014).

5) Apparel production

Printing

After the cotton fabric has passed all the finishing processes it is ready to be customised into the desired garment. For this case study the fabric is tailored into lyocell T-shirts. Before the fabric is cut it is printed with the same hip print, which was used for the cotton T-shirts. This means that the lyocell fabric is coloured dyed with another paste or ink on the surface of its fabric with a prearranged pattern. The printing technique applied is screen printing. Depending on how advanced the factory is different screen printing techniques can be used from automatic screen-printing, flat bed screen printing and rotary screen printing.

As lyocell fabrics are fairly advanced textiles, where digital printing is used in this case study, which is faster and allows direct printing from the printer on the fabric without additional screens. Through this technique no pigments are lost in the printing procedure. The print ink would however still be from reactive dye (Uiije, 2006).

Tailoring

The final stage of the lyocell supply chain, is the manufacturing of the actual textile good. For this case study the production of a lyocell T-shirt is chosen. Design and tailoring of the lyocell apparel either takes place onsite where the cotton has been turned into the fabric or is shipped to clothes manufacturers. As the supply chain of 1kg of lyocell is used in this case study 5 T-shirts can be made as an average T-shirt weighs about 200grams.

After the design and pattern have been chosen, the required shape is cut out of the lyocell fabric. Usually the shape is cut out very generously, which creates lyocell fabric waste. Afterwards the cut out lyocell fabric is tailored into a T-shirt either by hand or by a sewing machine. When the lyocell fabric has transformed into the T-shirt it is ironed or steamed. Sometimes lyocell T-shirts are printed on after they have been tailored.

When the lyocell T-shirt is finished it is packaged and sometimes stored or immediately shipped to retailers, who distribute and sell the goods to their customers (MacIntyre and Tilton, 2009).

6. Lyocell Material Flow Analysis

The material flow analysis (MFA) for 1kg of finished lyocell fabric is also calculated with STAN 2.5 provided by the Vienna University of Technology.

Also for the lyocell case study an import and export of substances and goods are used in the entire supply chain of lyocell garments. The steps included in the lyocell supply chain include the entire textile process from cradle to gate. This means that sourcing of wood, production of wood pulp, extracting and dissolving cellulose, manufacturing of the lyocell fibre and fabric, the fabric finishing process and finally the apparel production of the lyocell T-shirt are discussed.

It is important to mention that depending on the region, manufacturers, suppliers and processes, the exact order within the supply chain of lyocell fabric can vary. Especially for man-made regenerated cellulose fibres, which are sometimes considered as synthetics various chemical processes can be used. The decision is based on environmental and economic considerations, and occasionally also on the available know-how of sustainable techniques. As lyocell is promoted as a sustainable fabric, the supply chain analysis and MFA are integrating the most sustainable processes, which are applied by state-of-the-art manufacturers and recommended in scientific journals.
Therefore the supply chain of the discussed lyocell T-shirt is a case study.

On average a lyocell T-shirt weighs about 200 grams, so if each input and output process is divided by 5 the required measurements for 1 T-shirt is given.

For the lyocell case study average numbers from scientific journals, books and statistics are used. Despite the fact that this is a case study, the available options on how to produce lyocell fabrics, create input and output related uncertainties, which are included in this MFA.

All measurements in the MFA indicate how much is needed for the production of 1kg of finished cotton fabric.

The lyocell MFA can be viewed on the following page as figure 2.

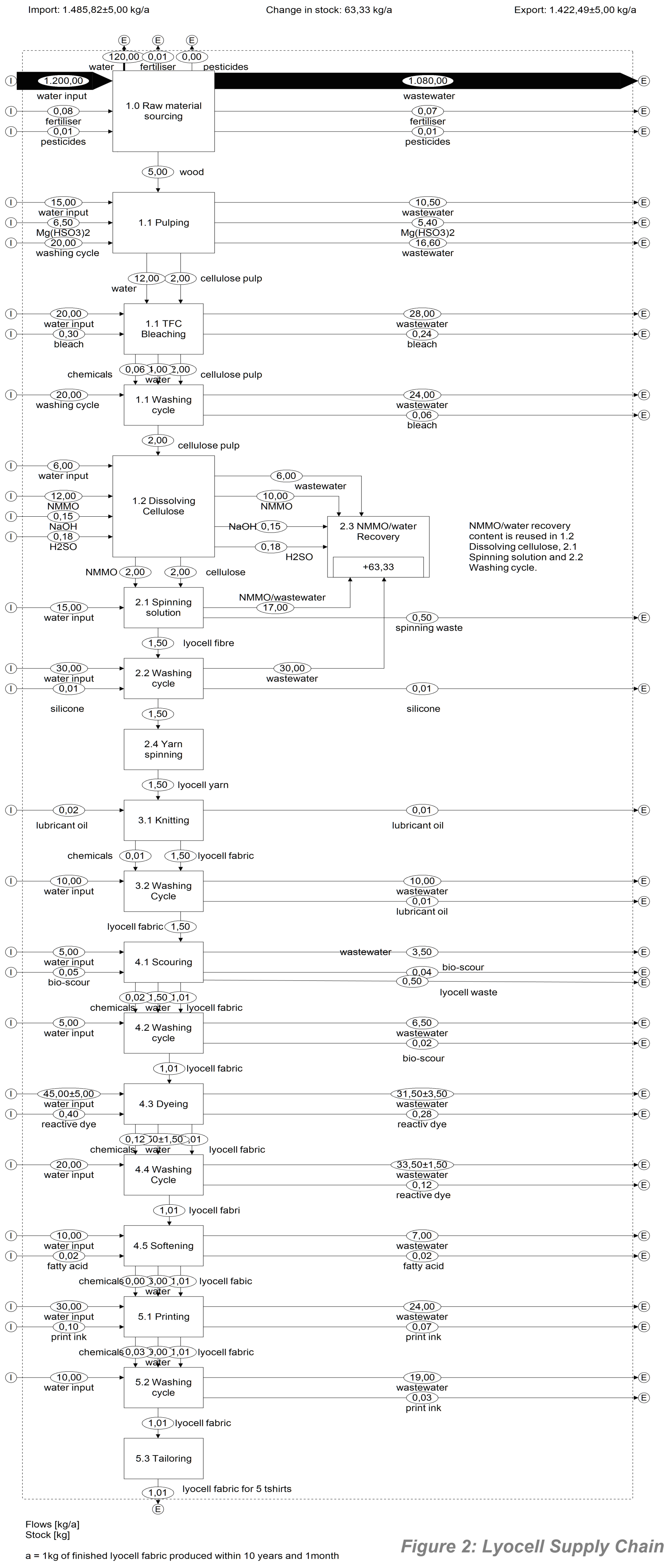


Figure 2: Lyocell Supply Chain

Lyocell MFA Input

Energy demand of lyocell MFA

The energy demand for tree cultivation is not included in this case study.
The total non-renewable energy demand in this case study is assumed to be 72 MJ/kg. From pulping to the knitted fabric 42 MJ/kg and for the fabric finishing 30 MJ/kg of non-renewable energy are used.
The total renewable energy demand in this case study is assumed to be 94 MJ/kg. From pulping to the knitted fabric 59 MJ/kg and for the fabric finishing 40 MJ/kg of renewable energy are used (Shen and Patel, 2010).

1. Raw material

1.0 Wood production

For this case study a beech tree is considered as the source of the lyocell T-shirt. A beech tree, which is grown on tree farms, is cut after many years of being cultivated.
Fully grown beech trees weigh between 650 – 800 kg/m^3 (Stemmann, 2005). From 1 ton of wood 400 kg of cellulose can be produced (Sappi, 2003). Therefore for the production of 1kg of finished lyocell fabric ready to be designed into a T-shirt, 5kg of wood are necessary.

Water

Trees in this case study are irrigated naturally. Trees extract their water demand from the soil and through their roots and then evenly distribute it within. A grown out and fully mature 200 years old beech tree has a higher water demand than a younger beech tree and it is recommended not to over water young trees so that they can survive dry periods when they get older. A ten-year-old beech tree is about 4 meters tall, is relatively thin compared to older beech trees with 40 cm diameter. A ten-year-old tree would weigh between 200-250 kg. A beech tree has a yearly precipitation of 600mm/m2, where two thirds reach the soil (Kluitmann, 2011).

The water demand of 5kg of a ten-year-old beech wood is therefore 1200 litres in this case study.

Fertilisers

For this 5kg of wood 75g of fertilisers based on 2/3 of nitrogen and 1/3 of phosphate are applied. The fertilisers improve the conditions of the tree and the soil, aid the tree growth and the amount applied may be higher depending on the tree farm (Shen and Patel, 2010).

Pesticides

As trees grown on tree farms, they are not in their natural environment as they are grown, cultivated and harvested in a rapid period of time in order to be manufactured for industrial or commercial uses small amounts of pesticides are used for the trees. Another reason for beech trees to be treated with pesticides is that they might get beach bark disease, which causes defect and mortality of the trees (Houston and O'Brien, 1998). The pesticides are a mixture of insecticides, herbicides, fungicides and acaricides (Marrotte, 2005). It is estimated that for 5 kg of wood 10g of pesticides are applied through tree injection or crop duster aircraft depending on the condition of the trees on the tree farm.

1.1 Pulping

During pulping the wood is chopped into small pieces and cooked in a chemical solution. This is called the magnesium bisulphite pulping procedure, which is said to be less toxic and more environmentally friendly than its counter parts, which use sulphate. This solution separates the hemicellulose, lignin and extractives room the wood pulp and only cellulose remains in the wood. Further also the consistency of the wood changes, as it becomes softer and lighter and can be rolled into spools once the procedure is over.

Water

The estimated requirement for cooking 5kg of wood in chemicals is 15 l. The water is mixed with magnesium bisulphite.

Pulping solution

The wood pulp is prepared in a cooking acid with the soluble base Mg(HSO3)2 magnesium bisulphite. The solution is enriched with SO2 gas, so that it becomes sour. The effective properties in the solution are the sulphite and bisulphite, which turn the lignin into hydrolysed and soluble substance. The magnesium bisulphite takes place in a 200-300 m^3 digester and is cooked at up to 150°C (Dilger, 2015). The difference between pulping for paper and for lyocell is that lyocell requires a slightly higher amount of chemicals and is cooked under higher temperatures. The required amount of Mg(HSO3)2 for 5kg of wood is 6.5 kg magnesium bisulphite (Shand, 2006).

Washing Cycle

After the wood pulp has been digested in magnesium bisulphite and cellulose remains in the pulp and weighs 2kg. The wood pulp is washed in order to get rid of chemical residuals. The water demand for this cycle is 20 litres (Wallenberger and Weston, 2004).

Bleaching

In order to guarantee and improve an evenly distributed brightness of the lyocell fabric, bleaching takes place at the cellulose pulp stage. As a more sustainable way to bleach is envisaged bleach free of chlorine is applied.

Water

The estimated water input to bleach 2kg of cellulose is 8 litres.

Bleach

The TCF (totally chlorine free) bleach consists of oxygen, ozone and hydrogen peroxide. For 2kg of cellulose pulp 300g of TCF bleach are required (Bajpai, 2012).

Washing Cycle

After bleaching another washing cycle takes place to wash out residual chemicals. Water requirements are 20 litres (Wallenberger and Weston, 2004). After the washing cycle the bleached cellulose pulp is dried, rolled in sheets or spools further processed.

1.2 Dissolving Cellulose

During this process, the cellulose left in the wood pulp is rolled out and the cellulose sheets are broken up and put in a dissolving solution, which dissolves the cellulose under high temperatures and creates a liquid solution. The solution consists of a water and amine oxide mix with a distribution of 60% biodegradable and reusable aqueous NMMO (N-Methylmorpholine N-oxide), 30% water and 10% pulp (Sen, 2011). The cellulose pulp, which weighs at this stage 2kg (10%), water (30%), and aqueous NMMO (60%) solution weigh together approximately 20 litres (100%).

Water

The water requirement for this process is 6 litres or 3 litres per 1kg of pulp. In the first production run it is regarded as an input. For further production runs, where water and NMMO are recovered, the added water is regarded as recycled (Krüger, 1993).

NMMO

The 60% aqueous NMMO part of the NMMO-water solution weighs about 12kg or 6kg per 1kg of pulp. It is then mixed with the water and the cellulose pulp. Further 150g NaOH lye and 180g sulphuric acid are required (Firgo et al, 1994). After the first production run the additional input of NMMO is about 30-60g/kg, due to residual NMMO-water sludge left over in the machines and vessels and due to the input of the NMMO/water recovery (Firgo et al, 1996).

In order to dissolve the cellulose, it is cooked at 85-95°C. Within the vessel the water evaporates and is captured to be reused later on. Within this vessel about 13% or 0.8 litres of the water remain. With more water the cellulose would not be able to dissolve. At 85° C the cellulose dissolves into a liquid solution called dope. Cooking above 100° C would lead to decolourisations of the liquid cellulose (Maron et al, 1994).

2. Fibre production

2.1 Spinning solution

When the cellulose is dissolved as the dope solution it is immediately spun in spinnerets after which they enter a spinning bath. When the cellulose strands enter the spinning bath they weigh between 1 – 1.5kg. This spinning bath consists of a solution of aqueous and diluted NMMO, which causes the fibre strands to set, strengthen and align. The water and NMMO within this diluted spinning bath comes evaporated water from the previous process and after the first production run from recycled NMMO and water from the NMMO/water recovery. The fibre strands can only set in a diluted and aqueous NMMO solution of higher temperatures at 90 – 120°C (Sen, 2011).

Water

The water requirements in the spinning bath are estimated to be 15 l/kg. After the first lyocell production run the water comes from the washing cycle in 2.2 and from the “NMMO/water recovery” unit (Wallenberger and Weston, 2004).

NMMO

The NMMO used for the spinning bath is sought from the previous process 1.2 dissolving cellulose. The water-NMMO solution for the spinning bath however is much hotter and has a higher degree of water dilution, which sets the cellulose strands. In the spinning bath the cellulose strands become lyocell fibre (Rosenau et al, 2001).

2.2 Washing Cycle

Water

After the lyocell fibres are set, they are washed in two washing cycles in order to remove residual NMMO. The water comes from the "NMMO/water recovery" is pumped back to the NMMO/water recovery, after the process is finished. The water and NMMO are filtered and individually purified so that they can be reused. The water requirements for these washing cycles are estimated to be 10 l/kg (Wallenberger and Weston, 2004).

Silicone softener

After the lyocell fibres are dried 10g/kg softeners based on silicone are applied in order to increase the smoothness and elasticity of the fibres. Softer fibres also facilitate an enhanced finish after yarn spinning and increase the quality of the lyocell yarn.

2.3 NMMO/water recovery

During the NMMO/water recovery, 98 - 99% of the used water and NMMO from process 1.2 -2.2 is filtered, separated, purified and reused. The NaOH and H2SO4 applied during dissolving the cellulose is included in the recovery. This process is a great improvement in the production of regenerated cellulose fibre and is the reason why lyocell is also called third generation viscose. As NMMO is reused over and over again and biodegradable if it was disposed this process reduces the amount of chemicals used in textile production drastically (Figro et al, 1994).

Water

The total water input of the "NMMO/water recovery" unit after the first production run of lyocell is approximately 51 litres. This water is filtered, purified and reused.

NMMO

The total NMMO input of the "NMMO/water recovery" unit after the first production run of lyocell is approximately 80-100g. The NMMO is filtered, purified and reused.

2.4 Yarn spinning

During yarn spinning, the lyocell fibres are twisted and spun into yarn. As the yarn fibre has already been softened with silicone, previously there are no additional softeners required during spinning. Yarn spinning is a dry process, which means that no water input is necessary (Terinte et al, 2014).

3. Fabric production

3.1 Knitting

During the knitting of lyocell, yarn is knitted together with needles. In order to reduce friction with the needles and other parts of the knitting machines lubricant oil based on mineral oil is applied.

Lubricant oil

Due to the already soft and smooth nature of lyocell and other regenerated cellulose fibres, less lubricant oil is necessary in comparison to other natural and coarser fibres. For 1kg of lyocell yarn 20g of lubricant oil are required (Terinte et al, 2014).

3.2 Washing cycle

Knitting is followed by a washing cycle, which washes out the mineral oil of the lubricant. The water demand is estimated to be 10 l/kg (Wallenberger and Weston, 2004).

4. Fabric finishing

The impurities in lyocell are less present than in cotton, therefore less finishing processes are needed compared to cotton.

4.1 Scouring

After the lyocell fibres are knitted into lyocell fabric, they undergo a finishing process, which improves the quality, removes potential impurities and chemical residuals from previous steps and increases the absorbance of dyes and prints. In order to reduce chemical waste and to continue the more sustainable manufacturing process of the lyocell fabric, scouring is carried out with bio-enzymes.

Water

During scouring about 5 l/kg of water are used.

Bio-Scouring agent

The bio-scouring agent is a blend of pectinase and cellulose enzymes. For 1kg of lyocell 50g of this bio-scouring agent is applied (Tao, 2001).

4.2 Washing Cycle

After scouring the treated lyocell fabric is washed to remove the bio-scouring agent from the fabric. The water input for this washing cycle is estimated to be 5l/kg.

4.3 Dyeing

At this production stage the lyocell fabric is ready to be dyed with pigments. Despite the fact that reactive dye is not the most sustainable and environmentally friendly dye, research found that it is still the most common dye even amongst industrial producers, who are known to be environmentally friendly (Terinte et al, 2014).

Therefore reactive dye NaCl is also used in this lyocell case study. The best available technology for conventional batchwise dyeing of lyocell fabrics is suggested to be the ultra-low liquor ratio airflow jet machines, which are associated with reducing the water consumption, minimising effluent loading during textile processing as well as with reducing energy requirements.

Compared to cotton, lyocell dyes to a heavier depth by exhaust techniques, which means that many shades can be attained at a lower cost, especially with reactive colours (Woodings, 2001).

The dye yield of lyocell is found to be greater than that on cotton or other rayon types. Reactive dyes have a higher natural affinity for lyocell than for cotton. Consequently, reactive dyes with good migration properties will be best suited for lyocell. Overall this leads to a reduction in chemical costs, treatment and the amount of total dissolved solids (Chavan and Patra, 2003).

Water

The water input to dye 1kg of lyocell is estimated to be 40-50 l/kg.

Reactive Dye

In order to dye lyocell with a blue dye between 300-400 g/kg of NaCl are used for 1kg of lyocell fabric.

4.4 Washing Cycle

The washing cycle is after dyeing is necessary to wash out any dyes that are left in the lyocell fabric. The water input for this cycle is 20 l/kg.

4.5 Softening

In order to set and bring out the full potential of the colours, while softening the dyed lyocell fabric, it is treated with fatty acid softeners. This process is sometimes also called saponification.

Water

For 1kg of lyocell fabric 10l of water are used during softening and saponification.

Softener

For 1kg of lyocell fabric 20g of fatty acid softener are applied (Figro et al, 1996).

5. Apparel Production

After the fabric finishing, the lyocell fabric centrifuged, dried and ready to be stored or shipped to a clothes manufacturer. The clothes manufacturer decides which shape the lyocell textile will be shaped into. Due to fibrillation lyocell can take the appearance of many different types of textiles and appear suede-like or silky smooth. For this case study the lyocell fabric's appearance is soft, drapeable and robust similar to cotton in order to be tailored into a high-quality lyocell T-shirt.

5.1 Printing

Likewise to dyeing, printing is optional. Prints in this case study are made with reactive dyes, which are mixed with urea, thickeners, resist salt, soda ash and water (Choudhury, 2006). Before the lyocell fabric is tailored into cotton it is printed with the same modern motive as the cotton T-shirt. Due to lyocell's higher absorbance of water and dye, a reduction in quantity of inputs is given. Additionally, lyocell in this case study is printed with digital print, which guarantees precise printing, where no pigments from the reactive ink are lost (Uiije, 2006).

Water

The water demand of 1kg printed lyocell is about 30 l/kg.

Print ink

In order to print a modern motive on 1kg of lyocell 100g/kg of NaCl of print ink is used.

5.2 Washing Cycle

After printing any residual print ink is washed out. The water demand for this washing cycle is 5-10 l/kg.

5.3 Tailoring

During tailoring 1kg of lyocell fabric is cut and sewn into 5 lyocell T-shirts with an individual weight of 200 g. For this process, no water, softening or other inputs are required. After the T-shirts are sewn they may be washed in order to tighten the seam and avoid shrinkage at the consumer stage. However, the lyocell fabric in this case study is treated too well and at an advanced stage that finishing treatments at the tailoring stage is not required anymore.

When the T-shirt is finished it is packed and ready to be sent to its suppliers and retailers.

Lyocell MFA Output

The material flow analysis also indicates the output of each production stage. The output numbers can show which direct or indirect link the material flow of the lyocell supply chain has to the environment.

During each production process the material input is used to alter and progress the cotton good. After the input material is used it turns into output material as it leaves the production process again. The estimated output of each production category, summarising all included production process, is explained in this section.

Total Output

Total water output

The total water output of 1kg finished lyocell fabric is about 1500 litres for the entire lyocell supply chain. This wastewater in the production sites is managed under Austrian regulations, cleaned and if possible recycled.

Total chemicals output

The total chemical output is 1.5 kg. This wastewater or sludge is managed under Austrian regulations, cleaned and if possible recycled or filtered and disposed.

Total stock

The total stock of the lyocell supply chain is 63.33 kg, which can be found in 2.3 NMMO/water recovery.

Water Output

As the production of lyocell takes place in Austria in this case study, it is assumed that the wastewater, which leaves the production mills, is later cleaned, reused and recycled.

1. Raw material production

1.0 Wood production

During wood production of 5kg of beech wood over ten years, about 10% with 120 l of irrigation water are evaporated. The remaining 90% with 1080 litres

1.1 Pulping

After pulping, about 60% with 9 l count as wastewater. This water was used during the magnesium bisulphite process. Together with the chemicals, which are used in the magnesium bisulphite, this wastewater is used for chemical and energy recovery. The waste, which is a product of the pulping, consists of hemicellulose, lignin and extractives from the wood. 1.5 kg of this waste can be found in the wastewater. Therefore the wastewater output is 10.5 litres.

Washing Cycle

After the pulping process a washing cycle takes place with an output of 70% with 14 litres wastewater. In addition, further 40% with 2.6 kg from the magnesium bisulphite process input is found in this wastewater. Therefore, the total water output of this washing cycle after pulping is 16.6 litres.

Bleaching

The water output after bleaching is 28 litres. These consist of the remaining 12 litres of wastewater from the pulping process, which leaves as wastewater and 80% of the water input required from bleaching with 16 litres.

Washing cycle after bleaching

The washing cycle after bleaching causes a water output of 24 litres. This includes the remaining 4 litres from the bleaching process, which is found in the cellulose pulp, and the total water input of 20 litres.

1.2 Dissolving cellulose

After cellulose has been dissolved, there is no wastewater, as everything is filtered and recovered in the NMMO recovery. The total water output of the raw material production and cellulose production category is therefore about 1280 l per 1kg of finished lyocell fabric.

2. Fibre production

2.1 Spinning solution

After cellulose has been spun and entered the spin bath, there is no wastewater, as everything is filtered and recovered in the NMMO recovery. However, there is a solid waste output of about 500 g of lyocell fibre waste, which is caused during spinning.

2.2 Washing Cycle

There is no output of the water used in the spinning solution, as the water is cleaned and reused in the 2.3 NMMO/water recovery.

2.3 NMMO/water recovery

There is an output of wastewater of about 0.01% with 0.0051 l as the remaining 99% water is recovered after 1.2, 2.1. and 2.2. The total water output for 2. Fibre production is therefore 0.0051 litres.

3. Fabric production

3.2 Washing Cycle

After the yarn has been knitted into lyocell fabric, the lubricant oil, which was applied, is washed out. 10 litres of wastewater leave the production site.

4. Fabric finishing

After 4.1 Scouring, another 500g of solid cotton waste are created. Every fabric finishing process has a water output of 70%. The remaining 30% leave the production site during the washing cycle. The washing cycles have a water output of 100%. The lyocell fabric is dried after each washing cycle, which means that water is also evaporated in this process. The total water output for fabric finishing is therefore about 90 l per 1 kg of finished lyocell fabric.

5. Apparel Production

The total water output, which is caused during apparel production, is 43 litres.

Chemical Output

1. Raw Material

1.0 Wood production

Out of the total output about 10% of the fertilisers and pesticides evaporate immediately with 7.5 g and 1g respectively. The remaining fertilisers and pesticides remain in the soil and are washed off in the timeframe of 10 years. The total chemical output is therefore 85 g per 1kg of finished lyocell fabric.

1.1 Pulping

After pulping, 60% of the chemicals in the wastewater leave the production sites and are filtered, recovered and reused for the production of regenerated cellulose fibres or for other purposes. These are 5.4 kg including the hemicellulose, lignin and extractives, which are separated from the cellulose in the wood.

50% with 4.5 kg of the pulping solution is called thick black liquor and is used for chemical recovery and energy generation.

10% of the chemicals with 0.9 kg per 5kg of pulped beech wood also leave the production site as wastewater and reused as by-products acetic acid, furfural, xylose and sodium carbonate (Lenzing, 2015).

Bleaching

After the cellulose pulp is bleached, 80% with 240 g of TCF bleach leaves the production site in the wastewater.

Washing Cycle after bleaching

After the washing cycle an extra 20% with 60g of the TCF bleach leave the production site with the wastewater.

1.2 Dissolving Cellulose

After cellulose has been dissolved there is no output of the chemicals, which have been applied, as they are recycled in the NMMO/water recovery and reused. The total chemical output of the raw material sourcing and pulping category is therefore about 6 kg.

2. Fibre production

2.1 Spinning solution

After the cellulose has entered the spinning bath, there are no chemicals leaving the production site, as everything is recycled in the NMMO/water recovery and later reused.

2.2 Washing Cycle

Also after the washing cycle, none of the chemicals used in the spinning solution, which are washed out of the cellulose leaves the production site but is recycled in the NMMO/water recovery.

Silicone Softener

The chemicals, which are washed out 100% with 10g of the silicone softener, are applied during the last step of the washing cycle in order to guarantee a smooth finish after yarn spinning.

2.3 NMMO/water recovery

As 99% of the chemicals are recovered in the NMMO/water recovery, only 0.01% with 1 g/kg finished lyocell fabric exit as output.

The total chemical output of lyocell fibre production is 11g per 1kg finished lyocell fabric.

3. Fabric production

The chemical output of every production process in this category is estimated to be 70 - 80 %. Each washing cycle washes out the remaining 20% and has an additional output of 100% of its input. The fabric production category has therefore an output of about 20 g per 1 kg finished lyocell fabric.

4. Fabric Finishing

Each fabric finishing process has an output of 70-80% of chemicals, which leave the production site in wastewater. The remaining 20% are washed out after the washing cycle. The total chemical output for the fabric finishing category is therefore 470g per 1kg of finished lyocell fabric, which leaves the production site with the wastewater.

5. Apparel Production

During the last finishing processes the lyocell fabric is customised into lyocell T-shirts. The printing process has a chemical output of 70% and the washing cycle, which washes out residual print ink, an output of 30% of print ink.

The total chemical output of the apparel production category is therefore 100g, which leaves the site with wastewater.

7. Environmental Impact Analysis of the Lyocell Supply Chain

This segment discusses the direct, short-term, indirect and long-term impacts of the supply chain within its environment. The environmental impact of the lyocell supply chain is not restricted to its system boundaries and time-span. Instead, the objective is to understand the wide-ranging effects of the lyocell supply chain on its ecosystem.

1. Air Pollution

Energy for production

The total amount of energy needed to produce 1 lyocell T-shirt with non-renewable energy is 14.4 MJ/kg and 18.8 MJ/kg with renewable energy.
It is believed that, if the biomass by-product from pulping was used as an energy source, the total energy demand for 1kg of lyocell fibre or 1 lyocell T-shirt would be half the original amount (Wallenberger, 2014).

In this case study the energy demand for 1kg of lyocell is lower than the energy demand to produce 1kg of cotton. However, this energy demand depends on where cotton was produced. In African countries and in China, the energy demand for 1kg of conventionally produced cotton would be lower than the demand to produce 1kg of lyocell (Wallenberger, 2014).

Some studies claim that conventional cotton is the most energy efficient textile to produce, whereas other studies suggest that new technologies have made the production of lyocell surpass cotton as the most energy efficient textile (Shen and Patel, 2010). Nevertheless, energy is one of the most important elements to produce lyocell, as without it wood would not be able to be cooked and transformed into a luscious fabric. Therefore it is crucial to find an energy source with the lowest environmental impact in order to support and guarantee the authentic sustainability of lyocell.

In Austria, where the lyocell case study takes place, the most common non-renewable energy sources in the industrial sector is natural gas (BMWFW, 2014).

Despite the fact that natural gas is a hydrocarbon fossil fuel, its global warming potential is said to be lower than that of coal or oil. It is believed that natural gas emits about 50% less carbon dioxide when it is combusted in an efficient natural gas power plant. Additionally, natural gas also emits about 20% less heat-trapping gases compared to gasoline, when it is burned in machines and vehicles. However, the drilling and extraction of natural gas as well as its transportation in pipelines, causes the leakage of methane (CH4), which has hazardous impacts on the ecosystem and has a more severe global warming potential than CO2. It is important to notice, that whether natural gas has a lower life cycle GHG emission than coal and oil depends on the leakage rate, the global warming potential of methane over different time frames and the energy conversion efficiency. Nevertheless, when natural gas is burned, it is the cleaner choice compared to other fossil fuels with lower amounts of mercury, particulates and sulphur. Additionally, natural gas produces less nitrogen oxides NOx, therefore producing less smog (UCSUSA, 2015).

The most common renewable energy sources in Austria are hydropower and biomass. Hydropower is said to be the most sustainable, most efficient and cleanest source of energy, free from emissions to the environment (BMWFW, 2014).

As Austria is a country rich in water supplies, hydroelectric energy is an ideal renewable energy option. Further, the energy produced by hydroelectric plants does not produce any toxic GHGs that pollute the air. The biggest environmental impact, contamination and stock are created when the power plants are built. What is more, hydropower has relatively low operating and maintenance costs and is believed to be one of the safest energy providers. Nonetheless, hydropower also comes with an environmental cost. The reservoir of water for hydropower releases large amounts of carbon dioxide, nitrous oxide and methane. When the area around the dam is filled with water, the plants and trees in them start decomposing without the use of oxygen. This creates large amounts of GHG, which are released into the environment and increase pollution (Tremblay et al, 2015).

The second option is to use biomass as an energy source. During pulping 60% of the wastewater or sludge is reprocessed and reused. Out of these, 50% of the wastewater or so-called thick black liquor is used for energy recovery and energy generation. Black liquor contains lignin, hemicellulose and other extractives from wood, which were separated from the cellulose in the wood. The black liquor contains more than half of the energy content of the wood that is digested and processed into cellulose pulp. Waste-to-energy methods allowed the recovery and utilisation of black liquor to turn it into energy. This reduces the water, chemical and use of other energy sources to produce lyocell fabric and would allow the lyocell producer in this case study to become energy self-sufficient by producing about 50% of their own electricity needs on site.

Still, the using biomass as an energy source also has an impact on air emission as its combustion emits nitrogen oxides (NOx,) sulphur dioxiod (SO2), carbon monoxide (CO) and particulate matter (PM). However, the amount of air emission depends on the combustion technology and installed pollution control technologies. Whereas this biomass option emits less mercury, SO2, NOx, CO and PM-10 than coal its emission into the air of these pollutants is slightly higher than natural gas or almost the same, depending on the boiler used (PFPI, 2011).

This means while energy is recovered during the combustion of black liquor biomass, it is not a cleaner option for air emission compared to the other non-renewable energy source in this case study. Still, leaving out one non-renewable energy source and replacing it with a self production energy source would create a balance and would indeed make this type of renewable energy source more efficient.

Energy for transportation

Moreover, similarly as in the cotton supply chain, oil is combusted in vehicles, which transport the wood from the tree farm to the factory and the intermediate products from process to process.

In addition to carbon dioxide (CO2), other pollutants are emitted when petroleum products are combusted. These include methane, mercury compounds, carbon monoxide CO and sulphur dioxide (SO2). When SO2 is not filtered it can cause acid rain and harm plants and animals. As these emitters also travel they do not only harm the direct but also proximate ecosystems. The amount of SO2 and mercury compounds may fluctuate greatly depending on the sulphur and mercury content of the oil that is burned.

Additionally, nitrogen oxides (NOx)and volatile organic compounds (VOCs) are emitted to the air during fuel combustion, which contribute to smog and ground level ozone. Also particulate matter PM is emitted, which contributes to lung diseases and asthma in humans. Moreover, lead and other air toxins including formaldehyde, acetaldehyde and benzene may be emitted when certain types of petroleum are burned, which all have crucial impacts on living beings. Apart from that, sourcing and drilling for oil can disturb and endanger natural habitats (EPA, 2015).

This means, oil and natural gas combustion are the largest industrial source of VOCs, contributing to the formation of ground-level ozone and smog. Human exposure to this ozone can create a large variety of severe health problems. Moreover, oil and natural gas industry is an important emitter of methane and other air toxins such as benzene, ethyl benzene and n-hexane, which cause cancer and other severe diseases (EPA, 2015a).

Therefore the environmentally conscious option would be to produce lyocell with renewable energy and recovered energy, even if this option has a slightly higher energy demand.

Chemicals in the air

The pesticides and fertilisers applied on tree farms is very limited with 10% of the initial input, which is evaporated on the tree farms. Pesticides and fertilisers are emitted into the air, either during the application or after the application. For 5kg of beech wood, which later turn 1kg of finished lyocell fabric this would be 7.5 g of fertilisers and 1g of pesticides. The remaining chemicals applied on the tree farms remain in the soil for a while and are later washed off, where further 50% of the content evaporates or is lost to the transport pathways of volatilisation, leaching and runoff. The remaining wastewater enters proximate water sites. It is believed that agricultural soil is the largest source of N2O, which results from the application of fertilisers. Further, when applied pesticides cause volatile organic compounds VOC to enter the air, which contributes to the formation of ground-level ozone, which is harmful to human health and vegetation when present at high concentrations. Nevertheless, as the application rate and amount in this case study is very controlled and little, the pesticides and fertilisers applied on these tree farms do not have a strong impact towards air pollution.

2. Water pollution

The production of 1kg finished lyocell fabric in this case study has a water demand of 1440 litres. This includes the water to naturally irrigate 5kg of beech tree over a period of 10 years with 1200 litres. This means that 240 litres are needed for the remaining processes. Out of these 240 litres, 35 litres are used during pulping, where 50% of the wastewater becomes black liquor and is reused as an energy and chemical recovery source and 10% are reprocessed into by-products acetic acid, furfural, xylose and sodium carbonate, which can be used for other industrial purposes. Further 50 litres are caught, filtered and recycled in the NMMO/water recovery and reused for further production cycles. This means that 225 litres leave the production site as wastewater together with 0.99 kg of chemical waste that is not recycled or recovered in any process. Despite the fact that the total chemical input in the lyocell supply chain is significantly higher than in the cotton supply chain, the chemical output is much lower and leaves the production site diluted in the wastewater.

Regardless of the fact that still very harsh chemicals are used in the production of lyocell, even though it is said to be a sustainable textile, the majority of these chemicals are reused and reprocessed and the residues therefore have a very low emission to water. During the finishing process of lyocell fabric, many producers choose to apply conventional processes, which add reactive dye and caustic soda. These methods can be replaced with more sustainable solutions, similarly to the chlorine free bleaching practise and scouring with bio-enzymes in this case study.

The wastewater is filtered and cleaned according to Austrian law with a very sound wastewater treatment mechanism. Austrian wastewater treatment manages to filter, clean and recycle municipal wastewater in a way that it is of drinking quality again. Austria's industrial wastewater treatment has managed to achieve a similar standard. There is a common wastewater regulation and many wastewater regulations for individual industries, containing the daily emission limit and concentration of chemicals in wastewater. Actions to be taken by all industries are to implement closed cycle production, which is happening in this case study with the NMMO/water recovery. The other action is to separately treat and pre-treat different flows of wastewater in order to reduce thinning effects before they enter an industrial or municipal wastewater treatment plant. Further, state of the art technology treats chemical aqueous and/or gaseous releases from chemical and industrial installations (UBA, 2015).

What is more, introducing further chemical recovery cycle during the finishing processes of the lyocell production would be another option to minimise chemical waste. Additionally, if all these harsh chemicals were replaced with biological and organic options and with the potential to be reused, it would reduce the toxicity and improve the environmental impact of the lyocell supply chain.

3. Soil depletion and pollution

There are two options to source the wood needed to produce lyocell or other regenerated cellulose fibres, either through cutting off trees in forests or by growing trees on tree farms. The logging and clear-cutting of forests is one of the leading causes of soil erosion. It is believed that 30% of viscose, rayon, lyocell and other man-made cellulosic fabrics turning into apparel come from dissolvable pulp sources from endangered and ancient forests and are cut down exclusively to feed dissolving pulp mills. Forest-based fabrics represent 5% of the global apparel industry and this number is predicted to grow at a 9% growth rate annually. Many studies suggest that the solution to the dirty cotton industry is regenerated cellulosic fabric, without considering the deforestation aspect (McCullough, 2014).

When vast areas of trees are deforested, they leave a large area of land vulnerable to rains, floods and storms. As tree roots hold the soil together and retain water in an ecosystem, habitat is destroyed by deforestation. All these aspects lead to soil erosion. It is believed that half of the world's topsoil has been lost to erosion and all the nutrients in the soil required to regenerate future vegetation is washed away by heavy precipitation now able to fully reach the soil as no trees are in the way. The consequences of erosion not only affect the forest soil directly, but can also other parts of the ecosystem. The washed away nutrients, which land in waterways can oversaturate them and disrupt aquatic food chains. Further, eroded sediment can also change the way rivers flow. Another consequence of erosion could be desertification, when enough plant cover is lost former forests can transform into infertile deserts. This environmental impact makes regenerated cellulose fibres unsustainable (Gijsman, 1992).

What many global apparel producers are now trying to do is to reassure across their supply chain that the cellulose pulp in their garments does not come from ancient

forests. Other companies are creating their own tree farms, and use these as the source of their wood. The lyocell in this case study is sourced from a tree farm.
However, tree farming also turns natural land into arable land. Commercial tree farming is a cultivated area, where species and structures have been simplified to produce only certain types of timber. Biological diversity is reduced to a few species of fast-growing trees, planted in homogenous packs of the same age. Moreover, commercial tree farming requires thorough control and intervention from humans, including the preparing the soil with fertilisers and pesticides. Similar to the cotton farming, weeds and pests must be removed using pesticides and trees must be planted in regular lots and cycles. Harvesting must take place as fast as possible in order to continue a new cultivation period (SinksWatch, 2015).

Despite the fact that in this case study smaller amounts of pesticides and fertilisers are applied compared to the cotton case study, with 75g and 10g per 5kg of wood, which later turns into 1kg of finished lyocell fibre, chemical applications like these also have an impact to the soil.

The direct and indirect impacts are similar to those explained in the cotton supply chain. It depends on the amount of fertilisers and pesticides applied, to consider the long-term effect on the soil's microorganisms and non-target soil, the air, and in the local water sites, where these chemicals are transported. Moreover, even though creating tree farms have an essential contribution to environmental security by stabilising the soil, preventing erosion, enhancing the soil's capacity to store water and moderating air and soil temperature, cutting them off after a few years of cultivation is threatening this environmental security.

4. Solid waste

To produce 1kg of lyocell fabric 5kg of wood are required. The amount of solid waste in this case study accounts for 0.5 kg for 1kg of finished lyocell fibre, which is lost during finishing processes. The remaining 3.5 kg are recovered after the pulping process and in the NMMO/water recovery. The amount of waste from the NMMO/water recovery is 0.01%. Apart from the fact that NMMO is biodegradable, this amount is in line with emission regulations.

Given that more than 1kg of lyocell fabric are produced, if larger amounts of lyocell fabric end as waste, depending on the fabric's condition, it can be recycled or reused in order to be manufactured into other textiles.

Additionally, Austria has a sound waste management system, so these 0.5 kg of lose lyocell yarn or fabric can either go to a well managed landfill or can be incinerated. In most cases, cellulose industries incinerate their waste and use it as energy recovery. Internal industrial incineration is managed under the same strict regulations as waste incinerators, in order to reduce the emission of particulate matter, NOx and other GHGs (UBA, 2015a). This way, the solid waste in this case study is reduced and transformed into energy recovery.

8. Comparing the Sustainability of the Cotton and Lyocell Supply Chains

Cotton

The total amount of water entering and leaving the cotton case study is about 18400 litres for 1kg of finished cotton fabric. 3000 litres are additionally used to dilute the wastewater. The total water demand is therefore 21 400 l/kg of finished cotton fabric.

The energy demand for 1kg of finished cotton fabric is 95 MJ/kg produced by non-renewable energy.

The total amount chemicals used in this supply chain is about 3kg per 1kg of finished cotton fabric. In order to determine the GHG effect of the cotton supply chain in this case study in a common unit, the Carbon dioxide equivalent is given. It indicates the equivalent global warming impact of this supply chain. For the cotton case study the carbon dioxide equivalent is estimated to be 3.5 kg CO2 eq/kg of finished cotton fabric.

Lyocell

The total amount of water entering and leaving the lyocell case study is about 1500 litres.

The total amount of chemicals used in this supply chain is about 19kg per 1kg of finished lyocell fabric, whereas about 17.5 kg are recovered and reused.

The total energy demand for 1kg of finished lyocell fabric is 72 MJ/kg with non-renewable energy and 94 MJ/kg produced with renewable energy.

Given that renewable energy is used the carbon dioxide equivalent of the lyocell case study is estimated to be 1.5 kg CO2 eq/kg of finished lyocell fabric.

Direct and Indirect Impact of Cotton and Lyocell on the Environment

When comparing the cotton and the lyocell supply chain it becomes clear, which supply chain has a bigger environmental impact. The cotton case study has a significantly higher water demand, while the lyocell supply chain has a higher demand in chemicals, where the majority is recycled.

The impact of ozone layer depletion is higher for the cotton supply chain, given the reliance on non-renewable energy, non-efficient factories with the absence of emission reducing technologies.

In addition, as the lyocell fabric is produced with renewable energy, the cotton supply chain has clearly the higher abiotic depletion impact.

Moreover, the impact on human toxicity and freshwater aquatic ecotoxicity is significantly higher for the cotton supply chain due to the large amounts of contaminated wastewater, which are released back into local water sites. Further, it has been reported that often workers in the textile industry in developing regions are directly exposed to the chemicals they work with on a daily basis due to missing safety regulations.

Also, the cotton supply chain creates more eutrophication due to the high amounts of water used, which are mixed with toxic chemicals and released untreated back into local rivers and lakes.

Besides, the impact on terrestrial ecotoxicity is slightly higher in the cotton supply chain due to higher amounts of fertilisers and pesticides being applied to the arable soil. Also the amount of contaminated and untreated wastewater getting in contact with water sites and soil add to the higher terrestrial ecotoxicity. The reason why it is only slightly higher in the lyocell supply chain is because to produce lyocell, deforestation, whether in ancient forests or on tree farms, has to be carried out. Deforestation destroys ecosystems and the more unworkable the soil becomes due to erosion the more fertilisers and pesticides have to be applied in the long run.

Photochemical oxidants form smog. SO2 is used during the pulping process to make the magnesium bisulphite process sour and is also emitted from energy production. Also during the entire cotton supply chain SO2 is emitted during energy consumption.

Therefore the impact of photochemical oxidant formation in both case studies is the same but not necessarily high.

Finally, the acidification impact of the cotton supply chain is much higher than that of the lyocell supply chain, due to the use of non-renewable energy as a source and due to the high amounts of toxins released during the fabric production.

From an environmental perspective, the lyocell case study is more sustainable. Also socially, workers in the Austrian industry can enjoy better working conditions and are protected by profound labour rights compared to industrial workers in India, a country where labour is often exploited due to a lack of audits and transparency. Nevertheless, cotton has an economic advantage over lyocell, as it is cheaper to produce. In comparison lyocell is known for being one of the most expensive regenerated cellulose fibres due to its state-of-the-art production technology and because of a lack of producers and competition in the textile market. Nonetheless, while the production of conventional cotton has an economic advantage it comes with an environmental and social burden.

To conclude, even though lyocell is not the most sustainable fabric as it is also produced with an environmental weight in its early sourcing stage, it is the more sustainable option compared to the conventional cotton case study. The reasons why lyocell is the more sustainable option despite applying more chemicals, are the use of efficient technologies and the presence of strict waste and water management laws, that the producers have to abide in the lyocell case study, which is set in Austria. Due to these laws, production of lyocell is forced to implement the recovery and reduction of its waste in a sustainable and efficient way. If production were also set in India, it would still need less water in its production, but it would possibly be as unsustainable as the conventional cotton supply chain.

9. Conclusion

To provide with final remarks and summarise the discussion, the cotton and the lyocell supply chains contain many processes that turn raw material into finished apparel. All these processes transform a natural material into a flawless, smooth and soft textile, which has the capability to wrap around the shape of a human body. In order to achieve this texture the raw material is prepared in chemicals and in water.

In the case of the traditional cotton supply chain, the cheapest and fastest chemicals were used, regardless of their toxicity and impact on the environment. The cotton supply chain comes with a great burden to the environment starting from the exploitation of natural soil in order to produce cotton crops, the heavy water use for the irrigation and throughout the fabric manufacturing process, as well as the application of toxic chemicals. The wastewater is not recycled or cleaned and dumped into local water sites. Unless these production practises are not stopped, the ecosystem, habitat and health of living beings around these production sites, will be endangered or even destroyed.

To respond to these environmental issues, sustainable and eco-friendly textiles emerge on the textile market, which claim to be a solution. Amongst all cellulose-regenerated fibres, lyocell is claimed to be the most sustainable, compared to viscose and modal. However, also the production of lyocell even with renewable and self-efficient energy comes with a great environmental burden.

The lyocell material flow analysis demonstrates that despite the fact, that the emission of water is drastically lower for lyocell compared to cotton, its production has a higher demand in chemicals and a high energy demand. Moreover, cellulose pulp is based on wood. Tree logging for the sake of cellulose production leads to deforestation and therefore destroys parts of our ecosystem. Lyocell, is input-wise, not more sustainable than conventionally produced cotton. However, strict water and waste management regulations in Austria, where lyocell is produced in this case study, necessitate the reduction of material output in order to diminish its environmental burden. As a result, the output of the pulping process is transformed into energy and chemical recovery and also into reusable by-products. The output of dissolving cellulose and cellulose fibre production is almost fully recovered, with a waste of 0.01%. What is more, waste produced within the production sites have to be incinerated and are used to re-produce energy.

State-of-the-art production technologies, recycling within the supply chain, as well as sound wastewater treatment systems are the reason why lyocell is the more sustainable option. The production of lyocell is a more sustainable option in regions, where all these sustainable actions are incorporated into the supply chain, or where they have to be legally incorporated.

Nevertheless, this does not mean that lyocell can replace the high demand in fabric in order to produce garments for the global textile industry. Textiles are continuously required for household and domestic products, medical textiles and are indispensable for the fashion apparel market. With the number of fashion brands, fashion cycles and efficient fashion marketing that exist, there will always be a high demand in textile fabrics. Whenever a good is continuously and excessively produced and removed from its natural habitat in an excessive quantity and treated with harsh chemicals it can never become a sustainable textile. Textile supply chains can become more sustainably aware by reducing the emission output or by improving the technology, but as long as overproduction and exploitation of natural resources exist, they will never be sustainable.

In order to reduce the environmental burden of the textile industry, conspicuous consumption and overproduction has to stop. Many fashion retailers have a large quantity of unsold apparel, which end on landfill or are incinerated. The textile industry itself will only be sustainable when sustainable actions are incorporated into the supply chain like in the lyocell case study, when season sales will not be overestimated, when there wont be an oversupply of textile goods, when purchased textile goods are consumed with care and when those unsold and finished textile garments are reused and recycled. However, a supply chain cannot be sustainable, regardless of how many sustainable actions are taken during production, when in its very first process, the sourcing of raw material, certain plant species are exploited or destroyed or when their natural habitat is destroyed.

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