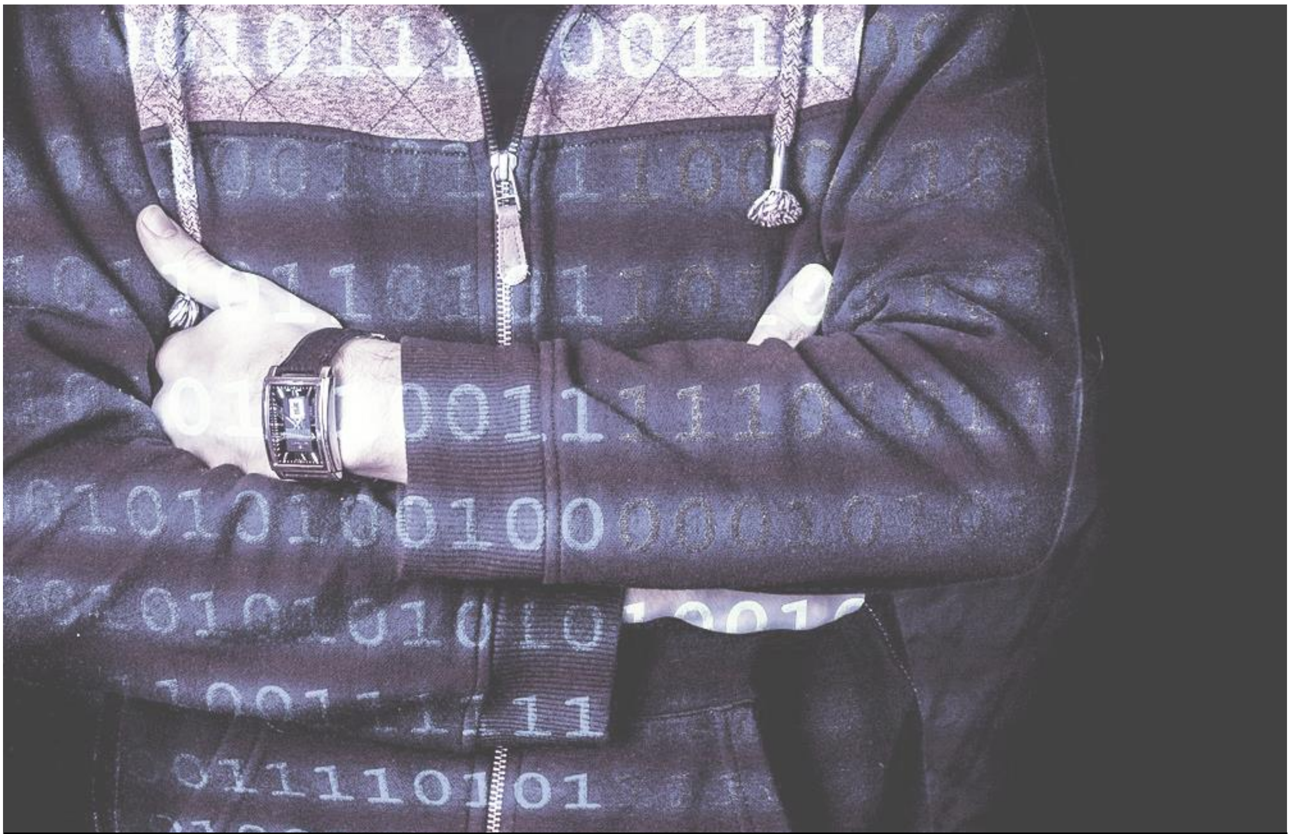
mistra future fashion



textile tagging to enable automated sorting and beyond

– a report to facilitate an active dialogue within the circular textile industry

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Ett effektivt användande av textila resurser är en nödvändighet i ett hållbart samhälle byggt på en cirkulär ekonomi. Återanvändning och lagning har, och ska ha, högre prioritet än återvinning, men till slut når alla textilprodukter ett tillstånd där de inte längre kan användas och de bör då materialåtervinnas.

Det **huvudsakliga målet för detta projekt har varit att klargöra tekniska möjligheter för en helt eller delvis automatiserad sorteringsprocess av uttjänta textilier för återbruk och återvinning**. Identifiering av fibersammansättning med hjälp av spektroskopiska metoder är högst aktuellt och önskvärt, och metodutveckling pågår på många håll främst av near infrared (NIR) spektroskopi. Spektroskopi kan dock inte ge annan information, som den fullständiga tillverkningskedjan, miljöeffekter förknippade med produkten, skötselråd och anvisningar för återvinning – värden som kan vara viktiga för t ex återanvändning.

Fokus i denna studie har, som komplement till den utveckling som sker inom spektroskopisk identifiering, legat på inmärkning, så kallade "taggar" eller informationsbärare, såsom QR (Quick Response)-koder eller RFID/NFC (Radio Frequency Identification/Near Field Communication)-transpondrar, vilka kan följa produkten genom användningen fram till sortering. **Störst potential inom inmärkningsteknologi bedöms ligga inom RFID/NFC-taggar**. Även om inte alla användare i dagsläget kan avläsa denna typ av tagg kan den ge information från produktion till användare och som stöder både återbruk och återvinning. Den **vanligast förekommande inmärkningsmetoden idag är QR-koder, som är billiga och kan avläsas i mobiltelefoner**. Däremot är detektionsavståndet för dessa relativt kort och idag måste inmärkningen först lokaliseras och sedan vändas mot en avläsningsenhet manuellt, vilket gör exempelvis en sorteringsprocess långsammare.

Utöver en utvärdering av lämpliga inmärkningsmetoder, har intervjuer med intressenter över hela värdekedjan utförts för att klargöra informationsbehov från olika vinklar**. Intervjusvaren visar att vinsterna med ett system för informationsbärande taggar inte bör begränsas till bara materialsorteringen av uttjänta textilier, utan stor nytta ses även under både produktions-, försäljnings- och under användarledet**.

En huvudslutsats i rapporten är att automatiserade moment i en sortering under överskådlig tid inte kommer att kunna ersätta manuell sortering mer än till en viss del. Det är dock fullt möjligt att man kan nå en ökad effektivitet genom en flerstegsprocess där automatiska processer svarar för en stor del av sorteringen. Automatiska moment kan dessutom agera beslutsunderlag åt de manuella moment som ännu är nödvändiga. Det kan också finnas behov av att vidareutveckla den fysiska utformningen av befintliga taggar för att svara mot textilproducenternas krav. Den viktigaste begränsningen i dagsläget av taggar som sorteringshjälpmedel är att en stor del av inkommande textilier är av äldre datum och därför inte utrustade med taggar. Ett absolut krav för införandet av taggar som en hjälp vid sortering är standardisering och möjligen myndighetsreglering, samt att systemet bör adopteras av en stor majoritet på den globala marknaden.

Automatiserad sortering är på väg att utvecklas och anpassas för textilområdet, men ännu återstår en del utmaningar. Väl fungerande taggar finns redan för en lång rad av olika ändamål, men deras funktion över längre tid kan behöva valideras för de krav och behov som lyfts i den här rapporten.

Summary in English

An efficient use of textile resources is a necessity in a sustainable society based on a circular economy. Reuse, remake and mending take priority over recycling, but eventually all textile products reach a point where they are no longer fit for use and they should then be recycled.

The chief aim for this project has been to clarify technical options for a fully or partly automated sorting process of discarded textiles for reuse and recycling. Identification of fiber contents by spectroscopic methods is very topical, and trials are currently undertaken in several places, primarily based on near infrared (NIR) spectroscopy. Other valuable information as the full manufacturing chain, environmental impacts associated with the product, advice for maintenance and how to best deal with the product when it is discarded — data which can be important for *e.g.* reuse — cannot be delivered by spectroscopy.

The focus in this study has, in addition to activities on spectroscopic methods, been on tags, or information carriers such as QR codes or RFID/NFC transponders, which can be attached during production and stay with the products through the use phase(s) until the sorting. **RFID/NFC devices are judged to have the largest potential for tagging of textiles**. Even if all users are not currently able to read such tags, it can convey information from producer to consumer and support both reuse and recycling. **The most common tagging technique today is QR codes, which is a low-cost technology, readable by most mobile phones.** They have a relatively short reading distance and the tag must be localized and manually oriented towards a reading unit, which slows down *e.g* an automated sorting line.

Aside from an evaluation of information carrier techniques, interviews have been conducted with stakeholders along the value chain to clarify information needs from different angles. **The interview responses show that the benefits of a tagging system should not be restricted to only material sorting of discarded textiles. There is also much to gain for producers, retail and consumers.**

A main conclusion in the report is that automated steps in a sorting process for textile waste will not be able to fully replace manual sorting in a foreseeable future. It is quite possible, however, that an increased efficiency can be reached by a cascade process where automated steps take care of much of the sorting. Automated data collection can also serve as a basis for decisions in the still necessary manual actions. A continued development of the physical form of existing tags may also be necessary to meet the requirements of textile producers. At the moment, the most important limitation for tags as sorting aids is that a large part of incoming goods is old and therefore not equipped with tags. An absolute requirement for an introduction of a tagging system as a tool for sorting is that the system is standardized. Regulations or legislation may also be needed, and the system must be adopted by a large share of the global market.

Automated sorting is well under way to be developed and adapted for the textile area, but some challenges remain. Well-functioning tags already exist for a large number of applications, but their long-term performance needs to be validated for the demands and needs highlighted in this report.

Contents

Foreword

The work presented in the report at hand initially began in 2014 as a component in the research on efficient online-sorting technology and tagging technology within Project 5 "Reuse, recycling and end-of-life issues" during Phase 1 in Mistra Future Fashion and was later incorporated into the Task 4.3.4 "New sorting technology for textile material" of Mistra Future Fashion Phase 2. The work was funded by the Foundation for Swedish textile research (TEKO) and Mistra Future Fashion.

This report aims at clarifying a route to develop and use a suitable textile sorting technology in the future. The work has been performed in a cross-disciplinary way between the Recycling Theme of Mistra Future Fashion and the Design Theme, in order to ensure that knowledge and challenges are mutually transferred from the two disciplines. This work has also involved close interaction with the online-sorting activities within the Horizon 2020 project "Trash-2-Cash", as a few studies within Trash-2-Cash were designed based on the pre-study in 2014. The technology validation and the review of challenges within tagging options for textile industry have been ongoing since the fall 2014. The interviews found in this report, aiming at achieving a fuller understanding of the needs of various actors in the textile sector as well as potential gains and other opportunities offered by automated sorting, were performed during the fall 2016.

Stockholm, 30th December 2017

Finn Englund, RISE Research Institutes of Sweden.

1 Introduction

To enable a circular economy within the textile and apparel industry, an action of prime importance is to stimulate an extended life of garments/textiles in general, *i.e.* to work for the most resource efficient use possible of textile materials.

Activities and mechanisms working towards this goal set new material streams in motion and they involve direct consumer-to-consumer interactions (lending/sharing/leasing) and new third-party services (mending services/garment libraries/manufacturers' take-back systems/remake). New streams and business models introduced bring a need of improved information exchange.

For the bulk of the textile consumption and their end of life, the organizations and industries involved in collection, sorting and further valorization of textiles play a pivotal role in the movement towards circularity. Manual sorting is a necessary step in all endeavors to create reuse and recycling opportunities of worn clothes. Reuse should generally take priority to recycling in the waste handling hierarchy (Figure 1), and a large number of criteria are applied in the, today mainly manual, sorting for reuse. These include age, style, condition and overall value for the second-hand customer.

For textile waste recycling, on the other hand, the material composition is of primary interest. The nature of the textile fibers determines the suitability of the used garments for different mechanical or chemical recycling processes. Technical methods determining material composition are available. The big challenge, however, is to adapt these methods to the benefit of textile recycling, managing the complexity of heterogeneous waste textiles, large volumes, and demands for high speed sorting with high accuracy.

Waste management hierarchy

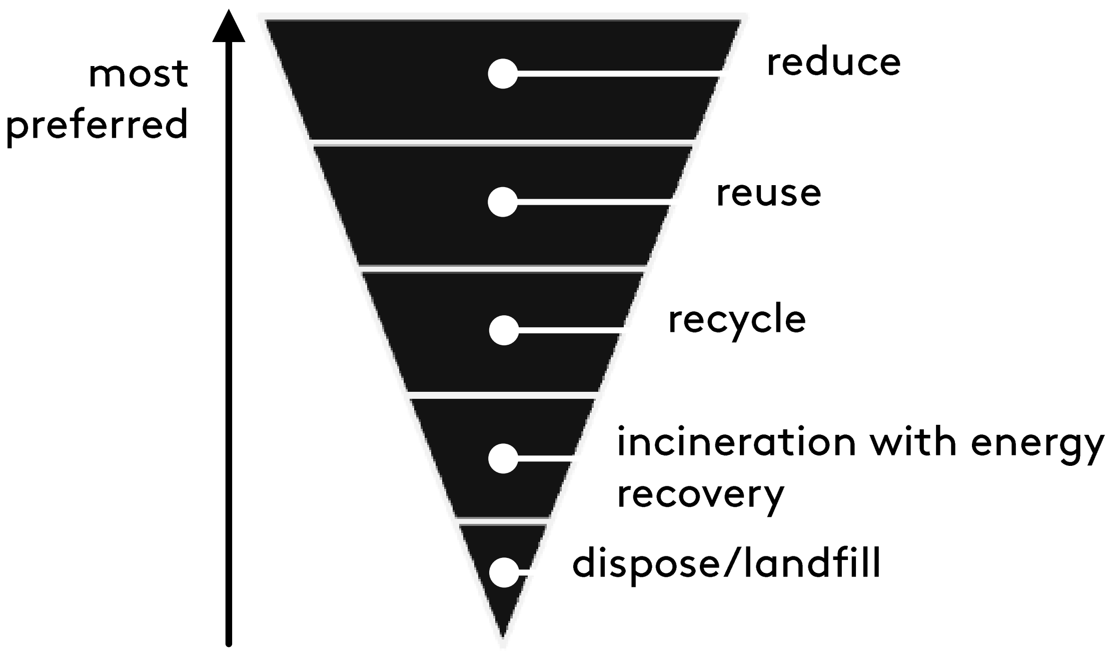


Figure 1: The hierarchical waste management strategy that became widely spread i.a. in conjunction with the adoption of the EU Directive 2006/12/EG on waste, here shown in an adapted version.

1.1 Objectives and scope of this study

The goal of this work was to review possibilities for versatile and large scale operational technologies to automatically identify and sort discarded textiles to enable reuse and recycling.

The aims have been to:

- assess the current situation by comparatively evaluate current identification and sorting technologies
- identify sorting technologies for recycling that are most efficient for future large scale operations.
- define gaps and potential routes for solutions to the current technology lack
- map stakeholders and how they are affected by new technology within the field

Automated sorting systems are currently undergoing a strong development but have not yet reached maturity and their full potential. Their capacity might not be a critical limitation, but their precision can be improved by further development. The most promising technique for rapid detection for sorting of textiles is the near infrared (NIR) spectroscopy. This technique is adapted, adjusted and developed in parallel through different initiatives (see 2.3.4). A study within the EU project Trash-2-Cash on the current status and technical potential in recognition based on testing of NIR devices from different manufacturers has been performed in parallel communication with our study and has recently been published[1]. Due to this, the scope of our study was concentrated to the potential of future tagging technology of garments and other textile products. It could be seen that the tags offers other possibilities by bringing information from the production through various stages throughout the life-time of a product.

The study involves both a mapping of the existing and potential future techniques for tags, the opportunities they generate and the requirements that are necessary to set. Connections with existing initiatives and technologies have been made and are analyzed in order to find a route to develop a suitable technology in the future. Furthermore, a number of implications for the entire value chain have been identified by interviews with stakeholders, and they are so far-reaching that they cannot be ignored in the discussion. Thus, attempts have been made to map expectations, wishes and ideas from many different types of actors on tagging as a support for recycling and for other functions where an embodied information carrier can be useful. In the transition towards a more sustainable apparel and textile industry it is of utmost importance that a system perspective is applied in order to avoid sub-optimizations and partial solutions that fail to utilize the full potential of progress.

2 Background to discarded textiles

The sorting for reuse or recycling of textiles needs to follow the so-called waste hierarchy, where reuse is the primary step of discarded goods. This is also the baseline in the outlined recommendation from the Swedish Environmental Protection Agency to the Swedish Government delivered in September 2016 regarding the future handling of discarded textiles[2]. In this report we have attempted to avoid the designation "waste" for used or unused (e.g. manufacturing surplus material or pre-consumer waste) discarded textiles, until they have reached a stage in a sorting process where they are not deemed suitable for either reuse or recycling.

Emphasis should thus be put on the reuse. Watson et al.[3] conclude that the environmental impacts arising from transportation and processing of used textiles are small in comparison to the savings caused by offsetting new textile production, which leads to overall environmental benefits. This conclusion underlines the value of reuse even more. Tight economic margins also drives the development towards a fulfillment of the waste hierarchy priorities, since the revenues are larger from the reuse market than from recycling, which in turn pays off better than other waste treatment methods.

2.1 Textile flows

In order to follow textile flows in Sweden Carlsson et al. made a study with the scope including both clothes and home textiles, but excluding shoes and private import after purchases abroad[4]. The net inflow, defined as domestic production volumes plus import minus export, was calculated to 132,000 tons or approximately 14 kg per capita. Recent figures regarding Sweden indicates that 11 kg of textiles are discarded annually per capita, including 3 kg brought to charity organizations[5]. Analyses of general household waste shows a content of textiles corresponding to ca 7.6 kg per capita each year, while the annual volumes of collected goods through charity organizations add up to 3 kg per capita[6]. The latter figure can be expected to rise, as more widespread and purposeful collection systems continually are established.

Even if the figures in Carlsson et al. [4] reflect the situation in 2008 they give a baseline for the volumes, and with a time series of similar analyses it is possible to predict reasonably well the expected volumes of discarded textiles in the future. Data given for the period 2000-2008 show that the net inflow increased by almost 50 %, with a drop in 2009, but on the whole it can be safely assumed that the volumes have increased further during this decade. Similar dramatic rises in the consumption have been reported in e.g. studies from Great Britain[7]. A more narrow view is given in a later analysis[8], which is limited to the flows of cotton textiles only, since the aim was to characterize the raw material feedstock situation for the emerging recycling pilot plant of re:newcell and future enterprises. The volumes are thus not directly comparable with those in Carlsson et al[4].

The fifth consecutive annual report on the development of the Swedish fashion industry, commissioned in a cooperation of several organizations, does not indicate volumes and material flows[9]. It shows, however, that the overall turnover in the Swedish fashion industry has increased by almost 50 % in the period 2011-2015. These figures do not correlate directly with volume growth, due to the complex flows of e.g. import and re-export and to currency exchange variations, but they are indicative of continued growth.

Figures from the Netherlands, presented in communications from the former European project Textiles4Textiles, are largely in accord with the Swedish figures: 15 kg textile waste generated, 10 kg ending up along with other household waste, and 4-5 kg collected, all per capita each year. Slightly more than half of the collected material, or 40 000 tons, in the Netherlands is reused. Estimates for the UK are markedly different, with an annual volume of 26 kg per capita consumed in the category clothing and household textiles, out of which 10 kg are collected for reuse/recycling[10, 11]. The discrepancy may be ascribed to different inclusion criteria (where different investigations have, for example, chosen to either include or exclude shoes, bags and other non-clothes items).

Discarded textiles are shipped to the sorting plants from many countries in Europe, including Sweden. In a recent interview-based study by Watson et al. it was found that among Nordic collectors of discarded textiles, 25% of the goods are sorted within the Nordic countries, and 10% are sorted out as high value goods to be sold within the Nordic countries[3]. The rest of the discarded textiles are directly exported to EU Member States, mostly in Eastern Europe, to be sorted. The goods that cannot be sold directly include a fraction which is to be seen as waste. If this is exported from the Nordic countries it either remains in the European sorting country and is treated responsibly there or shipped to Pakistan or India for mechanical recycling. Very little actual textile waste finds its ways to African receiving countries.

The primary aim of the manual sorting is to identify high value goods and sort textiles and garments according to a number of broad categories that determine their further fate.

Table 1: Collection categories and average collection streams of the total incoming material flow at three collecting companies. present the different categories used by the companies Gebotex of the Boer Group[12], the SOEX group[13] and Texaid[14], and the streams corresponding to each category. Figures given by SOEX are 62 % re-wearables, 32 % to remanufacturing, and 6 % to a combination of other material re-utilization and energy recovery[15]. The sorting at Texaid of goods collected in Switzerland and Germany amounts to about 80 k ton/y. The goods sorted in Switzerland are distributed into the following broad groups: 65 % reuse (including shoes), 15 % rags, 15 % to recycling, and a remainder of 5 % foreign objects or useless material which is incinerated

Table 1: Collection categories and average collection streams of the total incoming material flow at three collecting companies.

Company	Streams **in %**
Gebotex	
European quality approx.	9
Export A approx.	24
Export B approx.	16
Rags approx.	17
Recycling approx.	21
Refuse approx. (mostly for energy recovery)	8
SOEX group	
Re-wearables	62
Re-manufacturing	32
Re-utilization and energy recovery	6
Texaid	
Reuse	65
Rags	15
Recycling	15
Foreign objects and useless materials	5
The overall picture of collection streams	
Reuse	49-65
Recycling	30-38
Refuse	5-8

It should be noted that the category "Recycling" in the general summary of Tabel 1 is given as a combined category comprising both materials that are downcycled to e.g. carpets, upholstery or rags and those that may go to fiber regeneration processes. The most immediate fate of the refuse fraction is energy recovery, *i.e.* incineration, but there is a continuous development of new secondary products, and such remanufacturing is leading to a more and more complete utilization of the total volume of textiles. In most cases, energy recovery always remains as a potential gain after subsequent life cycles.

One category of textiles which seldom finds its way to secondary use directly is home textiles (bed linen, towels, pillows, mattresses, curtains, furniture textiles, etc.). It can be shredded and find another use as rags or other products, but it may retain a high value as a raw material for recycling. The data is scarce on the proportions of home textiles in the collected streams, compared to the volume of discarded clothes. The experience of SOEX is that home textiles and shoes constitute 20-25 % of all their incoming material, and Texaid similarly finds roughly 10 % home textiles and 10 % shoes in the goods sorted in Germany and Switzerland. Gebotex reports approximately 7% shoes in their goods.

2.2 Textile collector and sorting companies

The world's leading company in collection, sorting and recycling of discarded textiles is the SOEX Group (including The European Recycling Company (UK), I:CO and other subsidiaries in a total of 9 countries) and presumably, the SOEX sorting plant in Wolfen is the largest in Europe, with a throughput of ca. 300 tons/day. The SOEX Group has facilities in USA, UK, Germany, Switzerland, Austria, Bulgaria, Lebanon, United Arab Emirates, and India[16]. The SOEX Group (Germany), G.G.D. (France)[17], the Boer Group (the Netherlands)[18], Wilcox (UK)[19] and Wieland Textiles (the Netherlands)[20] are some of the most prominent actors in Europe, but sorting is also carried out in many other facilities. Wilcox states a collection volume of 500 tons/week, and Nathan's Wastesavers in Scotland 600 tons/week[21]. The Boer group states that approximately half of their collected goods are resold for continued use, and about 20 % end up as cleaning rags or are reverted to fibers for use in carpets, mattresses etc. One of the companies in the Boer Group, Gebotex, who has an annual throughput of approximately 20 ktons of clothes, presents an even more detailed breakdown of the end use categories[12]. Actors in Sweden are mainly Ragn-Sells, IL Recycling, Stena Recycling and Scanrec and a wide array of charity organizations mentioned in 4.1.6.

Furthermore, the large portion of textiles still wearable needs to be subdivided into types of garments (children's clothing, trousers, blouses, bedding, household textiles, shoes, etc.). Different sorting plants can apply somewhat different criteria for manual sorting and different numbers of sorting categories. There is a varying degree of vertical integration between collection and sorting companies, and some collection companies forward the material to partners who then perform the sorting, while others cover a longer stretch of the process.

More obscure collection entrepreneurs are also operating, claiming to be charitable organizations and often mimicking logotypes and printed material of recognized collectors. Their actions are in many cases illegal, and since the final destination of both the used textiles and the revenues are unclear, they may undermine the credibility of serious actors by creating uncertainty among donors. Their mere existence, however, is proof of the business potential in the trade with used textiles.

2.3 Options for sorting

Textile sorting as it is today in Europe is profiting from the high value products and the second hand use, which is very dependent on human knowledge on specific trends to selectively sort out the high value goods. However, many enterprises in the sorting business are currently also looking closely on possible aiding technologies that would allow a certain degree of automation, in order to reach a higher throughput capacity and thereby a higher profitability. Automated sorting of discarded textiles in a circulation process primarily aims at making a thorough identification of materials (fiber types) for reproduction of fibers or other polymeric material. In addition, an efficient automated sorting can contribute to the fulfillment of overarching goals concerning a higher level of transparency leading to a decreased use of toxic or environmentally harmful chemical additives. An efficient and accurate sorting process also has commercial consequences, since it will improve the profitability within the circular economy by increasing the value of the material resource and open up for new business models.

Methods for sorting of textiles can broadly be separated into three categories, two of which lend themselves to be incorporated into automated sorting processes. The third category has more far-reaching implications in the way it embraces the whole value chain and necessitates an implementation of technical devices already at the time of manufacturing, bringing forward information through the whole value chain:

- Manual sorting
- Sorting technologies for identification of materials or items, by e.g. spectroscopic online measurements such as near infrared (NIR) spectroscopy
- Information-based sorting, such as tagging with more or less hidden code carriers, suitable for automated reading at a distance.

2.3.1 Manual sorting

Until now, the human eye, experience and hand-feel-judgement has remained the chief or even the only instruments for evaluating the further fate of collected, discarded textile items. Manual sorting continues to be a required method, and this is partly due to the dual purpose of sorting. The reuse-recycling hierarchy carries with it an intrinsic prioritization: what can be reused should be reused before it is recycled. The items deemed amenable to reuse are sorted out according to a very complex set of criteria, best described as judgements based on market knowledge, experience, recognition, and value estimations. However, manual sorting is also currently employed in order to recycle the waste fractions by several actors in Europe, for instance the SOEX Group, Texaid, and the Boer Group.

The manual sorting procedure has a unique ability to make complex judgements and take into consideration how clothes are related to current fashion and other such subjective factors that are relevant for their second-hand market value. The different quality grades of re-wearables mentioned above are further subdivided into garment type (children's clothing, trousers, blouses, bedding, household textiles, etc.), which means that the total number of fractions may reach 40-50. Some companies state that they use an even more detailed subdivision. In general, the manual sorting does not separate all these fractions in one step but uses a 2-3 step sequence, where the goods first is sorted into broad groups which are then subdivided[10]. If all the destinies are included within reuse, downcycling to a variety of secondary products, and material recycling, the number of fractions may reach 400, or even higher if quality grades are included. The number of fractions is highly dependent on which business models and strategic cooperative alliances each sorting company operates with.

Identification of fiber type is of particular interest for the fraction that will go to material recycling. Skilled sorters can easily identify most materials and many blends, but their judgements are not infallible and cannot precisely pinpoint the percentages in the composition of *e.g.* polyester/cotton blends. The sorter may then rely on labels that specify the material composition. Such labels could be missing or worn out to be non-readable after many washing cycles, and sometimes the wrong labels are inserted already in production, or the labels do not include materials of threads etc. It should be noted that manual sorting can be used to separate the non-rewearable goods from the wearable, especially the high-value items, and thereby make a subsequent automated sorting more efficient (see 4).

2.3.2 Sorting technologies for identification of materials or items

To sort according to the fiber composition of textiles might have some relevance for the fractions that will be reused and sold on the second-hand market, but it is above all important for mechanical or chemical recycling purposes. A few options for material identification are possible, and they are briefly discussed in 2.3.2.

Two possibilities, density sorting and "olfactory" identification, deserve mentioning even though they fall outside the scope of this report and are not further discussed:

Flotation and hydrocyclone separation are two purely physical methods with a certain kinship, operating according to differences in density or hydrodynamic behavior[6, 22]. This option is of course limited to monomaterial garments with no other added elements like buttons or zippers or to individual fibers after a thorough shredding/carding. Even with separated fibers this method has serious drawbacks, not least the use of large volumes of various liquids which need to be dried off or stripped, but also the fact that the method will not be sufficiently discriminating to be effective when the density difference is small. Mixed fiber contents causes additional problems.

A completely different alternative method that also has been brought forward as an idea is the use of rapid heating and recognition of a typical pattern of released volatiles by the arrays of sensors in "electronic noses". A closely related method is the Sliding Spark Spectrometry, developed by GUT Environmental technologies[23]. However, these are destructive methods, albeit on a very small surface, and their feasibility for textile identification can be questioned.

2.3.2.1 FTIR/NIR spectroscopy

Reflected light is used in infrared (IR) spectroscopic methods for fast identification of various types of fibers in textiles. The information contained in the absorbance spectrum is somewhat different, depending on the range of wavelengths employed, and this has some influence on the relative precision and recognition capability of each method. Fourier Transform Infrared Spectroscopy (FTIR) is used in many applications for material identification and surface analysis. NIR spectroscopy is used industrially for e.g. online quality control in the food industry, and this method is very fast and has in some respects superior abilities to measure at longer distances.

An inherent obstacle for reliable identification is associated with darker colors, where a larger part of the radiation may be absorbed instead of reflected. In some cases black causes less problems than other dark colors, sometimes it completely blocks the identification, and the reasons for this are not fully understood[24, 25]. By combinations of light sources and detector systems, including the frequency range of ultraviolet and visible light, the color of textiles can also be determined. Some degree of compensation is therefore possible through ranges of reference libraries spanning over a longer frequency range, and it may also help to resolve some of the complications and error sources resulting from the presence of finishing agents. Color determinations can at least be helpful to sort out the pure white fractions, which are sometimes specifically requested.

Excessive moisture is a severe confounding factor for NIR analyses, and a dry state is a requirement. Normally this is not a problem for the sorting industry, who strictly specifies accepted moisture contents of the textiles they buy.

Yet another aspect of these spectroscopic methods is that they are dependent on comparisons with spectral libraries. Every detector and instrument has its unique sensitivity and the libraries are therefore not readily interchangeable and shared across the board. There is thus a lot of calibration, set-up and optimization to be done for each instrument, but it is possible that artificial intelligence and "deep learning" can create shortcuts.

Since the NIR and FTIR techniques focus on the identification of different materials, in our case textile fibers, based on chemical differences in the fibers' composition, they show their greatest strength in an efficient sorting as preparation for material recycling. A simultaneous determination of color helps to sort by color, which is relevant if a recycling process requires a preceding de-dyeing step for non-white textiles. Also for material recycling there may be quality issues, depending on *e.g.* the extent of fiber degradation during the use phase, but this discussion is not further pursued in this report. For the purpose of grading and sorting for reuse, these methods are not sufficient, since a number of other parameters come into play and have to be judged with other means.

The NIR technique is currently fast enough to allow determinations in the time range of a few seconds. For online applications it is important to know that the actual signal acquisition is made in a matter of milliseconds, so that the analysis, identification and sorting decisions can be made after the sensor while the textile item is moving on the belt. Thus, the NIR analysis does not become a rate-determining step in the process. Identifications can be performed with stationary sensors in an online sorting, as in the Fibersort system (Figure 2) developed by Valvan Baling systems[26], the sIRoSort or sIRoCube by GUT Environmental technologies[23] or test equipment by TOMRA[27] , as well as with smaller hand-held devices, as examples show below. Handheld equipment, as the mIRoGun, developed by GUT, and the microPHAZIR[28], manufactured by ThermoFisher Scientific, is versatile and requires a minimum of installation efforts. Such devices are of course still more dependent on manual or semiautomated handling than a fully automated sorting line. In general, a very important application field for NIR instruments is quality control in industrial production. They are also applied for various materials in recycling processes, some already since a considerable time while others are now on the doorstep to commercial use for the textile sorting application.

Figure 2: Above: The FIBERSORT equipment. Below from left to right: The microPHAZIR and the mIRoGun.

2.3.2.2 **Raman spectroscopy**

Another possible but less commonplace technique, Raman spectroscopy, is also a candidate for sorting purposes. It works according to different principles, with laser light at defined wavelengths, but it also has the ability to recognize and quantify a variety of materials. The principles of this technique are described in *e.g.* Ewing[29] and, more comprehensively, by Carron and Besli[30]. Raman is afflicted with one particular difficulty which is that it often induces fluorescence. These broad signals interfere with the useful spectrum, and the conclusion of Peterson in her comparative experiments is that this phenomenon prevents Raman from being a viable option for qualitative characterization of textiles at the time being[31].

An “application note” from a developer of the Raman technique demonstrates the ability of a handheld Raman spectroscopy device to accurately identify a selection of polymers, with a spectral correlation above 0.90[32]. The materials include polyamide and polyethylene terephtalate, which are also found in textiles. Outside of these two, common plastics polymers like polyethylene, polystyrene, acrylonitrile butadiene styrene, polycarbonate, polyvinyl chloride, and polymethyl metacrylate were tested, but there is no reason why the instrument should not perform equally well towards other manmade or natural fibers, provided that suitable spectrum libraries are built. Different colors need to be incorporated in the library models, but a serious shortcoming is also acknowledged here: The strong light absorption of dark colors, which severely impedes the signals and thwarts material recognition. Raman spectroscopy is also a markedly "near-sighted" technique, unable to scan e.g. textiles at a distance. This is certainly another factor to take into account in this context.

2.3.2.3 **Hyper-spectral imaging**

Hyper-spectral imaging is a sophisticated method that combines the speed and resolution of a camera with the signal resolution of spectrometers, with the choice to incorporate a broad range of wavelengths including the visual and the NIR spectra[33]. The method has previously been successfully applied to the sorting of minerals, paper and plastic materials. Trials on textiles have been performed and are ongoing in *e*.g. the Resyntex project[34] , and its performance in the textile sorting application appears to be very promising.

2.3.2.4 **NMR**

Nuclear magnetic resonance (NMR) spectroscopy is a mature field of analysis and structure elucidation of chemical compounds, but it is also still subject to a rapid method development. In particular, the possibilities to study solid materials have increased dramatically with the advent of cross-polarization/magic angle spinning (CP/MAS) techniques, which are now routinely used for the analysis of many solid materials, including polymers. In her study of characterization techniques, Peterson concluded that NMR is indeed useful for qualitative analyses of the composition of fiber blends, on small scale[31].

Classic NMR instruments utilize superconducting magnets cooled with liquid helium and are very large, very expensive and require rigorous maintenance. The last decade has seen a renaissance of much smaller and robust instruments equipped with permanent magnets, useful for many industrial applications of e.g. quality control. Portable instruments can even be so small as to fit in the palm of a hand (an "NMR mouse") and are capable of e.g. discriminating between different types of polymers when sorting plastic items.

A number of obstacles exist, however, for the use of NMR as an online tool in textile sorting. At present, it is relatively work intensive and the time needed for each determination is significantly longer than the times needed for IR identification. Furthermore, since the NMR technique utilizes a fundamentally different physical principle than the IR methods it is not self-evident that it is able to distinguish the same differences in characteristics. To separate wool or cotton from polyester should not present a problem, but it may be more difficult to tell apart all existing varieties of cellulosic materials alongside cotton. Furthermore the separate handling of small subsamples are far from a procedure that would work as a rapid online measurement. Another limitation of this technology is that it does not, in contrast to the IR methods, offer any possibilities for separations according to color. In conclusion, it is not foreseen that NMR will be a viable alternative in this kind of application, at least not until further method development and validation has been carried through [35].

2.3.3 Information-based sorting

2.3.3 presents various methods for incorporating information into textiles at the time of their production — tags that can carry information about the textile item, to be conveyed to a sorting process or for other purposes. The tags can consist of labels printed with a pattern or electronic devices that can communicate coded information to a reading unit when called upon. This is yet another example of the rapidly spreading phenomenon "Internet of Things", which we begin to meet in more and more situations daily.

2.3.3.1 Optical 2D codes

Optical identification tags, such as bar codes and quick response (QR) codes are furthermore extremely widespread in society, finding use on many household items including food packages in stores (*Figure 3*). But they are also used in applications that are further away from customers, as in the communication from producers to wholesale links in the mercantile chain, where they are tools for keeping warehouse stocks in order. They are already finding widespread use in clothing, but not in a way which is harmonized and adapted specifically for the information needs in automatic sorting of used garments. The primary role of such codes is generally to carry price information and aid stock-keeping at the retailer, but their potential use in connections via social media is increasingly explored[36].

Figure 3: An example of a quick response (QR) code.

QR

QR codes are readily accessible to a large and growing part of the population through several free reading apps. A clearly visible code on the outside of a garment gives further opportunities for conveying personal messages, and it is now possible to order garments with printed codes[37, 38]. They can then serve as advertisements for the wearer and give opportunities for political statements, to show social media profiles or links to a blog site, or promote contacts among strangers. Another purpose for openly visible QR codes is the marketing of the designer/manufacturer, who can for example let the code link to a website presenting their latest news in design.

A QR code is richer in information than a one-dimensional bar code. The standard QR code corresponds to 2953 bytes of binary code, which offer so many combinations that the information is almost unlimited. A QR code is not merely a link to a database but can contain in text and images all the information you want, direct accessible by an app or other reader which interprets it.

2.3.3.2 RFID

Radio frequency identification (RFID) tags and other readable identification markers have been developed for a vast number of applications and are finding an ever increasing and almost ubiquitous use in society.

The list of applications is long and includes such diverse examples as:

- Identification of vehicles at road toll stations
- Identification of runners in orienteering events and other sports
- Identification of items and pallets in industrial plants
- Control of restricted access to buildings, including hotel keys
- Skipasses
- Traceability of wood from log harvesting through sawmill to products
- Military applications
- Retail anti-theft systems
- Identification of individual cows who voluntarily and regularly walk into milking stations

and many more.

Gamification is a rapidly growing phenomenon utilized for marketing purposes, and a few examples where RFID or NFC (described below) technology has been used are connecting on social media when two RFID-equipped glasses are clinked in a bar, and an NFC enabled ad in a magazine which opens up a video describing some product details. In the apparel trade it has appeared in a store in Singapore, where a selected piece of music is played for the customer bringing a garment to the dressing room, alongside with an offer for a free download of that song. In Burberry's flagship store in London every item is RFID tagged, and when a shopper brings it to the fitting room, a video with specific information about the item will begin to play[39].

In the introduction of a report from 2014, BCC Research claims that the global market for RFID technologies was valued to $9.7 billion in 2013, estimated to grow to $24 billion in 2019[40].

The two basic elements of an RFID tag are the chip, which stores the information, and the antenna, which receives and transmits signals. The physical size of the chip is very small, in the millimeter range, while the size of the antenna is dependent on the desired reading distance and other circumstances. One example of a commercially available tag for laundry tracking, Tagsys MuTrak UHF RFID Tag, has the dimensions 7 x 7 x 1.4 mm and is designed for temperatures between -50 and +200 °C. It is suitable for insertion in a hem[41]. The minimum size available, or which the minimum size is for a given reading distance, is not known at the present, but these specifications will probably be subject to change due to a rapid ongoing development. Much thinner tags can be produced in the form of printed electronics, but the ability to withstand organic solvents and other stress factors must be taken into account. This applies especially to the carrier materials that the chip is mounted on, since the life of the chip itself is very long in the absence of really extreme conditions. Without a doubt, a future agreement on a system for textile tagging must be preceded by a thorough work of adaptation to the particular requirements of this application.

Figure 4: Examples of physical appearances of RFID tags. The size of antennae is adapted to the intended use and required sensitivity.

Different frequency bands are used for RFIDs. The Low Frequency (LF) range is 125-134 kHz, with a reading distance limited to approximately 10 cm, and it is standardized mainly according to the protocol EM4100. High Frequency (HF) RFID operates at 13.56 MHz (protocol NTAG216) and has a reading distance of a few tens of centimeters. The former is the dominating solution used for controlling access to office buildings today, while the latter is used by *e.g.* the public transport system in Stockholm. Things are made more difficult, however, by the fact that different and non-compatible varieties of the NTAG exist. Ultra High Frequency (UHF) RFID in a band of 856-960 MHz allows reading at greater distances, up to 100 meters. The UHF band is therefore more suited than the others for purposes of *e.g.* inventory tracking. Within the UHF Frequency range, there are two primary subsets:

a) The FCC (US) standard frequency range of 902-928 MHz
b) The ETSI (EU) standard frequency range of 865-868 MHz

The FCC standard is used throughout North America as well as the majority of the Caribbean and much of South America. The ETSI standard is used throughout the European Union and most countries adhering to EU standards.

For the specific purpose of tagging garments and other textiles it appears possible to apply any of the solutions above, but the optimal choice can only be made after weighing pros and cons related to specific needs of all intended users in the value chain. It is of course highly important that one single, standardized variety is chosen for the whole trade.

The integrated circuits of a chip can harbor a tremendous amount of data. It will not, of course, contain directly readable information in clear text but it is programmed with a 128 bit word (but other word lengths also exist), which is no more than a string of 0's and 1's which identifies the textile and links to information stored elsewhere. The databases for this information can be kept locally, but more plausible for a common textile tagging system is that links lead to data sets and web pages in "the cloud". The 128 bit word corresponds to 2^{128} possible combinations, which is equal to 3×10^{38}. This number is much smaller than the number of combinations for a QR code, but still so vast that if one were to print all possible unique codes all over the surface of the earth, every square millimeter would carry about 10^{18} codes (or a billion times a billion). Even if some of these theoretical combinations are sacrificed as redundancy or check sequences, a very large number remains. This highly unrealistic thought experiment just shows the magnitude of the information capacity, obviously quite sufficient to give every single textile item its unique identification code for a very long time.

A very important trait of such a system of links is that the information can be stratified. By recognizing the status of the linked device, different levels of information can be shown. The consumer may be interested in data on the manufacturer, the materials, and some more. The retail stores may want to know that plus more about the manufacturing batch, shipping information etc., while the sorting industry can limit the information they obtain to what really matters to them. RFID tags can furthermore be either active or passive. An active tag carries its own power source, and this is essential in order to reach the longest possible reading distances. It enables communication with various types of sensors, which makes it possible to add information pertaining to the use phase of *e.g.* a garment. Such user generated data are then transmitted and stored in the database that holds the previously recorded information details. Passive tags are powered simply by the incoming signal from the reader's antenna. Intermediate forms are possible, where the tag is powered temporarily by one of several forms of "energy harvesting". To include an internal power source in the form of batteries increases the costs. The passive form of tag appears at present to the authors of this report as the most realistic and perhaps the only needed alternative for textile tagging on a larger scale. A dependence on batteries limits the time frame for which the tags can be useful and introduces an aggravating element to be taken care of in the recycling process, but it should be noted that the most recent development of energy harvesting tags has led to tags that require extremely small energy amounts[42].

The majority of RFID chips have a read-only configuration. ”writable tags” is something of a misnomer, since the code on the tag itself is not affected, but the concept involves addition of further data into the database, as mentioned above. It is conceivable to make automatic updates of the database through the interaction with sensors in *e.g.* a washing machine. Active updates by the user is another alternative. In either case, the access to the database is governed by some external service, and its ownership and control is an open question. For several reasons, this is not seen as a part of a development in the near future for the textile industry, and this is discussed also in 3.3.

The costs for the tags themselves are low and should not as such be an impediment for a tagging system. The price range is rather large, but it goes down to approximately 10 euro cents[43]. This figure is certainly dependent on the technical specifications but also very much on the scale in which they are procured. The cost of attaching an RFID tag is estimated by Humpston et al. to 2-3 euro cents, very similar to that of attaching a label[43]. Even small added costs can amount to a significant proportion of cheap items, and this was clearly identified as a potential barrier by some respondents in the interviews described in 3.3. Others maintained that the main problem we have today for sustainability reasons is that many clothes are too cheap anyway, and if tagging would become mandatory it would not change the margins and the competition.

One example of a tagging system in full operation is also an example of a local, company owned database, where there is little need for communication with the outer world: The company TvNo in Norrköping, Sweden, has contracts with e.g. hospitals, to which they an established routine of distributing bedsheets, workwear, patient clothing, and other textile items. They receive the goods for laundry and keep track of every item by a RFID tag which is sewn into a seam of it. The tag communicates with a database which then can record the location of a garment and count the number of laundry cycles it has gone through. (This is incidentally a very important measure for some special textiles used during medical surgery, where they are sorted out of the loop after a predefined number of cycles when they are deemed to have lost some of their leak-proofing properties). The business model in this case involves that the company in question procures the clothes and other textiles already equipped with the tag and then has the ownership of them throughout their cycle of use[44]. This mode of action is of course not unique but is used in many existing laundry companies.

Another development for the use of RFID in textiles is the use of RFID chips that are integrated into a thread and then woven into garments, linens, luxury items or industrial products. The thread is nearly impossible to visually identify as an RFID tag. In 2017, the company Content Thread was awarded the H&M Global Change Award for facilitating sorting and recycling of clothes using a digital thread including RFID technology[45]. An exploratory work was performed by Miriam Ribul at University of Arts, London in a design–science collaboration between RISE Bioeconomy (at the time SP Technical Research Institute of Sweden) and Chalmers University of Technology, funded by COST, the European Cooperation in Science and Technology within Action FP 1205. It involves a potential material coding system that can be embedded at fiber level of regenerated cellulose to inform users of material origin, type, process and recycling. The aim of her work was to propose a vision from a designer's viewpoint rather than to set new technical development in motion. See Appendix 3 for details.

2.3.3.3 NFC

Near Field Communication (NFC) is basically a special case of RFID, running under its own protocol and with the reading distance limited to a few centimeters. It operates in the 13.56 MHz frequency band.

There seems to be no reason at this point to treat NFC separately from RFID in general, since they are techniques of the same family and there are still so many variables to decide. The short reading distance of an NFC tag may be fully consistent with an automated sorting line for textiles, provided that a small enough gap can be held between a reading unit and a moving belt. Only practical trials can fully evaluate the feasibility of various solutions.

The RFID/NFC technology is not only adopted by an ever broadening range of industrial applications. Recently, a new breed of man has begun to emerge – the chipster, or the bodyhacker. A small chip, furnished with a minute antenna, is embedded in an inert capsule in the size of a rice grain and then implanted into *e.g.* the palm of a hand[46]. This device can be used for gaming or to identify a person before a door lock or to allow a commuter passenger to travel without bringing the card, all provided that compatible systems are used.

2.3.4 Activities within automated sorting development

The growing demand in developing more efficient sorting methods for textiles has its background in the wish in reaching a higher level of sustainability through increased reuse and recycling opportunities. The attention given to these issues is manifested in many research projects and industrial efforts. Some relevant endeavors in this emerging field are listed chronologically below.

Development of the FIBERSORT technology (2009- until today):

> **Textiles4Textiles** (an EU FP7 project, 2009-2012)[47], was led by Stichting Kleding Inzameling Charitarieve Instellingen (KICI) and had six additional partners[48], one from Germany and the rest from the Netherlands. The most tangible result of the project was the first generation of an automated sorting machine with NIR detection. This aimed at sorting garments according to their material composition and color. The development of the sorting machine, under the name FIBERSORT, was taken over by Valvan Baling Systems[49], progressed into the Textile Sorting Project.
>
> **The Textile Sorting Project** was an independent continuation of Textiles4Textiles. It was initiated by Wieland Textiles, Valvan Baling Systems, and Circle Economy and it aimed at launching the FIBERSORT equipment.
>
> **The FIBERSORT project** (funding from the European Commission INTERREG NWE programme (2016-2019) is a direct continuation of the two projects above. It seeks to optimize, validate and launch the FIBERSORT technology in the global market[50].
>
> **Auto-Tri** (funded by Eco-TLC during 2016) involve the partners Synergies TLC and Valvan Baling Systems, which here tested the Fibersort machine further.

PASTA (an EU FP7 project, 2011-2015) was coordinated by Imec and the consortium consisted of 10 partners in Belgium, France, Switzerland and Germany[33]. The project made a very interesting combination of research on electronics and textiles, with the goal to develop interactive textiles of various kinds[51]. RFID tags for product verification was one of the applications, as well as embedded light spots, sensors for stress or moisture, and more. A few demonstrators developed during the project, but more exhaustive results have not been made publically available.

Resyntex (an EU project within Horizon 2020, 2015-2018) is led by SOEX and has 20 partners from 10 member states[34]. This is a research project which aims to create a new circular economy concept for the textile and chemical industries to enable production of secondary raw materials from unwearable textile waste. The project involves further development of the hyperspectral imaging techniques for online textile sorting.

Textiles back to textile (financed via the "Test bed" program of Vinnova and Västra Götalandsregionen, 2015-2016)[52], led by Innovatum and was composed of a consortium of 15 partners from industry and academia. The aim was to review and develop the value chain from collection of used textiles to new garments, including studies on automatic sorting.

Spill till guld (Waste to Gold) (funded by the Vinnova program Challenge driven innovation, 2014-2016)[53]. Led by Swerea IVF and involves 24 partners from research institutes, industry and start-ups. The project had a scope that covered three very different waste streams: metals, textiles and powder varnishing. For the benefit of textile material recycling processes it gathered information on how to best track chemical compound information used during textile manufacturing.

SIPTex -the Swedish Innovation Platform for Textile Sorting (funded by the Vinnova program Challenge driven innovation, 2016-2018) is led by IVL, the Swedish Environmental Research Institute, in collaboration with a wide consortium of research institutes, authorities and industry partners[54]. The aim is to create a sorting solution tailored to the needs of textile recyclers and the garment trade to enable high-quality textile recycling. The textile sorting innovation platform, now under development, is intended to leverage a 45 000 tons textile recycling sorting capacity.

Trash-2-Cash (an EU project within Horizon 2020, 2015-2018) is led by RISE Research Institutes of Sweden and has 18 partners from 10 member states[55]. The project aim is to establish a solid technology which closes the loop from used textiles and paper, to new textiles. This project includes a study on the current status and technical potential in recognition based on testing of NIR devices from different manufacturers for automated sorting of textiles.

2.4 Textile recycling activities

At present, textile material recycling is an emerging industry. Besides the commercially existing mechanical recycling, chemical recycling processes that actually can regain lost qualities from the use phase are developing worldwide.

Biobased fibers are being manufactured from virgin cellulose containing biomaterials, such as cotton, trees, bamboo, algae, etc. In addition to a direct utilization of biosynthesized cellulose, like cotton, several different variants of regeneration processes exist for converting more inaccessible cellulose (tree cellulose for example) into man-made textile fibers. Common or proprietary names of man-made cellulosic textiles fibers include viscose, modal and lyocell, Tencel and rayon.

Man-made cellulosic textile fibers cannot only be obtained from the cellulosic raw materials mentioned above, but also from used cellulosic textiles, such as cotton. A vast study on how cotton changes during the use phase and it's suitability for regeneration into man-made fibers has been performed by Dr Anna Palme within the Mistra Future Fashion program[56]. Lenzing, based in Austria, uses both wood and cotton fabric waste to produce Tencel fibers[57]. The re:newcell demonstration plant in Sweden[58], operative in the middle of 2017, produces a refined pulp from cotton waste for further processing into regenerated fibers, with a capacity of 7,000 tonnes/y. Researchers at Saxion University of Applied Sciences in the Netherlands have developed a similar process to transform domestic cotton waste into a regenerated fiber by the name of SaXcell[59]. Their process includes steps for decoloring and wet spinning. In Finland, both Aalto University and VTT have regeneration equipment for production of new cellulosic fibers from discarded cellulose sources, although they are mainly focusing on two different dissolution technologies: the Ioncell-F and the carbamate process respectively. In the US, Evrnu converts cotton garment waste, pre- and post-consumer, into new pristine cellulosic fibers[60].

Likewise, synthetic fibers, e.g. polyesters, can be dissolved or degraded and regenerated[61]. Teijin Fibers Ltd[62] and Jeplan[63] in Japan have been particularly active in developing proprietary processes for the production of high-performance recycled polyester fibers. The latter company is at present erecting a new processing plant in Japan. Also in the US, Ambercycle Inc. describes on its home page[64] that they "develop chemical technology to produce conventional polymers, such as polyesters, from a variety of fibrous waste streams", but gives no further details.

However, waste textiles often consist of fiber blends, and the most common blend is the polyester/cotton (polycotton) blend. British Worn Again[65] works towards fiber recycling processes for both cotton and polyester. Recently, the Mistra Future Fashion program in Sweden launched their process on recycling of polycotton blends called Blend Re:wind[66], as well as the Hong Kong Research Institute of Textiles and Apparel (HKRITA) launching their breakthrough in the same field together with H&M Foundation[67].

The still emerging development of textile recycling, and its dependence on certain materials and blends attest that improved identification or information technologies would benefit the recycling industry. Accuracy will be important to maximize the incorporation of all materials used in the process into the final product, as well as prevent waste fractions.

3 Interview-based review of the potential of information carrying tags

A stakeholder mapping and the interview-based part of this study can be found below. As described in the objectives of the study (see 1.1), two of the four aims were to "*define gaps and potential routes for solutions to the current technology lack*" and "*map stakeholders and how they are affected by new technology within the field*". These two aims are here partly answered by stakeholders in the field.

As also mentioned in the objectives, the technical development of the automated sorting (see also 2.3.4 Activities within automated sorting development) and the evaluation of such have been executed in parallel by the sister project Trash-2-Cash[1]. As a result of this, the scope for this report has been on the potential of future tagging technology of garments and other textile products. It could be seen that the tags offers other possibilities to the automated sorting, and beyond, such as bringing information from the production throughout the life-time of a product.

The purpose of the stakeholder interviews was to review the opportunities that information carrying tags can provide in the transition towards a more sustainable apparel and textile industry. It is of outmost importance that the full potential of these tags can be foreseen. This report includes a series of interviews made with individuals from 23 organizations or companies, representing a spread of stakeholder groups within the value circle of textiles.

As a basis for the interviews, a document (see Appendix 1) was compiled with questions that would categorize how the respondents described their place in the value chain and their potential interests in a future system with tagged textiles. Other questions were deliberately left more open to invite new ideas and promote a more open discussion. The interviews were performed over phone or during physical meetings and the result of these interviews are described further down in 3.2 and 3.3.

3.1 Stakeholder groups identified for the use of tags

The major part of the stakeholders selected in for the interviews are companies or organizations with vested interests in various parts of the textile value circle and with a variety of potential benefits and opportunities of a future system based on information carrying tags. The stakeholders have been grouped, presented as a list below, in order to present their potential interest and to interpret the outcome from interviews from a more holistic viewpoint in the analysis (see 4 Analysis).

- Garment manufacturers and other producers (textile manufacturers, producers and designers)
- Retailers (textile importers and retail stores)
- Collection and sorting companies
- Charity organizations and second hand shops
- Service textile and industrial laundry companies
- Textile recycling companies
- Cities, municipalities, public procurers
- Consumers

In the interviews, a more detailed subdivision of stakeholders has been used, because it is apparent that some companies cover several steps in the value chain, and many cases are found when an individual company or organization cannot singularly be related to one stakeholder group only. For instance, there are today retailers that take an active part also in collecting, and further business model changes could happen rapidly. The grouping should for that reason not be seen as definite but as facilitation for the discussion and analysis in this report. The detailed outcome from the interviews can be found in Appendix 1 and 2.

3.2 Interview results

This part of the report discusses the replies and points of view that emerged during the interviews. Interrelated questions are grouped and discussed together.

The 23 interviews carried out cover representatives from most of the stakeholder groups. The number of interviews is not large, but it must be emphasized that the exercise was not an attempt to create a statistically valid overview of attitudes and standpoints in various parts of the trade. It was however rewarding to find that the initial reaction of all contacted persons was unanimously positive, with expressions like "highly interesting" or "exciting", and none of them turned down our request for input. Some companies assembled up to four specialists to join the discussions.

3.3 Questionnaire output

The ambition was to carry out as many as possible of these interviews in direct meetings, where discussions were allowed to evolve and expand beyond the basic set of questions drafted in a document sent in advance (see Appendix 1). The interviews intended to let the discussions vary from very straight-forward responses, to more open-ended, inviting free and more speculative answers. These pages were thus not meant to function as merely a questionnaire, crafted for solitary filling out and returning by the respondent, but more as a stimulus for discussions which would bring out new ideas. Some minor adjustments of the document were made after a few interviews in order to clarify certain points. Especially the question on the desirable elements of information (question 2, in Appendix 1) was found to be best divided into the interests of the respondent and those of the trade in general.

The nearest following pages describe and review the answers of the questionnaire.

3.3.1 Which are the information and data requirements in tags of the textile and fashion cycle?

The respondents were first asked to list their roles in the textile value cycle (choosing from the different roles: Producer, Designer, Garment manufacturer, Specialized garment manufacturer, Manufacturer of other textile products, Textile importer, Retailer, Textile collector, Sorter of collected used textiles, Material recycler, Public procurer, Consumer, Launder, Washing machine manufacturer, and/or other). Only six of the respondents pinpointed only one single category.

In the following questions, regarding useful information in the tags, we invited the respondents to think firstly about their own information needs that could be met by tags, then to consider the whole trade. It turned out that even if their own interests were narrow, most respondents realized that there would be potential benefits for many others, if not all, which is reflected in two separate sections in Table 4, Appendix 2. Two companies, defining themselves as collector/sorter and recycling industry, respectively, limited their own interest statements to material contents, while acknowledging a wider scope of interests among other stakeholder groups. Almost half of the respondents did include all stakeholder categories. The assessment of overall data needs indicated that tags can be used all through the value circle of textiles and fashion.

One of the most obvious pieces of information that a tag could carry is the identity of the producer. This can be expanded to include several steps in the production chain, going back through sewing, finishing, dyeing, fiber production and ultimately create a track to the raw material origin (viscose from a certain forest, sheep's wool from a certain farm, a specific cotton region, etc), as already demonstrated by *e.g.* the company bioRe[68]. Production year was also generally seen as reasonable to include.

The alternative to include an identification number of a production batch was interesting to everybody. It was seen as essential by some respondents, while others regarded it only as something others would need. Identification number, unique for every individual item, was more of a divider however. Respondents, who were thinking about gamification, added user information, creating a provenance and a history for a garment, or support for a lease/loan system, were interested or even thrilled by the possibilities. On the whole, the majority were indifferent or even opposing the idea of a recording/data collecting tag, mainly for reasons of personal integrity of the owner of a garment.

Material issues involving fiber composition, dyes, prints, water proofing agents, additives etc. were, seen as important information to include in a tag by almost all respondents. The information types dealing with social responsibility and sustainability measures (environmental footprint, social responsibility and comprehensive sustainability measure), were generally seen as valuable, too. The small nuances in the frequency of positive answers are not significant though, for such a small cohort of answers.

Model, size and color were among the least desired information categories. While shopping, consumers can more comfortably find that out through their own judgement or through conventional hangtags. Such information can, however, be useful in sorting processes and for the second-hand market.

Additional uses for the tag appeared in some discussions, for example a possible integration of theft alarm functions in stores that now are handled by bulky buttons which also involves a cost. Tags could potentially be utilized also to discourage or to resolve large-scale, organized thefts from transports and warehouses.

Useful data suggested to be added on the tags was the weight of the tagged textile product, as proposed by one of the respondents. This could clearly be a factor of interest for the recycling fraction, since the mass of collected fibers is of prime interest to the recycling industry, rather than the number of garments it comes from. In addition to this also a list of the chemical content could be included. Such information must be transparent, but digestible, i.e. it cannot be a list of Chemical Abstracts Service numbers but must be presented in some aggregated and interpreted form.

Interview data covering this part of the questionnaire can be found in Appendix 1, questions 1-3 and in Appendix 2, Table 4.

3.3.2 Preferred technical solutions and added features

The further use and implementation of information carrying tags opened up a discussion on what kind of additional data could be logged by the user, which drew quite scattered comments. Many respondents could easily imagine that information added during the user phase could be interesting, but most said that it sounds a bit unrealistic, an unnecessary complication, and nothing that has a very high priority today. A few manufacturers were more enthusiastic about the quality feedback they could be able to get if retrieved items from their own production could be evaluated in the light of what they had been through. Other aspects on this included gamification; e.g. what would it mean to a producer of sportswear if the owner of a jacket could couple information from GPS tracks and be able to tell how many meters of vertical drop it had accumulated on ski slopes? This could have implications also for the second hand trade.

Regarding input on the preferred technical form of the information carrier (a bar or QR code sewn-on patch, a bar or QR code weaved or knitted into the fabric, a read only transponder RFID or NFC, a read-and-writable transponder RFID or NFC, or another solution), transponders of some sort were clearly favored in comparison to QR codes. However, it was pointed out that QR codes are already very commonplace, and it might be possible to begin with them and make a smooth and seamless transition into another technical platform. Writability was not generally seen as a very valuable trait in transponders, with the exception of a few respondents who showed some enthusiasm about the possibilities for gamification and story-making on special functional clothes.

Interview data from this part of the questionnaire can be found in Appendix 1, question 5-7.

3.3.3 Which are the technical and cost considerations related to tags?

One of the technical methods to read a tag could be through an app in the smart phone. The views from the interview respondents diverged very much on this aspect and the answers reflect how consumer behavior is *perceived* by actors in for example retail due to their experience, and cannot be said to represent a true picture of actual consumer preferences. During several interviews a discussion evolved around the readiness of consumers to use an app as the main instrument to gain information about a garment before buying. Most respondents argued that it did not seem to be the most practical way and that the information needs to be seen in print, on hangtags etc. Others, who agreed that the willingness to pick up the phone for this purpose is low, claimed that it is a cultural thing which may very well change rapidly. The respondents further emphasized that certain countries in Asia are more liable to utilize mobile apps , and the younger generations in

Sweden has a far lower threshold to this and a more symbiotic relationship with their smartphones. It was argued by one respondent that customers equipped to read all possible information on their own would potentially liberate time for shop attendants and that creativity and transparency is rewarded by customers. In fact, transparency was a keyword used by many respondents in the production and sales part of the chain.

Connected to the technical specifications for a tag, the maximum reading distance of a tag can be connected with the personal integrity of the user of the garment. This seemed to be difficult to give a comment on by most of the respondents. It requires a thorough understanding of how data is stored and retrieved. For an automated sorting process it is of course of central importance, but then it is more a question of optimizing the process.

Whether a tag must be removable before recycling or not, was a question most respondents confidently placed in the hands of the recyclers to answer. The representatives for this industry were equally confident in saying that they are already good at separating out various non-textile objects and that tags should not present serious problems. Interview data covering this part of the questionnaire can be found in Appendix 1, question 8-10, 13-15.

For technical development or adaptation of existing technologies it is important to critically consider specifications or factors that the tags should meet. The following list, presented in Table 2, of properties for a tag, regardless of type, was drafted at an early stage of this study, and discussed and developed further in the interviews. Regarding the physical or technical requirements that a tag should meet, practically all respondents perceived the presented list as complete. A few important additional comments clarified that the proposed temperature tolerance range was far too narrow to cover both extreme cold outdoor situations and laundry processes, which industrially use superheated steam of up to 220 °C. Another comment was that "concealed" must not mean that there is any doubt about where to look for it, if the reading distance is very small. Furthermore, the tag must be safe from an environmental point of view.

These implementation factors are important to consider when choosing or developing tags. Most of the criteria are valid for both optical and electronic tags, but a few are particular for the electronic case.

Table 2: List of possible essential properties of a tag, regardless of type.

	Property
1	**Contents:** *Producer, Material(s), Production date, Model, Size, Color, Weight, Individual ID, Washing instructions*
2	**Mechanically robust**
3	**Washable**
4	**Able to withstand extreme temperature (-40°C to + 220°C)**
5	**Able to withstand mangling**
6	**Able to withstand bleaching and other chemical washing additives**
7	**Able to withstand dry-cleaning solvents**
8	**Readability:** Fast and reliable
9	**Non-disturbing during use (concealed, but easy to find)**
10	**Inexpensive**
11	**Easy to apply**
12	**Remain in place during the full user phase**
13	**Maintain integrity of the user**
14	**Removable in a material recycling process, or non-disturbing**
15	**Resistant to relevant temperatures (during user phase and recycling)**
16	**Writable (ability to record and log e.g. the washing cycles)**
17	**Reusable**

After choosing the type of tag to be used, similar considerations must be drawn up for the reading system and its use, which will incorporate many construction aspects.

Concerning the distribution of costs and added values along the value chain, the discussions covered three main views:

- *The costs for a tagging system would probably be paid ultimately by the customers. Without a deeper insight into the full system costs, but realizing that the tags themselves are not particularly expensive, it does not seem to have any marked influence on the consumer prices. In any case, the main problem today is not, however, that clothes are too expensive. What counteracts a more careful use of the textile resource is rather the large amount of too cheap imported clothing from low-labor-cost countries.*
- *Costs would be compensated by a larger stream to a growing recycling industry, giving an overall cheaper raw material feedstock to the textile industry.*
- *It depends on which information the tag carries. But when opportunities open for various actors on the market, they will be ready to pay their part of the price in order to gain the potential benefits of a tagging system.*

A totally free and voluntary adherence to a tagging system was not advocated on the whole, however. Many comments on costs also underlined the importance of agreements across the value circle, as unanimously as possible, and support through standardization, regulations and legislation is probably necessary.

3.3.4 What is the view on reuse and recycling options?

The questions relating to collection for reuse and recycling of textiles had the main purpose of stimulating discussions and collecting views that would otherwise be left out when only discussing the use of information carrying tags.

Interview data covering this part of the questionnaire can be found in Appendix 1, question 4,11-12, and Appendix 2, Table 2.

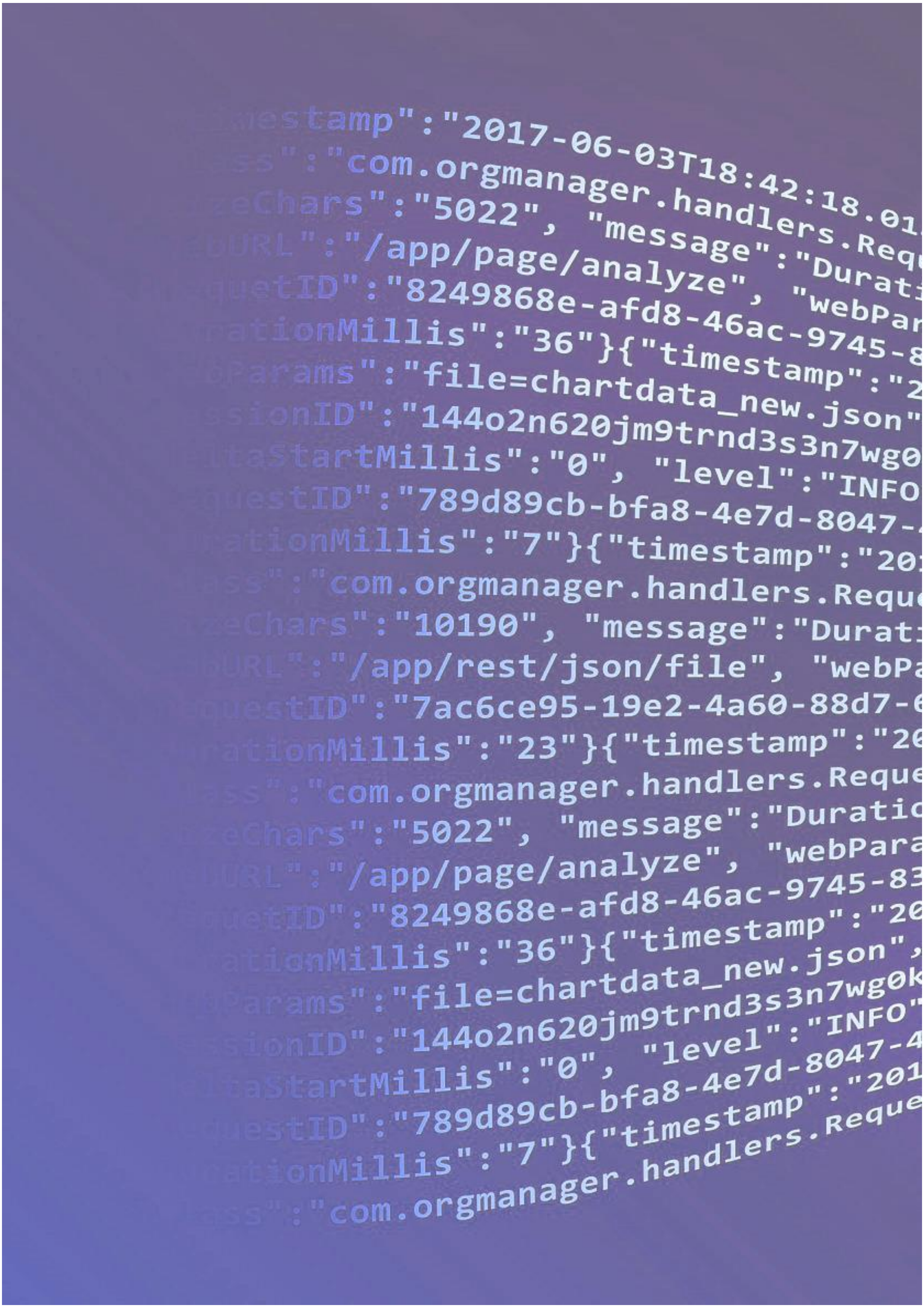
In the question on how to collect discarded textiles by in-store collecting, practically all respondents preferred all used textiles to be maintained according to the principle "all textiles, regardless of origin". The arguments for this collection mode underscore that it is the only possible way to collect with a reasonable effort for consumers. It does not prevent, however, that it can remain interesting for individual specialized producers who already collect only their own goods, for goodwill or for remake purposes. To collect only textile products from your own production goes hand in hand with ideas about an extended producer responsibility (EPR) that are fostered by some, but when this issue was raised most respondents ruled it out as completely unrealistic and counterproductive as a main solution. The arguments against it are for example that it gives automatically a non-optimization of the collection, that many smaller companies will not have the ability to live up to such requirements, and that the producers are difficult to identify and find by customers when it is time to discard a garment. A more thorough treatment of the feasibility of EPR schemes is given in the 2017 report by Elander et al.[69]. Regarding the current mode of collection, this was only discussed with the respondents involved in direct consumer contacts. Respondents from four large chains of retail stores said that they collect according to the first alternative, *i.e.* all textiles, regardless of origin. Three manufacturers of specialized garments, among the respondents, accept returns only of their own production.

When it comes to the technical issues of how to recycle textiles it appeared that the majority of the respondents believe that chemical recycling is more important, prior to mechanical recycling, since it gives a superior regenerated fiber. This answer partly reflects the types of material the respondents usually work with. There was also a great deal of understanding that there is a place for both recycling types, serving different end uses and markets.

In the view on which fiber types to prioritize in recycling, cotton was mentioned by most. This was motivated by the known issues with limitations in further increased cultivation and the environmental burden associated with cotton. On the other hand, as long as synthetic fibers come from a fossil raw material source it is very important to extend the life of these polymers once formed. A general view was also that chemical recycling of at least polyester is easier than it is for cotton. The discussions within this field were usually not distinct but weighed pros and cons and captured several angles. Several respondents among the manufacturers further explained that they are going in the direction of more monofiber fabrics, since mixed fabrics leads to more downcycling. This is presumably good news for the recycling industry. On the other hand, there is also a trend towards more multiple use garments that can be separated into parts, and that may require separate tags.

When discussing the automated sorting issues and the necessary accuracy in the detection of specific material compositions, this was only answered by respondents from the recycling industry. Nevertheless, those who answered were quite unanimous, saying that the precision needs to be "pretty high" or "very close to 100 %". At the same time it was acknowledged that some secondary uses do not require a very high purity. One manufacturer raised the question if it would be helpful for the recycling if all threads in seams were of the same material as the fabric itself.

The outcome from the interviews are further discussed and analyzed in the following part of the report, to facilitate a future dialogue and possible applications for a circular textile industry.



4 Analysis

The goal of this work has been to review possibilities for versatile and large scale operational technologies to automatically identify and sort discarded textiles to enable reuse and recycling (see 1.1). Thus, an important element has been the analysis of potential benefits, perceived values, and pitfalls and obstacles connected to a system for tagging of garments. A central activity has been the interviews with selected stakeholders, to capture views from a wide array of actors, representing various roles in the value circle of textiles; from production, through sale and the user phase, further to reuse and recycling. Additionally, this chapter adds a holistic view of the potential use of information carrying tags throughout the life-cycle of textiles, by a further analysis and discussion by the authors.

4.1 The use of information carrying tags in textiles

The concept of using information carrying tags in the handling of textiles is by no means new. A tag can, in principle, take different physical forms, as previously presented (see 2.3.3). The information carried by the tag can have either the purpose of internally logging and keeping information about an item, or to externally spread information about the item to give transparency to the user. It is already in use in several areas, with various purposes, such as in manufacturing, inventory control, warehousing, logistics, distribution, object tracking, supply chain management etc.[70]. One practical example is the RFID system set up by the service textile sector holding industrial laundries to support public sectors with garments and textiles, and another example is visible QR codes used in marketing of the designers and manufacturers, who can for example let the code link to a website presenting their latest news in design (see 2.3.3).

An example of an ambitious goal that reaches far beyond the sorting of used textiles is to use tags to convey information about the production and its environmental social impact according to recognized metrics to generate transparency about the product. Such a scheme is being considered by the Sustainable Apparel Coalition[71] as an attempt to drive the sustainability agenda of the industry by building up the Higg Index. Individual initiatives to bring sustainability information about garments through *e.g.* QR and NFC codes are growing, exemplified by the companies bioRe[68], Povigy[72], and Provenance[73].

Features offered by tagged items in general at various stages of a product's life cycle have been described by the Horizon2020 project TagitSmart[74]. Although it is not addressing textiles *per se*, the overview described by the project is fruitful for the understanding of many possible features of a tagging system and connected services.

It is furthermore obvious that the introduction of an information-based sorting system calls for patience. Immediately after introduction, the newly tagged clothes will constitute a minute fraction of all clothes worn by or residing with consumers. It then takes another period of time until appreciable amounts of tagged clothes begin to appear in the collection bins and in the sorting lines. This lag is schematically shown in figure 5 where a tentative development of the tagged proportion of the new production is represented by the blue curve, while the relative appearance of tagged clothes among the discarded textiles is shown in red. The shapes of the curves and the time scale are not to be seen quantitatively.

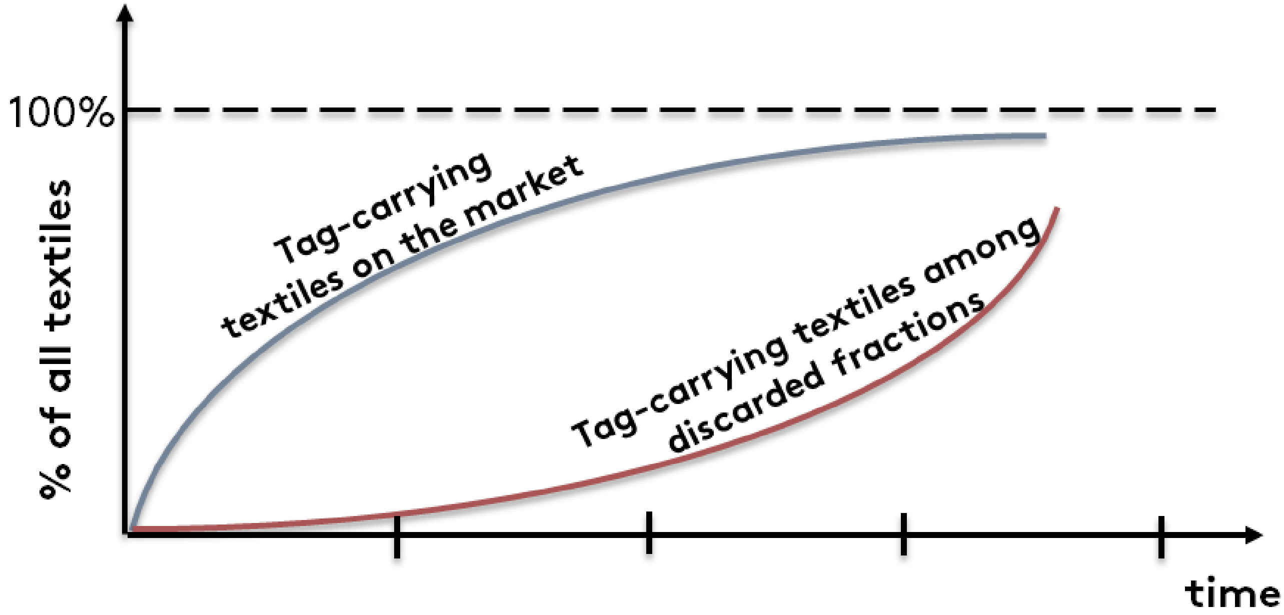


Figure 5: A non-quantitative estimate: Percentage of all newly produced textile items carrying a tag (blue curve), and percentage of all items reaching the sorting lines carrying tags (red curve). The time scale and the relative development of the two curves are not possible to predict with confidence.

The following question then arises: how big proportion of all textiles needs to be tagged for the tagging to be perceived as worthwhile and useful? This can probably best be answered by the conclusion that the reason for bringing in a tagging potential in textiles should be motivated by all relevant uses and not only to facilitate sorting of discarded textiles.

4.1.1 Comparison of identification and information technologies

Table 3 below compares some currently explored spectroscopic alternatives with the two main types of information carriers. The information aspects are so different in character that is difficult to give performance in quantitative measures. Some of the statements are theoretical, like the ability to inform about added finishes etc., since this hinges on which information the tag is loaded with.

The rating "very good" for the ability of tags to determine the fiber composition is only valid if a strict protocol can be maintained that ensures that falsified or erroneous tags are not attached during production, which is a known, occurring problem today. The speed of reading has been rated equally as "good", since exact measures for this are not known, but they are all fast and none of them is probably the rate-determining factor for a sorting line.

The statement "fair but rising" regarding the material recognition by spectroscopy has its background in the shortcomings of spectroscopic methods to accurately determine the proportions of mixed fibers and the possible muddling influences of texture and dark colors. The statement is positive, though, in expectation of refinements of the methods and not least a possible aiding mechanism in machine learning in the near future. In its present form, the recorded spectra are compared with a large number of stored reference spectra in a library, and the closest match is found by chemometric methods. The quality of the match is highly dependent on the quality of the references, but a continuous improvement is possible if smart combinations of indata are applied in an active learning process. New algorithms have to be built in order to apply such machine learning, but this is a rapidly developing area.

A more direct step to improve the sensitivity of near infrared (NIR) spectroscopy to dark colors is to use a combination of parallel sensors for different radiation wavelengths, including the visual spectrum. It is unclear to what extent this measure can alleviate the color problem.

A distinction has been made between the spectroscopic methods and the bar/QR codes in terms of orientation sensitivity. In principle, the former methods could take a reading anywhere on a garment, but they need a reasonable surface to inspect. QR codes, on the other hand, definitely need to be presented to the scanning device, and this takes an automated or manual reorientation of the textile item which slows down the process.

Table 3: Performance characteristics – the abilities of selected methods to give information. Statements are made non-quantitative to give a better comparison.

*) Not taking into account that overdyeing or laundry dye transfer during the use phase will not be detected by a tag.
$) NIR can only see one surface and not inside materials. QR codes must be presented to the reader.
The different shades of green-colored boxes in the table try to visualize where there is an advantage for one method or another.

Information type	NIR/Raman	NIR/Raman + vis	Bar/QR codes	RFID/NFC tags
Fiber composition	Fair but rising	Fair but rising	Very good	Very good
Material identification of unmarked goods	Yes	Yes	No	No
Dyes, finishes, prints, etc.	Poor	Poor	Very good	Very good
Color identification	No	Very good	Very good*	Very good*
Color influencing material recognition	Some darker colors less accurate	Partly helpful	Indifferent	Indifferent
Influence of fabric structure	Possibly	Possibly	No	No
Multifabric garments	No	No	Very good	Very good
Speed of reading	Very good	Very good	Good – very good	Good – very good
Sensitive to orientation	Yes$	Yes$	Yes$	No
Age	No	No	Yes	Yes
Costs for tag	None	None	Low	Somewhat higher
Reading equipment costs	High	High	Low	Low

A special advantage of RFID tags, besides being superior in information content, could be their ability to act as aiding tools for citizens with visual impairments. There are already apps that can translate information on QR codes and translate that into spoken word, but first the QR code has to be found and scanned. With an electronic tag this could presumably become easier.

A central conclusion from Table 3 is that none of the solutions alone will cover all information needs required within the textile value cycle. Instead, a combination of identification and information techniques is most likely needed. Furthermore, an automated system for end-of-life of textiles will never be the only solution, even after reaching a mature state. For a foreseeable future, manual judgement will continue to be a central part of the sorting. It is very likely, however, that a combination of techniques can be established in the sorting process, where the automated parts give an optimal efficiency. Such a semi-automated process has been proposed also by Palm et al[75].

4.1.2 A possible end-of-life system including information and identification technologies

A simplified cascade of sorting steps is shown in figure 6 where *1. Incoming goods* are separated primarily based on whether they have some sort of information tag, or not.

In *2. Manual sorting step*, the line 2a, is supported by information about e.g. the quality, brands, etc., which most likely makes the evaluation more accurate in the judgement for reuse/remake. It is today difficult to minimize step 2 by more automated handling, as this is also where a necessary evaluation is performed for sorting out goods that is torn, moth-eaten, spotted or otherwise made unsuited for direct reuse. If the item is equipped with a writable tag, information on waste not suitable for reuse (contaminated or non-wearables), can be directed to 3a.

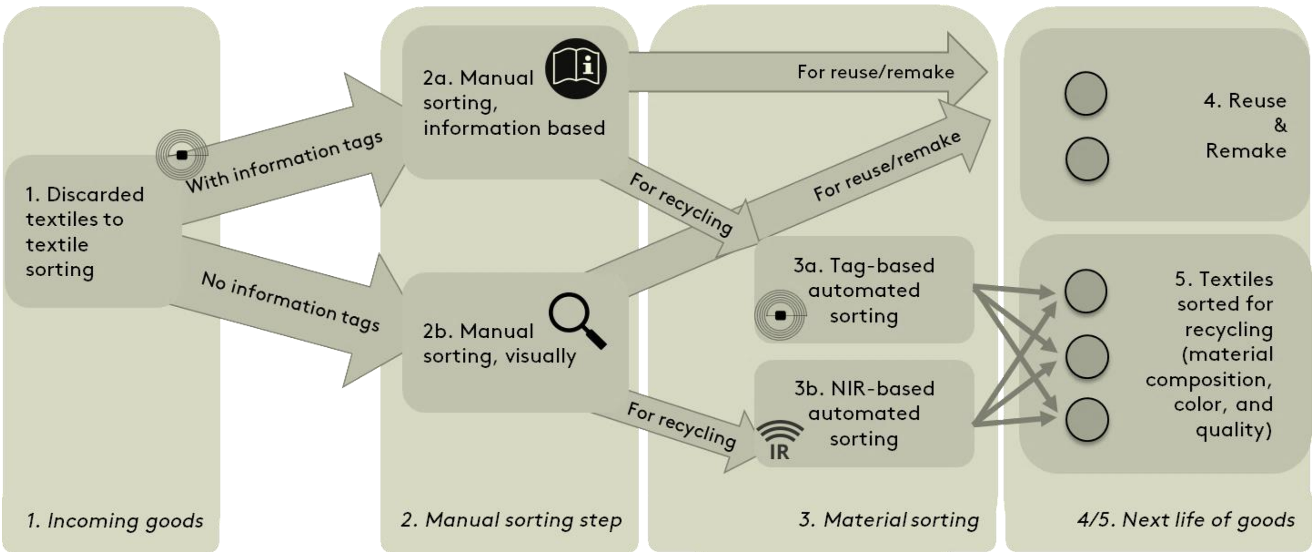


Figure 6: An example of a potential route to optimize the sorting and to make the manual evaluation more efficient.

In *3. Material sorting,* the items that now have been sorted for recycling are further sorted according to fiber contents, so for the goods holding a tag this would give the fastest and most accurate sorting -step *3a. Tag-based automated sorting.* The non-tagged goods will go through step *3b NIR-based automated sorting,* and is sorted according to fiber content. This technology today suffers in accuracy and might need manual operational support in feeding of the material etc.

It must be emphasized that this cascade configuration is **only one** of many possible routes, and this particular example is not the result of any in-depth analysis of an optimal system. It is likely that the manual inspection may come in at more than one stage.

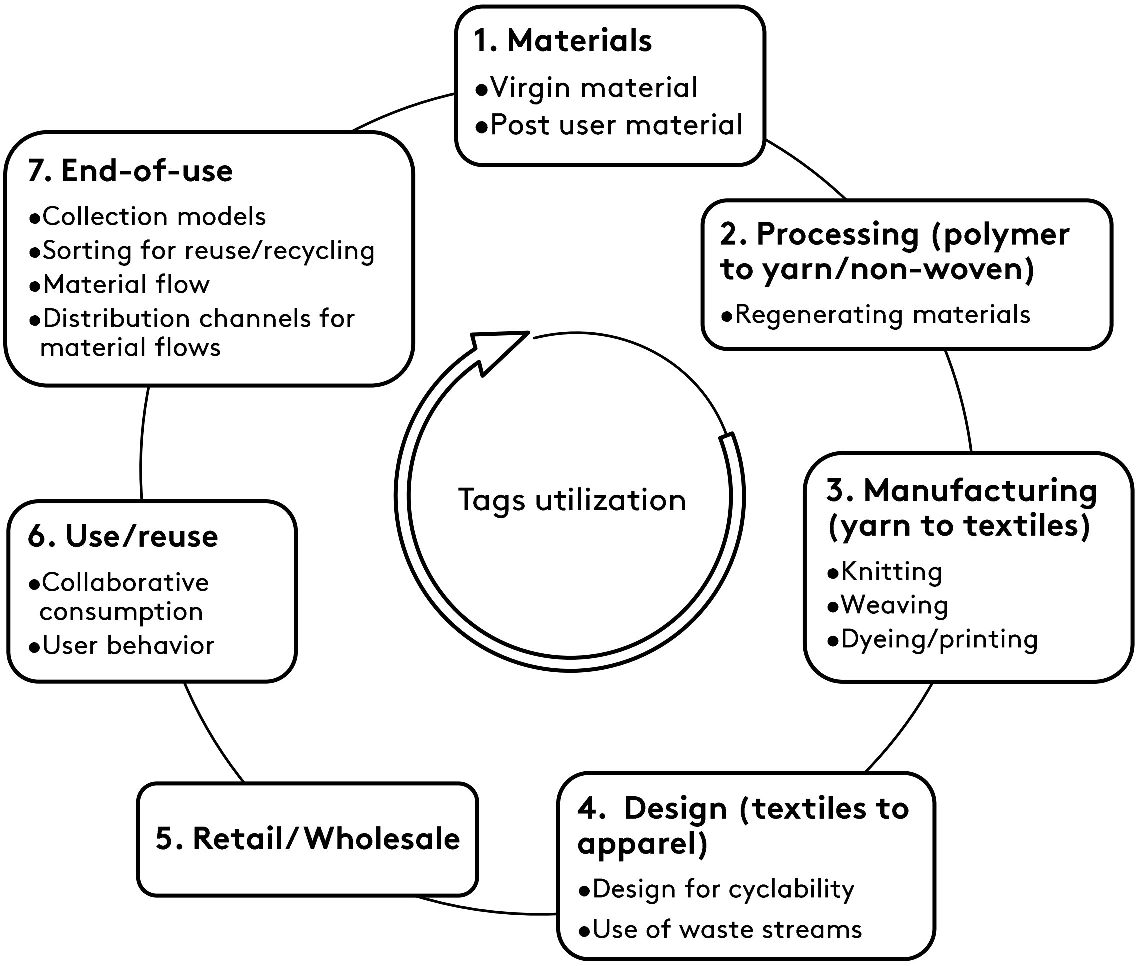


Figure 7: An overview of the various stages within the life cycles of textile products, which is used as an overview of the work within Mistra Future Fashion. This overview has here been modified to visualize how tags can be used within the life cycle. The dotted segment of the inner circle depicts a stage where the tag can no longer follow the material circle and has to be revived.

Figure 7 indicates that the information carrying tags can practically all stages in the circular life cycle scenario of textiles employed by Mistra Future Fashion. Information exchange in either direction is indicated by the "spokes" of the wheel. By connecting the main steps 1-7, from "1. Materials" to "7. End-of-life", in the wheel to the stakeholder groups described in "3.1 Stakeholder groups identified for the use of tags" we have the ambition of communicating an overview on how tags can be of value to enable transparency and use throughout the life cycle.

One of the remaining questions is whether the tags will be accepted and embraced by customers to the extent that they will affect the decision-making process and the consumption behavior by the transparency that can be given via tags. In order to get closer to each stakeholder group along the value cycle of textiles, the potential use for each stakeholder group has been described below.

4.1.3 Garment manufacturers and other producers (textile manufacturers, producers and designers)

During production, stages 2-4 in Figure 4, a textile product can be equipped with a unique tag, to be loaded with information. Besides facilitating the actual manufacturing process by informing on stock levels, location and movements, performance of different steps in the production line, and packaging requisites; information about material specifications and the complete manufacturing process (quality review, production line, factory date, etc.) can also be included[70]. Furthermore, tags may also give information of designers' choices and how to handle the product upon disposal, i.e. reuse and recycling options/recommendations, where it links to stage 6-7 reuse and end-of-use in Figure 4. These data can be stored in a database and further accessed with the designated software according to level of reading rights.

A few examples of companies among those interviewed have the end-of-life of their products included in their business models and have take-back systems of their own products for remake or upcycling. Recycled polyester and/or polyamide is also used by several of the interviewed producers and many others. Pantyhose made entirely out of recycled polyamide from old fishing nets were introduced on the market a couple of years ago by Swedish Stockings[76], and this particular company also collects pantyhose and stockings from any producer, delivering them for recycling into other products. A pioneering step in developing new business models has been taken by the brand Filippa K, who markets a special line of garments that have been used, then upgraded and sold again, but also offer brand new clothes from new collections to be leased in a range of concept stores[77]. Another initiative is the mending services included in the offer of Nudie jeans to their customers[78]. Such business models would beneficially be spread along with the garment in order to have the possibility to be updated by the manufacturer and to not be cut away by the user, as for a hangtag or a label attached to the garments in other forms.

There are growing numbers of manufacturers who seriously foster sustainability considerations as an integral part of their company profiles and identities, and this aspect is reaching a larger impact as awareness grows among consumers. This kind of information could easily be communicated via tags, such as the company´s responsible choices of fabric procurement sources, or to be transparent in their social responsibility during production, or how to take a more active role in the circular economy development[79].

From the interviews, it was seen that possible incentives for a system of tagged textiles within the stakeholder group of manufacturers, producers and designers could be double: Internal information such as production efficiencies and material data, and external information beneficial for consumers regarding company values and profiles as well as product details, such as origins and environmental footprints. If a tag would be writable, this can be used as a feedback channel from the consumer, on for example performance or usage, and also identify certain products in a sorting for possible take-back to certain companies.

4.1.4 Retailers (textile importers and retail stores)

Prior to stages 5-6, in Figure 4, (retail, wholesale, and use/reuse), the tag may be updated with information about the transport of the product (such as temperature, humidity, transport choices, etc.). In the store, the staff and the customers/consumers can both utilize all the information loaded on the tag from the earlier stages in Figure 4, and information regarding stock levels, accuracy of deliveries without opening of boxes, as well as prevention of stealing by control of garment movements[70]. During the use phase, which may comprise several use cycles, the information flow can be limited to the user or be extended to allow social interactions and third party services. Upon disposal of the product the user can reach information about a recommended route for reuse or end-of-use alternatives through the information on the tag. Several chains of retail stores have initiated take-back systems where customers can deliver used garments, often associated with a small return in cash or as a discount when conducting new purchases. This is often communicated as a part of their contribution to a more circular economy, and as an element in their competition for customers.

From the interviews, it appeared that possible incentives for a system of tagged textiles are in line with the discussion: a route to inform about company values and profile, as well as details about the product, its origin and environmental footprint, as well as advice for maintenance and disposal at the end of its service life; a shortcut to satisfy the most information-craving customers; facilitating in stock-keeping, inventory control and theft alarm functions. Handling of complaints could also be an interesting function, especially in combination with a writable tag that keeps a log from the user phase.

4.1.5 Collection and sorting companies

As soon as a garment is discarded by its owner, it should primarily be considered for reuse and secondly for other end-of-use-options, i.e. stage 6-7 in Figure 4. In the possible incentives for a system of tagged textiles, the tag could give the user information about these options. If the product ends up for reuse the tag could be updated with the information on how it has been used, and if it ends up in material recycling the material information loaded on the tag during manufacturing can now be used for fast automated sorting. The benefits of sorting are discussed in 4.1.2. Furthermore, practical data for managing collection can be added to facilitate logistics, such as weight and type of garments in a batch.

From the interviews it can be concluded that information about the material contents is the prime concern of sorters. It was also underscored that the full potential of these benefits is mobilized only after a tagging system is in place for a large majority of the textiles on the market.

4.1.6 Charity organizations and second hand shops

Some charity organizations focus on domestic resales of wearable items, letting the revenues end up in charity funds, while others direct more of their collected goods to third world countries in need or to refugees in Europe and elsewhere. In some cases there is a flow also between these organizations to fulfil different sales opportunities.

To give an account of the corresponding web of charity organizations in all parts of the world is not an easy task, but also not very relevant for this report. It suffices to say that there is a vast score of such organizations throughout the wealthier parts of the world. Some of them work predominantly on a non-profit basis with a work force of volunteers, while others are established as companies who may "do well by doing good".

In Sweden the most well-known charity organizations are Emmaus, Myrorna, Lindra/Human Bridge, Stadsmissionen, Röda korset, Erikshjälpen, and Återbruket, but there are also many more local enterprises.

These actors are focusing on reuse (see stage 6 in Figure 4) and the tagging option may be attractive also to them. By adding new information onto the tag (either about the former owner or just by the fact that this garment is a reused product with very low carbon footprint) could be part of a story-telling about the garment and increase the value of the garment. Furthermore, the in-store benefits and opportunities of retailers can be translated also the group of charity organizations and second hand shops.

The interviews pointed out possible benefits for this stakeholder group, including keeping records of transports and stock, as well as underpinning the value of special garments in the second hand trade. Product warranties may be additional drivers, and so would information about the previous use phase.

4.1.7 Textile recycling companies

In material recycling garments are no longer identified as singular products but as material resources. Tag information on material contents is thus central. During the recycling stage "7. End-of-use", enters "1. Materials", in Figure 4), the wheel becomes a full circle. However, the tag might not be suitable for the same recycling as the textile based materials, and can thus not be reintroduced in the same cycle again. It might instead be subjected to its own material recycling, and re-enter the textile cycle at stage 1 or 2. Possible benefits of tags in recycling are discussed more in detail in 4.1.2.

From the interviews it appeared that possible incentives for a system of tagged textiles: Their roles are a combination of the categories Retail stores and Collection entrepreneurs, and their potential benefits comprise the ones mentioned above.

4.1.8 Cities, municipalities, public procurers

Cities and municipalities are stakeholders too, in the sense that they, to varying degrees, strive to communicate that they actively support a systemic change towards a more sustainable society. Municipalities and health care authorities play an important role also as customers. In public procurement processes for *e.g.* hospitals and other public services they may have a large influence on quality and other specifications of textile goods. There is a number of ways in which local authorities can facilitate efficiency in textile collection operations, for example by providing a suitable infrastructure for transports, allowing collection containers on public land, or through waste fee schemes. This is also related to the legal considerations described in 4.2.3.

From the interviews possible incentives for a system of tagged textiles: For the society as a whole there is an indirect incentive, in the sense that anything that helps to achieve a better circularity in the textile sector is an element in the change of the whole society towards circularity. Municipalities, who at present have a de facto monopoly on collection and handling of every kind of waste, have the possibility to utilize the intrinsic values in the stream of used textiles. Tagging can therefore be important if it can contribute to a more efficient sorting.

4.1.9 Consumers

With "Consumers" we refer to the entire population, essentially, and this is a very heterogeneous group with different economical potentials, preferences, habits, prejudices, and interests. It is thus difficult to exactly predict consumers' reactions to novelties in their everyday life, at least on a collective scale, but broken down into sub-groups, their attitudes and expected behavior can be gauged semi-quantitatively [80-82]. Dividers between sub-groups can be found pertaining to a number of parameters, including socio-economic circumstances, age, education, political preferences, and an interest in questions around sustainability.

Ultimately, one of the most important driving forces for the whole operation of textile collection and recycling is the consumers' acceptance of used garments and, respectively, new items made from used and recycled fibers/fabrics or regenerated fibers. Their purchases generate the value that gives returns back through the value chain.

The fraction of collected goods that are immediately sorted out and judged as the "wearable" fraction, has two distinct user categories. The first is the domestic market consumer who is prepared to choose high quality second-hand as a fully acceptable alternative to newly produced garments for their shopping, even more fun and giving opportunities to dress uniquely while it is also more affordable[83]. This consumer behavior is gradually becoming embraced by a growing part of the population, as the awareness of finite global resources is getting more widespread, bearing in mind the existing gap between attitudes and behavior[80]. It is undeniably much more socially accepted than a few decades ago to replenish the wardrobe with second-hand clothing, even if this is not corroborated by any studies that we are aware of. A strongly contributing factor is also trends in fashion, where the "second-hand" concept is replaced by "vintage". A growing awareness about the importance of recycling of all sorts of materials should be helpful also in the respect that a larger proportion of all used clothes and other textiles are carried by consumers to collection points, rather than being put in their garbage bins. An efficient tagging system has the potential to be helpful for the consumers at many stages: For making informed choices at the time of purchase, for ascertaining proper maintenance, and as a help in selecting end-of-use options.

Clothing items made from used fabrics is an example of up-cycling, and although it exists as an option in the take-back undertakings of some manufacturers it is not common. It may be somewhat more often practiced by artisan fashion makers. A recent example of a brand which is devoted to upcycling is the initiative Remake by Stadsmissionen, present in a handful of shops[84]. The attitudes towards such upcycled garments are influenced by the same mechanisms as the ones affecting high-end second-hand clothes (see above). Other items made from used fabrics and used fibers liberated by shredding/carding includes cushions, upholstery, mattresses, etc., where their presence is less obvious and any possible negative attitudes are less likely.

The growing interest in reuse is manifested in too many ways at present for all to be referred to, but a striking example of this is a shopping mall[85], recently established outside the city of Eskilstuna, Sweden, which is completely dedicated to second hand shopping. It contains 14 shops with a range of products including building materials, furniture, home electronics and clothes.

The second category of users of wearable clothes is the recipients of clothes which are exported, which can either be done for commercial reasons, to be sold on markets with higher needs, or to be distributed to people in need in poorer economies as part of charity programs. This category gives sometimes very little revenue back to the value chain, depending on the market prices for these garments and, presumably, depending on the number of actors involved in the collecting/sorting/exporting chain and their relationships. Even so, consumers in low-income economies can exert some influence on the sorting if their preferences are fed back and allowed to adjust the boundaries between what is sellable and what is best suited for material recycling.

Aspects of personal integrity are particularly important in the consumers' perspective, and this is briefly discussed further in 4.2.2 Ethical considerations. Provided that the information about garment ownership can be logged and stored in a way that fulfils all integrity criteria, tags may be helpful for tracing back lost goods.

From the interviews, possible incentives for a system of tagged textiles were identified as: Access to an abundance of background information about new garments, second-hand garments and other textiles. This information can complement what is written on hang-tags or partly replace them. Not only can basic information about materials and their origin be conveyed, including instructions for care, but also details about the designer/re-designer, the (re-)manufacturing process, post-consumption options, environmental aspects, corporate social responsibility, possibly even previous history of second hand garments. The consumer is thereby helped to make more informed choices.

4.2 Considerations of clothing tags

4.2.1 Technical considerations

A particular concern in the discussions around electronic tags has been raised by some about the introduction of alien objects into textile products, even if they are very small, from the viewpoint of complicating the recycling. The possible disturbance of chemical recycling processes has already been discussed above, and it is not seen as a big problem in a dissolution step to remove tags effectively. And even if they do contain small amount of troublesome elements, the recycling industry is confident that we have sufficiently capable systems to handle them[86]. In mechanical recycling these tags may, however, be more difficult to remove, but we have found no studies addressing this.

A related question is whether manufacturers and retail outlets become *de facto* distributers of electronics. Which implications for producer responsibilities would that have? The legislation given by the RoHS Directive from the European Commission necessitates for a producer to ensure compliance with the rules for hazardous substances in electronics and includes requirements on CE marking of these[87]. The Directive WEEE further sets rules for the disposal of such equipment when it is taken out of use[88]. By referring to a document of FAQ's on the RoHS, contacts at the Swedish Chemicals Inspectorate have confirmed that an RFID tag in a piece of clothing is formally subject to this legislation, but whether special exceptions can or will be made for a product where the electronic component is such a minute part is too early to say. Of course, this is a question for all kinds of uses of RFID technology and not particular for textiles.

Furthermore, the robustness and operability of a tag must be sufficient for the environments of textiles in general. That includes conditions of both washing and the influence of non-repellent and water-repellent dye stuff and finishing. It has been shown by Hvala et al. that water might have a negative impact on the reading rate of UHF RFID tags, since it absorbs the radio frequency waves[89]. The wetting and its influence could also differ dependent on fiber type, and its ability to take up water, however, the readability of tags seem to stand several washing cycles according to Virkki et al[90]. Positioning of several tags after another, between layers of fabric, could cause shadowing and reductions of reading rates, which might also be of relevance for the operability[89].

A general view of most discussion partners have been that both mechanical and chemical recycling has important roles to play in a sustainable society with best possible circularity of textiles. A consequence of this may be seen as an additional difficulty, and it stems from the realization that one loop of mechanical recycling may come before a subsequent loop of chemical recycling. How do we then keep track of the materials through such a complex journey? At the moment this question can only be noted but not adequately answered.

4.2.2 Ethical considerations

The integrity aspects of clearly visible QR codes, which in principle also apply to RFID tags, should be seriously considered. As already mentioned in 1.2.3, some clothing manufacturers have already taken this concept to an extreme by offering personal codes printed on garments, but such a purchase is completely voluntary and does not infringe anybody's integrity more than he or she is willing to.

Problems arise only when a garment is equipped with a code that can be read without the consent of its owner, and only if there is anything personal associated with the information.

RFID tags, at least NFC, can in principle be read already now by ubiquitous smartphone apps. Many scenarios can be drawn up where stalking passers-by could, conceivably, find out more about your wardrobe than you were prepared to tell them, even if the risks of that are minimized by very short reading distances. However, a relieving insight is that the information on an electronic tag is not readable directly. It must be relayed from a data source, which can control which information is sent to whom. The database can even identify the individual device asking for information, and unauthorized devices can be barred from reaching any personal information.

4.2.3 Legal considerations

The starting point for our study was to review a solid system for automated sorting of discarded textiles, where tags easily can bring the information needed and to facilitate fast and reliable detection of textiles. It is obvious that a tagging system must be widely adopted and used by a large majority of manufacturers and other involved in the value chain to become meaningful. This, in turn, requires agreements on technical solutions as well as the contents and format of the data to be included. Standardization efforts are probably necessary, and in order to introduce and propagate such a system it may be to some extent necessary to go via regulations and legislation within a system for extended producer responsibility (EPR)[69, 91]. In addition, several other challenges in introducing take-back systems have been discussed, for example logistics and technical barriers [94, 95]

Regardless of technical platform (ie electronic tags or printed 2-dimensional codes on labels) the efficiency of a system with information-carriers will be highly dependent on a rigorous control of the data entered. Less responsible producers constitute today a real problem, although it is difficult to estimate to which extent erroneous or false labels are attached to clothes. The data entered in the tags must be quality assured, and the only way to prevent forgery and neglect is presumably to establish a strong pressure from wholesale procurers and others who are the manufacturers' customers, not accepting erroneous tags. A quality control system must therefore also be set up. In comparison, fiber identification by e.g. NIR spectroscopy is indifferent to the information on any sort of label but can only provide information about the material and not about other types of information.

A potential threat to a swift development of a fully coherent, encompassing and purposeful system for collection of used textiles is the legislative situation. The Swedish Environment Protection Agency (Naturvårdsverket) delivered an official report in September 2016 which recommends that used textiles are unambiguously to be categorized as waste[92]. Municipalities in Sweden have the ultimate responsibility for collection of household waste and have, in a sense, a monopoly in this. Consequently, the emerging collection schemes in retail stores (where e.g. H&M alone have collected more than 1,000 tons since the start in 2013) have in principle been illegal right from the beginning, if collected items are seen as household waste and not a resource. This may also be a considerable problem for the charity organizations, for which the collection of used clothes is the backbone of their operations since a very long time.

The Swedish Trade Association TEKO has commented on the conclusions regarding waste in the aforementioned report[92], saying that it is important to maintain the harmonization of waste legislation and its interpretations across Europe and that it would be unfortunate to make national exceptions. An introduction of a producer responsibility, as has also been suggested, would create a burden for the domestic manufacturing industry and impede its competitiveness, while the same sustainability benefits can be achieved by regulations demanding a high degree of sorting.

The Swedish EPA report stirred considerable debate, and it is unanimously agreed that there exists a gap between the legislation and the reality which must be closed. The charity organizations are well established and widely recognized by the population, and it has been argued that it would be very counterproductive to hem an initiative taken by the industry itself, when all efforts essentially are working towards the same goals of a more sustainable society. Instead of labelling used textiles as waste, it would be better for the whole society if we could agree to see it as a resource. The Swedish government is currently preparing legislative changes with an extended municipal responsibility of all waste handling as a central element, but there is widespread disagreement and resistance both among politicians and in the private sector. In this context it is noteworthy that textile recycling is specifically indicated by the Ministry of the Environment and Energy as an area that needs to become better developed.

Similar situations prevail in other countries, as demonstrated by a presentation at the Textiles Recycling Conference organized in London in October 2016. Ross Bartley, trade & environment director at the Bureau of International Recycling (BIR), talked about a communication from the European Commission to the European Parliament, which implies that even if mixed clothing is sorted after collection it would still be classified as waste. The existing dichotomy in viewing used textiles as either waste or a resource is thus a common European problem, even if the member states until now have chosen partly different interpretations of the legislation.

4.2.4 Cost considerations

An important consideration regarding implementation of tags is the cost related to the implementation. It might be a concern that the return of investment of for example RFID tags could be a problem if not utilized widely and at large scale[70]. The price for a RFID tag was according to Nayak et al. in 2010, 30-40 cents at lower volumes (compare to a barcode that costs 4 cents) but could be reduced to around 7 cents if you have a volume of 10 million units or more. However, Humpston et al. report a somewhat smaller cost, 3-4 cents, for RFID chips[43].

Furthermore it might not only be the actual tag and technical parts that need to be covered by the implementer, but also quality assurance systems. Despite this, it is emphasized that both RFID tags and 2D bar codes are economically favorable compared with manual sorting and manual sorting supported by FTIR in a case of full adoption of this technology[93]. Since a mixed end-of-life scenario is likely (see 4.1.2), economic evaluations of holistic systems including all relevant uses in the value chain must be thoroughly performed.

5 Conclusions

Based on this study it can be concluded that:

- Current development of the automated sorting technologies by NIR detection is ongoing, but the accuracy needs to be improved
- The development of information carrying tags is fast and include potential digitalization content to the whole value circle of textiles

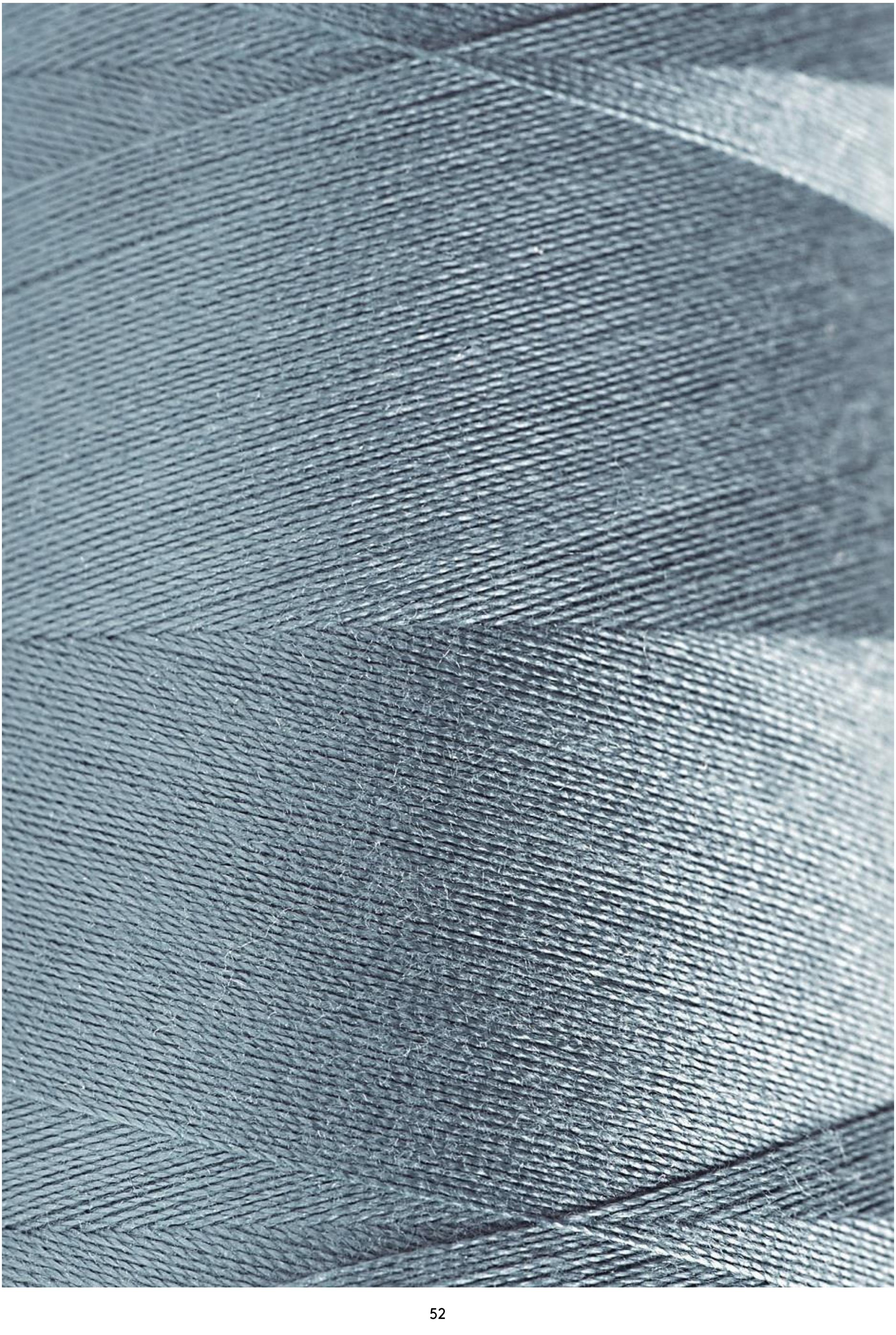
If, or when, a system of information carriers would be established in the trade it would be a strong contender to any technique for identification of textiles in the sorting. If every future garment produced would carry a universally accepted tag, not only the end-of-life sorting line could automatically get the exact fiber composition, but these tags could also facilitate during the user phase of a garment and give transparency throughout the whole life-cycle. . The reason for bringing in a tagging potential in textiles should be motivated by all relevant uses and not only to facilitate sorting of discarded textiles, to be valuable and thus accepted through the whole value cycle of textiles.

Several prerequisites have been identified together with stakeholders along the value chain of textiles, for an introduction of a tagging system:

- The system must be adopted by all parts of the value circle. This, in turn, makes it necessary to shape the system in such a way that all actors can utilize their particular potential benefits.
- The system must be adopted on a large geographical scale, in principle globally.
- Standardization is necessary, most likely together with regulatory measures and legislation.
- The personal integrity of consumers must be seriously taken into account when choosing the way forward.

An additional benefit with a tagging system is that it can be helpful in ascertaining authenticity. In this context RFID/NFC transponders are more difficult to falsify and copy than QR codes. Tags can also be helpful in improving traceability in the supply chain and in bringing better information to manufacturers, importers and retail from upstream, provided that a quality assurance can be applied to the chain of custody. RFID/NFC gives other opportunities than QR codes for a stratification of the information, so that some information is restricted to only those who are interested in it or need it. "Writability", *i.e.* the possibility to upload additional data from the use phase, is a trait that is valued very differently by different actors. Some companies, *e.g.* among producers, see big opportunities while others are disinterested.

For the sorting industry of discarded textiles, information from tags can probably not fully replace the incumbent method of manual sorting. Fiber recognition tools through spectroscopic identification are maturing and will likely be introduced as element in sorting on a larger scale within a near future. Neither of these aids for automation is sufficient for all purposes, and the most probable scenario is a combination of sorting methods in a cascade.



6 Companies and organizations engaged in structured interviews

(All interviews were undertaken in the period August-December 2016).

Berendsen (laundry, respondent Håkan Olsson)

Boobdesign (garment manufacturer, respondent Jenny Kaleinik)

Filippa K (garment manufacturer, respondent Elin Larsson)

Electrolux (producer of washing machines, respondents Lovisa Sunnerholm, Carl Jonsson)

FOV Fabrics (fabric producer, respondent Fredrik Johansson)

H&M (retail respondent Cecilia Brännsten)

Hemtex (retail of home textiles, respondent Petra Pettersson)

Houdini sportswear (garment manufacturer, respondents Mia Grankvist, Malin Wetterborg, Eva Karlsson, Jesper Danielsson)

KappAhl (retail, respondent Fredrika Klarén)

KemI (Swedish Chemicals Inspectorate, respondents Anne-Marie Johansson, Emma Westerholm, Helen Klint)

Lindex (retail, respondents Anna-Karin Dahlberg, Agneta Säll)

Myrorna (textile collector, respondent Emma Enebog)

Nudie jeans (garment manufacturer, respondent Eliina Brinkberg)

Ragn-Sells (recycling company, respondent Lars Tolgén)

Remake (second-hand manufacturer/retail, respondent Jennie Johansson)

Re:Newcell/Girindus (recycling, respondent Henrik Norlin)

SOEX/I:Collect (sorting, respondents Chetan Gupta, Pailak Mzikian)

Sveriges Konsumenter (consumers' organization, respondents Sandra Douglasdotter, Anna-Lisa Persson)

Swedish stockings (garment manufacturer, respondent Nadja Forsberg)

TvNo (laundry, respondent Henrik Möller)

University of the Arts, London (designers, main respondent Kate Goldsworthy)

Wargön Innovation (recycling "facilitators", respondent Maria Ström)

Åhléns (retail, respondent Mona Lindskog)

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Appendix 1: Document with questions as basis for interviews

Automatic sorting of used textiles – why and how?

Automatic sorting of textiles in a recirculation process primarily aims at making a thorough identification of materials (fibre types) for recirculation and production of new fibres. In addition, an efficient automated sorting can contribute to the fulfillment of goals concerning increased sustainability, decreased consumption of resources, and a decreased use of health-impairing or environmentally harmful chemical additives. An efficient sorting process also has commercial consequences, since it may help to improve the profitability of the recirculation, create a higher value in the material resource, and liberate opportunities in new entrepreneurial niches.

Automated sorting systems are currently limited in their capacity and precision, even if a rapid development is taking place (e.g. NIR technology). A future marking technology of garments and other textile products, however, offers other possibilities for bringing information from the production through various stages of the products' lives. Several technical solutions are possible, some of which are already in very widespread use in other contexts. Not all of them are specifically adapted to the purpose of giving detailed descriptions of the materials.

Within three parallel projects (*Trash-2-Cash*, http://trash2cashproject.eu/, the Recycling theme in *Mistra Future Fashion*, http://mistrafuturefashion.com/, and the project *Automatic sorting* for TEKO) we are trying to map stakeholder needs, opportunities, and limitations given by different technologies, with the aim to contribute to a further development of viable alternatives.

We now solicit ideas, views, and attitudes around "tagging" as a support for recycling and for other functions where an embodied information carrier can be useful. What is possible, what is desirable, what is best? Our primary focus is material recycling, while we acknowledge that reuse always will be an integral part of the picture and remain a very important driver for the sorting endeavours.

1. Which category(-ies) of stakeholder do you represent?

- ☐ Weaving/spinning/knitting/fabric production/
- ☐ Design
- ☐ Garment manufacturing (industrial scale, long series)
- ☐ Specialized garment manufacturing (bespoke/short series)
- ☐ Manufacturing of other textile products
- ☐ Textile importer
- ☐ Retail
- ☐ Textile collection
- ☐ Sorting of collected used textiles
- ☐ Material recycling
- ☐ Public procurer
- ☐ Consumer
- ☐ Laundry
- ☐ Washing machine manufacturer
- ☐ Other:

General comment:

2. Let us think about goods that are furnished with a coded information carrier. Which information would be desirable to convey with the code?

(firstly for your own sake, secondly for the whole of the textile trade)

- ☐ Producer
- ☐ Materials: fibre composition
- ☐ Materials: dyes, prints, water proofing agents and other chemical additives
- ☐ Production year
- ☐ Model
- ☐ Size
- ☐ Colour
- ☐ Washing instructions
- ☐ Environmental footprint
- ☐ Social responsibility (e.g. no child labour)
- ☐ Comprehensive sustainability measure (e.g. Higg index)
- ☐ Identification number of the production batch
- ☐ ID number, unique for every individual item
- ☐ Other:

General comment:

3. For whom can the information embedded in e.g. a garment be useful?

- ☐ Weaving/spinning/knitting/fabric production/
- ☐ Design
- ☐ Garment manufacturing (industrial scale, long series)
- ☐ Specialized garment manufacturing (bespoke/short series)
- ☐ Manufacturing of other textile products
- ☐ Textile importer
- ☐ Retail
- ☐ Textile collection
- ☐ Sorting of collected used textiles
- ☐ Material recycling
- ☐ Public procurer
- ☐ Consumer
- ☐ Laundry
- ☐ Washing machine manufacturer
- ☐ Other:

General comment:

4. Some points of view regarding the sorting of used textiles for reuse or recycling?

a) Technical solutions: Any points of view?
b) Mechanical vs. chemical recycling, which is of most interest?
c) Which materials are most important to recycle?

d) Which level of precision is necessary in the sorting for it to be interesting (in other words, how many percent errors are acceptable)?

5. A tag can be designed only for reading.

An electronic tag can also be made writable, which means that it can collect various sorts of information. Possible data collected during the use phase can include the number of days used, the number of laundry cycles, the number of hours exposed to intense sunlight. Is such data interesting, and more specifically what?

6. What could be the purpose of such collected information: performance feedback to the producer/designer, for the consumer, for retailers in cases of complaints, or something else?

7. Which type of marking is most interesting?

- ☐ A bar code or QR code, sewn-on patch
- ☐ A bar code or QR code, weaved or knitted into the fabric
- ☐ A transponder, RFID or NFC, read-only
- ☐ A transponder, RFID or NFC, read-and-writable
- ☐ Other solution

General comment:

8. If the reading of a tag requires special equipment this will limit who it is that can read the information. Is it important that anybody can read it through e.g. a mobile phone app?

9. For integrity reasons it may be desirable to limit the reading distance. If so, which distance? (1 cm, 10 cm, 1 m, 10 m…?)

10. The marking or tag can be more or less difficult to remove in a recycling process. Alternatively it can stay, if it does not disturb the process. Points of view?

11. Some shops and producers now collect used garments for reuse/recycling. Which mode has the bigger benefits for society in general?

That a shop or producer accepts

a) used goods from its own sale or production
b) all textiles

12. If you are a producer or a retail store: Do you collect used items today?

If so, is it according to alternative 1 or 2 above?

13. Other requirements on the marking:

☐ Unaffected by laundry
☐ Tolerates hot ironing
☐ Withstands bleaching agents and other washing powder additives
☐ Temperatures -30 to +100 degrees
☐ Flexible, bendable
☐ Mechanically robust
☐ Simple to read
☐ Concealed
☐ Small, not noticeable
☐ Non-chafing
☐ Staying in place during the whole use phase
☐ Other:
General comment:

Some other questions:

14. Costs for a general marking system may first fall on the manufacturers but may in the end be paid by the consumers. How can costs be distributed over the value chains?

15. Similarly, added values are mainly created in some segments of the value chains. Can it be further distributed?

17. In our report, do you want us to associate your replies with your company, or do you prefer that we only refer to you as belonging to one or more category (-ies)?

Appendix 2: Interview results

Table 4: Categories of respondents and their assessment of the potential benefits, as well as their priorities of information contents.

Respondent	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	
Producer												×					×					×		
Designer										×		×	×	×			×	×		×			×	
Garment manufacturer										×		×	×	×			×	×		×			×	
Specialized garment manufacturer																	×						×	
Manufacturer of other textile products																		×						
Textile importer										×		×						×		×	×			
Retailer										×				×			×	×		×	×			
Textile collecter							×		×	×		×		×				×		×				Respondent category
Sorter of collected used textiles							×		×								(×)							
Material recycler	×						×			×		×					(×)		×					
Public procurer					×											×								
Consumer															×									
Launder					×											×								
Washing machine manufacturer				×		×																		
Other		×	×					×	×		×													
Producer		×	×	×	×	×	×	×	×	×	×	×	×	×			×				×		×	
Designer	×	×	×	×	×	×	×	×	×	×	×						×	×	×			×	×	
Garment manufacturer	×	×	×	×	×	×	×	×	×	×	×	×	×	×			×		×			×	×	
Specialized garment manufacturer	×	×	×	×	×	×	×	×	×	×	×	×					×		×			×	×	
Manufacturer of other textile products	×	×	×	×	×	×	×	×	×	×	×	×					×		×			×	×	
Textile importer	×	×	×	×	×	×	×	×	×	×	×				×	×	×		×		×	×	×	
Retailer	×	×	×	×	×	×	×	×	×	×	×	×		×	×		×		×	×	×	×	×	Interesting for which categories?
Textile collecter		×	×	×	×	×	×	×	×	×	×	×	×		×	×	×				×	×	×	
Sorter of collected used textiles	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	
Material recycler		×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×		×	×	×	×	
Public procurer		×	×	×	×	×	×	×	×	×	×				×		×					×	×	
Consumer	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×		×	×	×	×	×	×	×	
Launder	×	×	×	×	×	×	×	×	×	×	×			×	×	×	×	×	×			×	×	
Washing machine manufacturer		×	×	×	×	×	×	×	×	×	×				×	×	×							
Other		×	×	×	×	×	×	×	×	×	×						×							
Producer				×	×	×				×		×	×	×			×	×		×	×	×	×	
Materials: fiber composition	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×		×	×	×	×	×	×	×	
Materials: dyes, prints, water proofing agents, additives etc.	×	×	×	×	×	×	×	×	×	×	×	×		×	×		×	×	×	×	×	×	×	
Production year			×	×	×	×			×		×		×	×			×	×		×	×	×	×	
Model					×				×	×			×	×		×	×			×	×	×	×	
Size					×				×	×				×		×	×			×	×	×	×	
Color				×	×	×								×			×			×	×	×	×	Which info? (own interests)
Washing instructions				×	×	×			×	×			×	×		×	×	×		×	×	×	×	
Environmental footprint		×	×	×	×	×		×	×	×	×		×	×	×			×		×	×	×	×	
Social responsibility (e.g. no child labour)		×		×	×	×		×	×	×		×	×	×	×			×		×	×	×	×	
Comprehensive sustainability measure (e.g. Higg index)		×		×	×	×		×	×			×	×	×	×			×		×	×	×	×	
Identification number, of the production batch			×		×					×	×	×	×	×						×	×	×	×	
identification number, unique for every individual item					×											×				(×)	(×)	(×)	(×)	
Other			×		×					×	×									×	×			
Producer	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	
Materials: fiber composition	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	
Materials: dyes, prints, water proofing agents, additives etc.	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	
Production year	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	
Model	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	
Size	×	×	×	×	×	×	×	×	×	×	×	×		×	×	×	×	×	×	×	×	×	×	
Color	×	×	×	×	×	×	×	×	×	×	×	×		×	×	×	×	×	×	×	×	×	×	Which info? (for the whole trade)
Washing instructions	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	
Environmental footprint	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	
Social responsibility (e.g. no child labour)	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	
Comprehensive sustainability measure (e.g. Higg index)	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	
Identification number, of the production batch	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	
identification number, unique for every individual item	×			×	×	×	×							(×)	(×)	(×)	×	×	×	(×)	(×)	(×)	(×)	
Other			×	×	×	×	×			×	×	×		×			×			×	×			

* "/" replacing the "x" where the respondent wanted to make a s

Table 5: Categories of respondents and their views on recycling and tagging.

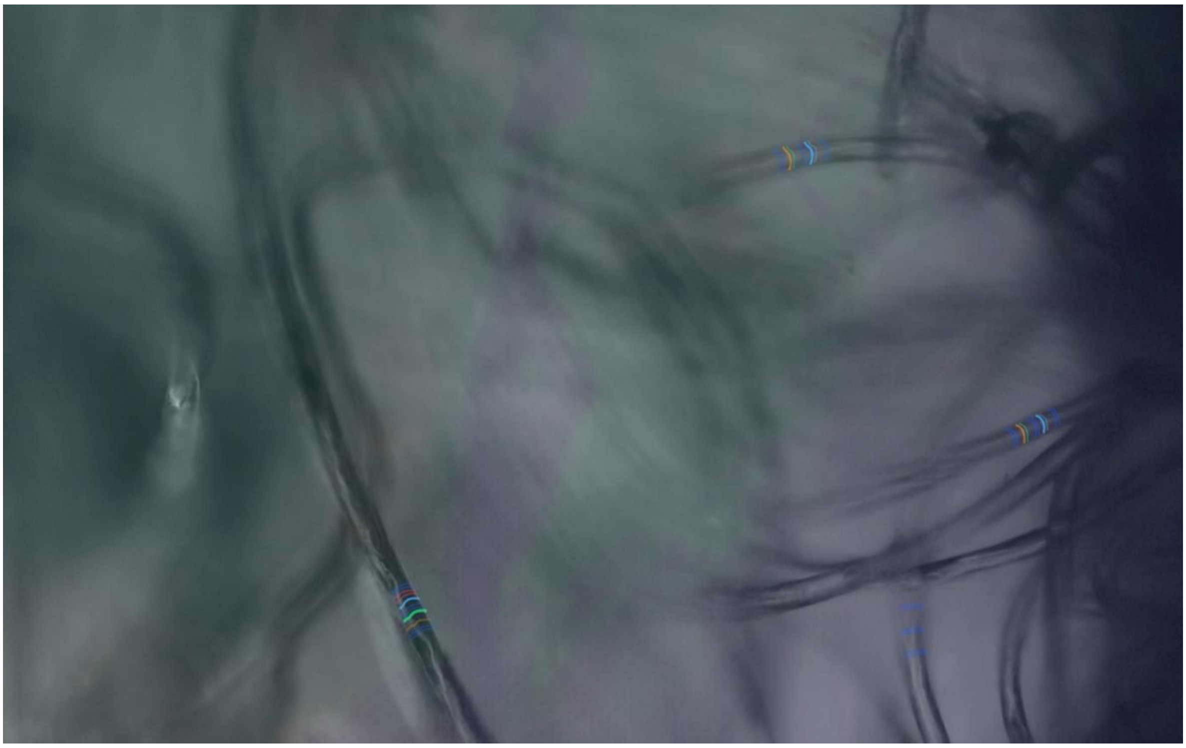
Respondent	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	Question
Producer												×					×					×		Respondent category
Designer										×		×	×	×			×	×		×			×	
Garment manufacturer										×		×	×	×			×	×		×			×	
Specialized garment manufacturer																	×						×	
Manufacturer of other textile produc																		×						
Textile importer										×		×						×		×	×			
Retailer										×				×			×	×		×	×			
Textile collecter							×		×	×		×		×				×		×				
Sorter of collected used textiles							×		×								(×)							
Material recycler	×						×			×		×					(×)		×					
Public procurer					×											×								
Consumer															×									
Launder					×											×								
Washing machine manufacturer				×		×																		
Other		×	×					×	×		×													
Chemical recycling	×	×	×	ı	ı	ı	×	×	×	×	×	×	×	×	ı	ı	×	×	×	×	×	×	ı	Which recycling
Mechanical recycling		×		ı	ı	ı	×	×	×						ı	ı							ı	
Cotton	×	×	ı	ı	ı	ı	×	×	×	×	ı	×	×	×		ı		×	×	×	×	×	×	Which fibres
Polyester	×	×	ı	ı	ı	ı	×	×	×		ı	×			×	ı	×	×	×	×	×	×	×	
Other synthetic		×	ı	ı	ı	ı	×	×	×		ı	×			×	ı								
Time in use	ı	×		×	×	×	×	×	×	×		×	×	×	ı	×	×	ı	ı	ı	ı	ı	ı	Logged information
Number of wash cycles	ı			×	×	×	×		×	×		×	×		ı	×	×	ı	ı	ı	ı	ı	ı	
Accumulated UV exposure	ı		×	×		×	×				×				ı		×	ı	ı	ı	ı	ı	ı	
Other	ı	×		×		×	×	×							ı		×	ı	ı	ı	ı	ı	ı	
For producers	×	×	×		×		×	×	×	×	×	×	×	×		ı	×	ı	×	×	×	ı	ı	For whose benefit
For retail	×	×			×		×	×	×	×		×	×	×		ı	×	ı	×			ı	ı	
For consumers		×			×		×	×	×	×		×	×	×	×	ı	×	ı		×		ı	ı	
Other		×			×		×	×	×	×				×		ı	×	ı				ı	ı	
QR code on patch									ı	×			×		ı					ı				Type of tag
QR code, weaved in									ı						ı					ı				
RFID, NFC read-only	×	×	×	×	×	×	×	×	ı	×	×		×	×	ı		×	×	×	ı	×	×	×	
RFID, NFC read- and writeable				/		(×)			ı			×	(×)		ı	×				ı		(×)		
Collection of own products		×	×	×	ı	×		×	×		×					ı						×	ı	Collection mode
Collection of all products	×	×	×	×	ı	×	×	×	×	×	×	×	×	×	×	ı	×	×	×	×	×		ı	

Appendix 3: DeNAture - a Vision for Transparency of Material Information through an In-Fibre Tracing System of Regenerated Cellulose Materials in a Circular Economy

By Miriam Ribul

DeNAture - a Vision for Transparency of Material Information through an In-Fibre Tracing System of Regenerated Cellulose Materials in a Circular Economy

Miriam Ribul



Top image: DeNAture garment (Ribul, 2014). Photography by Phllip Koll.
Bottom image: DeNAture film still – fibre coding (Ribul, 2014)

Introduction

DeNAture proposes a vision for an in-fibre tracing system to achieve transparency of regenerated materials in a circular economy. With the development of closed loop regenerated cellulose materials for the textiles and fashion industry, the coding system embeds transparent material information into its very fibres.

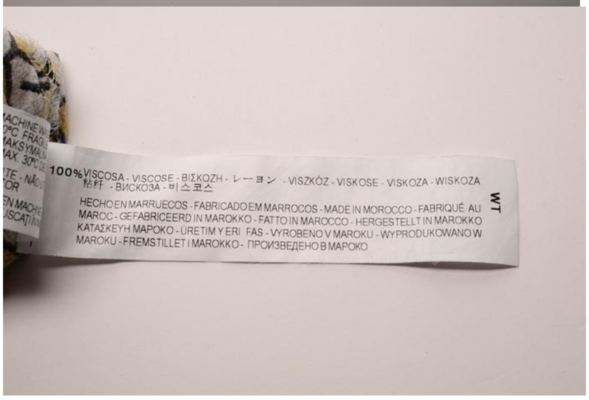
Design researcher Miriam Ribul developed the first material coding system that can be embedded at fibre level of regenerated cellulose to inform users of material origin, type, process and recycling. Conventional garment labels do not offer sufficient information about the manufacturing processes of regenerated cellulose materials. They are often removed or washed out during the use phase of garments, and lost by the time a garment reaches its recycling stage. This information is needed for applying the correct recycling processes, and it requires expensive and time consuming processes to sort materials at the end of life. With the possibilities emerging from ground-breaking scientific research in closed- loop regeneration of cellulose fibres, Miriam identified an opportunity to embed material information within these technical fibres through the chemical regeneration process. This information can be read, and materials traced, at every stage of the material lifecycle.

The proposed design possibility explores the existing barriers for achieving closed loop chemical recycling: One of these includes the missing transparency of materials at hand. Scientific processes are needed to identify materials at the recycling stage, industry requires sorting technologies, while designers and users need material information to make sustainable choices and informed design decisions. Acknowledging the missing transparency of material composition of textiles and fashion products in the use and recycling stage, DeNAture proposes a new communication system for information on regenerated fibres that is accessible to all users across the lifecycle. The design adds a missing layer of information to fibres that is not considered in current garment labelling: information on material origin, type and manufacturing process is connected with information on recycling technology. This will enable information flows of materials for a circular economy.

Embedding transparent information in regenerated fibres

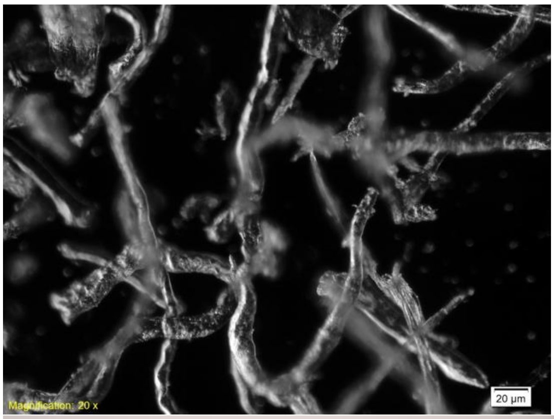
Science develops methods to recycle end of life garments. One of the main barriers to the regeneration of fibres is to know the materials at hand. To measure the exact composition of the many fibre blends that are currently used in fashion, scientific research uses specialist processes such as solid-state NMR for small scale samples. Currently, no commercial recycling system exists for the chemical recycling of fibre blends (Östlund et al, 2015), and at sorting stage there are many barriers to enable circular material flows. Closed loop regeneration for cellulose-based textiles is possible, however the missing information of materials at the end of life hinders the application of the correct recycling process in the vast landscape of global suppliers and manufacturers.

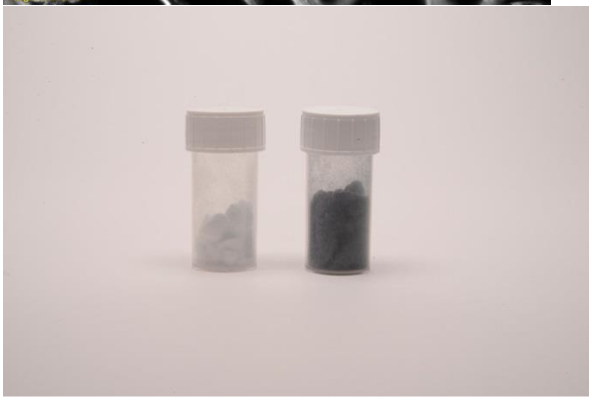
Recycling companies, designers and consumers do not have access to scientific tools for analysing the true value of materials. Current tagging technologies usually address a specific stakeholder group: garment labels inform consumers, sorting explores the recycling stage, and specialised tools are required for scientific research. Conventional garment labels have evolved to include a unified system that quantifies material composition and washing instructions (Elasser, 2005). However, designers and consumers may find that what sometimes is described as 100% polyester, can result as being a blend of materials that is not correctly labelled. Therefore, designers design products with materials from unknown provenance. Also when it comes to recycling, the smallest blend can hugely impact the recycling stage in the regeneration of high-value fibres. DeNAture addresses the need for transparent communication of material information in a shared approach that addresses all stakeholders.



Images: Left, Garment for recycling and right, traditional garment label (Ribul, 2014)

Chemical recycling for the regeneration of fibres requires shredding of fibres into their smallest scale for the dissolution process. Analysis of materials in scientific research relies on microscopes and other specialised tools. At this scale, all information of the material's provenance as provided on textile garment labels is lost. Furthermore, labels only inform of approximate material composition and do not consider information that is required for regeneration in chemical recycling. Issues of tracing materials at their smallest scale also expand outside of the science laboratory, where microplastics have reached our oceans and beaches through the garment laundry system. DeNAture considers material information that travels with its smallest scale.





Images: Left, Microscope studies (Ribul, 2014) and right, shredded cotton and denim fibres for recycling (De la Motte, 2014)

The code is designed so that it can be read with UV microscopes and sensors, and embedded within fibres so that even when shredded, smallest particles can be traced back to the production process. Materials that are altered in the manufacturing process reveal a traceable code that communicates invisible material information for chemical recycling.

Design and science collaboration for regenerated materials in a circular economy

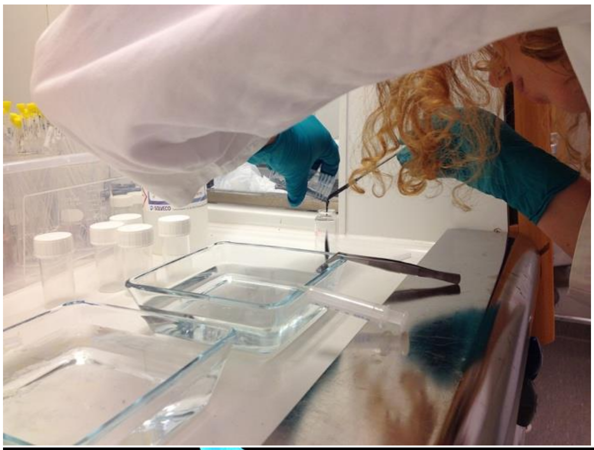
The project is the outcome of a design-science collaboration funded by COST, the European Cooperation in Science and Technology. The collaboration developed from a joint proposal by the material scientist Dr Hanna de la Motte and design researcher Miriam Ribul for a short-term scientific mission (STMS) at SP Technical Research Institute of Sweden and Chalmers University of Technology at the beginning of 2014. Dr Hanna de la Motte is a technical scientist developing innovative methods for chemical recycling of materials including regenerated wood-based cellulose fibres at SP Technical Institute of Sweden. Miriam Ribul is a design researcher investigating the role of design in material resources and production models with completed projects that connect transparency, technologies, and making with people. The context of the research was the scientific development in closed loop chemical recycling of textiles and the development of regenerated cellulose from wood-pulp to create strong new fibres. The aim of the project was to map the design possibilities for regenerated cellulose materials.

Images: Left, dissolving wood pulp and right, dissolved cellulose at SP (Ribul, 2014)

The outcome demonstrates how design thinking can be applied in the context of recycling in the science laboratory to aid systems for circularity of materials through compelling communication strategies of materials' provenance, type, processes, recycling and life-cycle**.** Acknowledging global scarcity of resources, the design researcher developed the vision of an in-fibre code to support the new generation of sustainable materials derived from end of life cellulose textiles. The identification of barriers in textile recycling and the observation of the processes that are needed to identify materials, lead to the development of the DeNAture coding system. In this context, design took on a problem-solving approach for the identification of materials and proposes a change within the existing circular recycling systems for regenerated materials.

The design researcher's creative response to the regenerated cellulose research considered translating processes for regenerated materials from their scientific context into an accessible format for all users. The design researcher's development of the first material code to tag fibres considered a holistic assessment of codes that all stakeholders can connect with: DNA is the code for living organisms, and binary coding makes the programming language of today's communication technology. DeNAture signposts the missing link for a unified material coding system that informs users of the invisible material processes in chemical regeneration processes. The outcome is a meta-design solution 'to advocate design that operates at systemic levels, that invites interdisciplinary collaborations and that seeds or sets up the conditions for emergent processes of change' (Tham and Jones, 2008). It built on tacit knowledge of previous projects concerning transparency of material processes, materials as places for connectivity and production, and design skills for communication and visualisation.

The close design and science collaboration, the opportunity to access materials and technologies, and the insights into the recycling processes through observation and hands-on practice, enabled the exploration of design interventions at the beginning of the material lifecycle in a circular economy. The coding system demonstrates how design and science can collaborate at the raw material stages of the material lifecycle. A material coding system that is embedded during regeneration of cellulose fibres proposes a new interface to engage all users in a faster identification of materials. This will reduce the impacts at the collection and recycling stage. The use of codes enables a systematic and immediate understanding of materials in the regenerated materials lifecycle for the new circular systems.



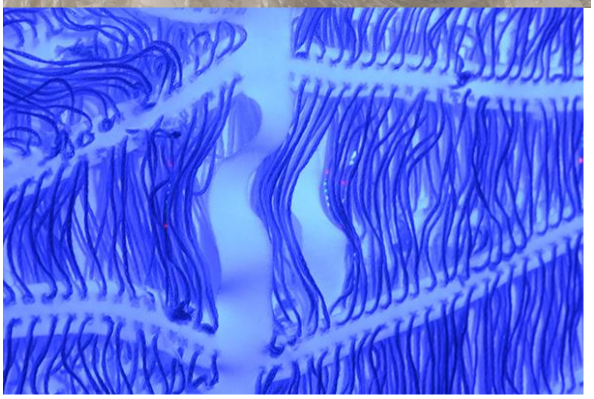
Images: Left, denim dissolution and right, coded regenerated cellulose (Ribul, 2014)

The proposed system responds to the observation, participation and documentation of regenerated cellulose processes in the science laboratory. The design vision signposts an opportunity to create new possibilities for regenerated cellulose materials that is rooted in existing scientific research for the requirements of circular regenerated material systems. While Tonkinwise argues that speculative design often engages through presenting an alternative vision of one reality in a specific context (2014,) in this project, the vision was applied to the current fashion system, and therefore considers a holistic approach that connects all stakeholders (Elander and Ljungkvist, 2016). As closed loop regenerated cellulose production will be up scaled to a commercial demonstration scale by 2020, and commercial full-scale by 2030 (Östlund et al, 2015), DeNAture can impact the future circular systems. The material coding can grow with the regeneration processes as they are up scaled to replace the current linear systems of manufacture.

The future of materials information

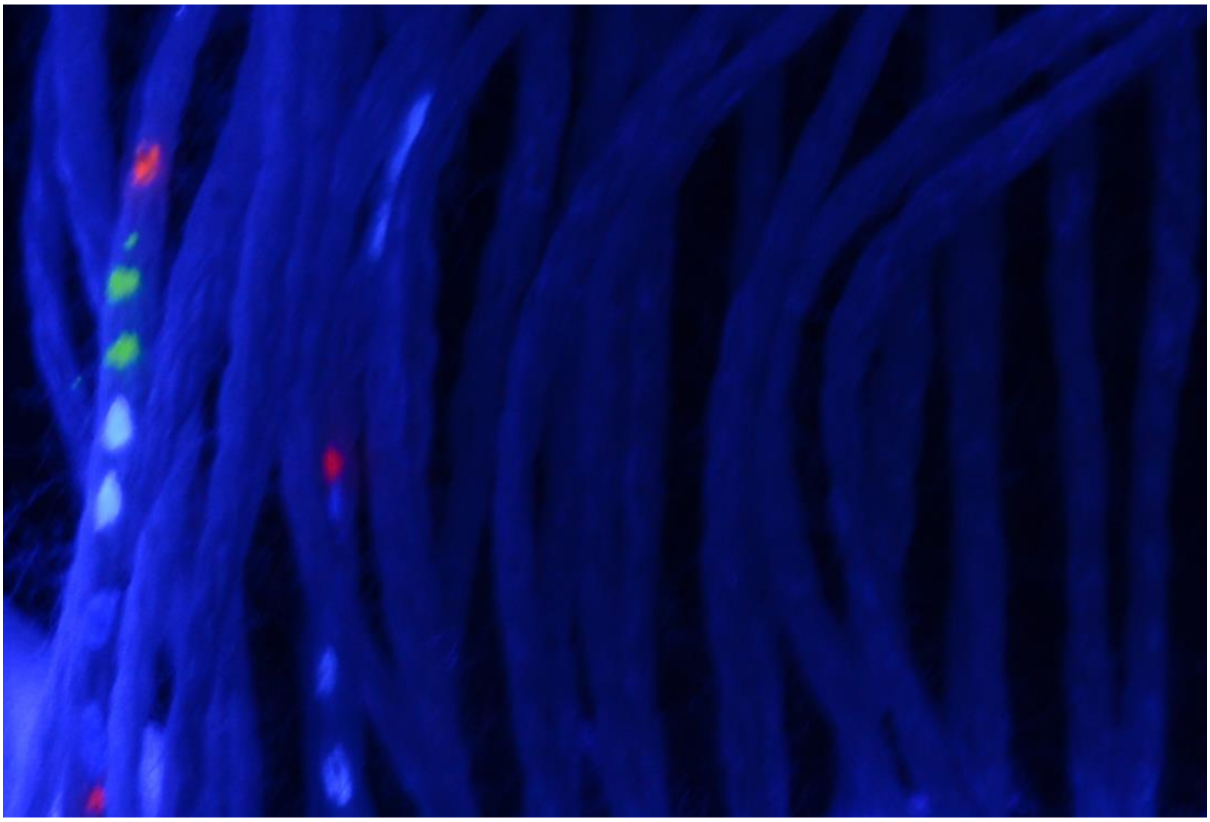
The DeNAture material coding system can be added to any regenerated cellulose material to provide a new layer of information in garments that goes beyond specialised language. The development of a shared information system for materials transcends disciplines and connects all users along the lifecycle.

The large variety of existing eco-labels is difficult to categorise, and often does not reach consumers. Reports that companies are buying into eco-labels also make identification of sustainable materials and practices difficult. The DeNAture codes are designed into visual patterns to overcome language barriers. Through colour and pattern, the aim is to make them engaging and accessible for all. The visual coding system also allows industry with newly developed regeneration technology to participate in the tagging of their regenerated materials, while sensitive data is transformed into a code that enables materials to reach their correct recycling process. The codes support industry to take back their materials at the end of life.



Images: Left, DeNAture garment detail and right, DeNAture garment fibre coding in UV light (Ribul, 2014)

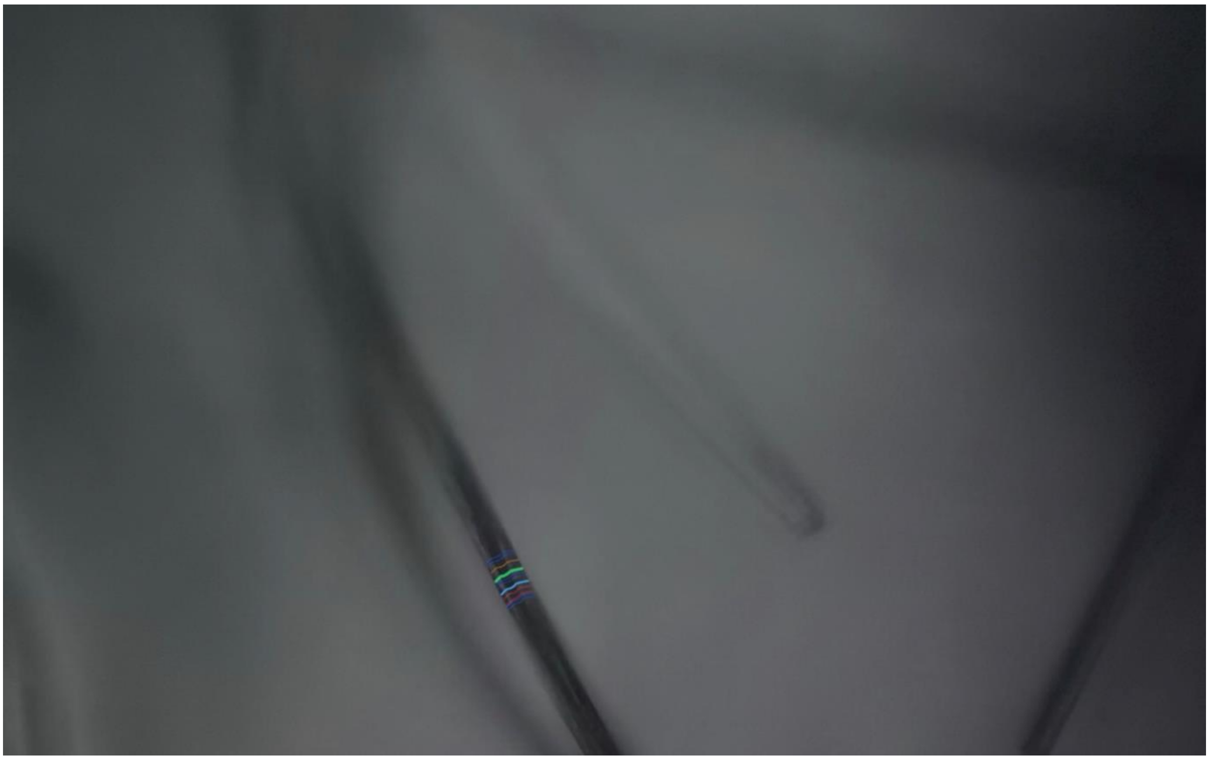
Recent breakthrough technologies in chemical recycling of cotton would use this code to close the material loop. The code proposes a collaboration between industry pioneers developing closed loop regenerated cellulose materials, thus providing a shared coding system for the resources of the textile and fashion industry of the future. Global pioneers in Sweden, Finland, US and the UK are providing new possibilities for recycling cotton and creating strong cellulose fibres. With DeNAture, each material has its own fingerprint to trace it back to its origins and point discarded clothes towards the best recycling process. This will enhance communication within closed loop recycling, collaboration between innovative companies and consumer understanding of materials. The code simplifies key information into patterns, and supports industry in finding a united approach that is not dependent on the vast variety of eco labels and sustainable certificates. Designers, recycling plants, scientific researchers and consumers globally can read the code with inexpensive and immediate tools, and materials are brought back to the correct recycling process.



Images: DeNAture garment fibre coding in UV light (Ribul, 2014)

A further development of the project is a Recyclopaedia, a publication and online platform to collect and present the data of coded materials, and provide a visual archive for the research that is pioneered worldwide. The Recyclopaedia maps the development of closed loop regenerated materials and acts as a digital tool that connects the materials information that is tagged in the fibres to an interactive platform. These codes create the fingerprint for each material, and like tree rings more layers of information can be added over time: the codes can consider other stages of the lifecycle such as dyes, finishes and the use phase.

DeNAture proposes a new type of wearable technology in its development of a new information delivery system through the in-fibre material tagging. Current tagging technologies require add-ons to garments, either through a physical label or through apps and phones required for reading. Similar to conventional labelling systems, they do not explore the origin or chemical process with which the material was made into account. The DeNAture coding system will inform new interactions with textiles and materials: This could be in-store 'code reading' technologies for consumer awareness and engagement; It might lead to the development of new codes as cellulose regeneration technologies evolve, creating a library of codes where users can connect the feeling of a specific material with the process this has been made. Increased transparency would inform sustainable choices and behaviour. Further possibilities developing from this technology are many, as in-fibre tagging provides a new interface for communication within materials that goes beyond verbal communication or digital tools.



Images: DeNAture film still - fibre coding (Ribul, 2014)

Closed loop regenerated cellulose fibres point to a future fashion where virgin resources are no longer required, and all waste will be reinvested into new lifecyles. As the existing scientific achievements for closed loop recycling and regeneration of cellulose are up scaled, fibres may also transform into communication carriers of the future. As a disruptive technology, DeNAture may inform new ways to communicate and inform circular systems through material lifecycles.

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mistra future fashion

Mistra Future Fashion is a research program that focuses on how to turn today's fashion industry and consumer habits toward sustainable fashion and behavior. Guided by the principles of the circular economy model, the program operates cross disciplinary and involves 60+ partners from the fashion ecosystem. Its unique system perspective combines new methods for design, production, use and recycling with relevant aspects such as new business models, policies, consumer science, life-cycle-assessments, system analysis, chemistry, engineering etc.

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