Title: Can automated NIR technology be a way to improve the sorting quality of textile waste?

Subtitle: D4.1

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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 646226
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<td>Work package</td>
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<td>Date of submission</td>
<td><strong>2017-10-25</strong></td>
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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 646226.
2017
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SUMMARY

This report has been produced within the project Trash-2-Cash, funded by the EU Horizon 2020 research program and carried out in response to the call H2020-NMP-2014-two-stage “Material solutions for use in the creative industry sector”. The aim of the Trash-2-Cash project is to explore and pave way for a design-driven methodology in the development of textile-to-textile recycling processes. Within the Trash-2-Cash project, a sub-target has been to analyse the potential for automated sorting of post-consumer textiles. This has resulted in this report focusing on NIR technology to become an important automated online tool for an increased sorting quality for textile recycling. The work has included experiments on sorting, and the outcomes of these studies are described here with the exception of some technical details which are restricted from public view due to binding obligations in the project’s Grant Agreement for the protection of intellectual property rights.

At present, the sorting of post-consumer garment and household textile waste for recycling has limited accuracy. Manual sorting relies to a large extent on label information attached to the garment and such information is often missing in collected goods. Erroneous labels and human errors in the manual sorting add to the difficulties of achieving the requested quality. A central issue is whether the quality requirements of the recycling processes can be met. This is especially critical for textile-to-textile recycling, which generally requires high-quality sorted textile waste fractions. Potential chemical fibre recycling processes, such as the key processes within the Trash-2-Cash project, are likely to need high quality-sorted fractions of post-consumer textile waste to produce new textiles. Provided that a material recognition technology can sort for textile-to-textile applications, this technology would be a promising solution for the textile sorting industry.

This study endeavours to assess the current state and the potential of automated near-infrared (NIR) technology as a material recognition technology for sorting towards higher quality. The NIR technology is still under development for textile sorting and a fully automated system has not yet been demonstrated and validated. Performance tests have been conducted as part of this study during the period from May 2016 to February 2017 on four NIR units. Based on the observations from the testing, the potential capability of the automated NIR technology to improve the sorting is discussed.

Based on the test observations, garments made of pure fibre types/groups such as cotton, polyester, polyamide, acrylic, wool, man-made cellulosic or silk were identified, as well as cotton and polyester blends. Some blends presented larger difficulties and were more frequently unidentified. In particular, blends with a low content of a minor fibre constituent were often unrecognised, mainly blends with elastane. Further observed difficulties for the automated NIR sorting are blend garments were the fabric exposes different fibre types and composition on the inside than on the outside.

The potential of NIR sorting is very large if it is integrated properly, but many unanswered questions remain regarding its ability to meet performance requirements and the acceptable levels of contamination for recyclers. These challenges can not only be met by improvements in the sorting system; there is also a call for designing for circularity, especially considering fibre blends during product development.
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INTRODUCTION

Scope
The goal of the study is to assess if automated material recognition technology could be a way to improve the sorting of post-consumer non-wearable textile waste for recycling. Near-infrared spectroscopy (NIR) is currently the favoured tool, and such systems must be compared with and benchmarked against today’s manual sorting, which has to rely on label information. The current state-of-the-art and the potential of the automated NIR system for post-consumer non-wearable textile waste sorting are addressed in this report. Tests have been performed on NIR systems that are under development for textile waste sorting. Based on the test results, the report provides conclusions on what automated NIR technology currently is able to recognise and the potential of the technology for sorting textile waste by material type.

The report addresses the following research questions:

- What is the state-of-the-art of fully automated NIR systems for sorting non-wearable garments and household textile waste?
- What is the potential of automated NIR system to recognise and sort non-wearable garments and household textile waste? Can a NIR sorting system match the output quality requirements of different existing and potential recyclers needs?
- How does a fully automated NIR sorting process compare to manual sorting?

It should be recognised that a full technical evaluation is not yet possible, since there are still many unanswered questions regarding the performance characteristics of the NIR systems. Larger volumes need to be processed under realistic conditions for a full validation.

Background
Manual sorting for textile recycling has been performed for a very long time, e.g. in Prato in Italy and in Panipat in India. The industry in Prato is known for recycling of wool and cashmere blends, whereas Panipat is known for recycling of cotton, polyester and also many other textile types. Garments are recycled to new yarn by mechanical recycling (shredding or garneting). This recycling process reduces the original fibre length and the produced yarn is therefore of lower quality than yarn from virgin fibres. Only yarns produced from garments of one single fibre type can be used (mostly mixed with virgin fibres) in textile-to-textile products to achieve similar quality as virgin textile products. Yarns produced from garments with different fibre types can be used in textile-to-textile recycling, but in products of lower quality such as backings of carpets or blankets.

The raw material for textile recycling processes can originate from post-production or post-consumer feeds. A clear distinction must be made between these two streams. The post-production textile material is generated during the production processes and often consists of fibres, yarns and textile clippings, whereas the post-consumer materials are garments or household textiles that consumers have discarded. These garments can be unused, used or mutilated. There is a huge technical difference in the recycling of post-production and post-consumer textiles. For recycling of post-
production textiles, the information regarding the blend and composition is easy to collect, since a specification of the received material can be retrieved from the producer. Post-consumer textiles, in contrast, consists of a mixture of all types of fibre blends, and the information on their composition, originally recorded on a label attached to the garment, is often missing or misleading. The sorting of post-consumer garments and household textiles by material type is a huge challenge, and current procedures need improvement to increase the textile waste recycling/upcycling rates. In this report the emphasis lies on post-consumer textile wastes, since there is a huge need to improve the sorting of this stream, especially for textile-to-textile recycling applications. The report is aiming for an assessment of automated material recognition technology and its potential for improving sorting efficiency and quality of the sorted fractions.

Textile sorting today

Post-consumer garments and household textiles are currently collected through various routes such as charity donations, municipality bins, retailer in-store collections, online take-back activities and door-to-door charity bag collections. These collection routes are common to most countries in Europe, but it must be recognised that a wide variety is found from country to country concerning their levels of development and efficiency, partly reflecting differences in commitment from both public bodies and consumers. Collected garments and household textiles are subsequently sent to graders, where they are sorted manually according to different criteria:

- Wearables (undamaged garments that can be worn again) or Non-wearables (recyclables).
- Wearables are then sorted according to quality/design/condition/style, e.g. by using up to 350 different criteria.
- Non-wearables are sorted according to different recycle stream criteria based on the type of material, such as materials made of one fibre type (pure cotton, pure wool etc.), majority fibre type (cotton-rich, wool-rich etc.) or fibre blends. These could also be further sorted according to colour.

Usually, a minority of the collected goods is sold domestically on the second-hand market, while the remainder of the wearables is exported to other countries. Non-wearables constitute a large fraction which may lie in the range of almost half of all the goods.

In the sorting plant the non-wearable textiles are processed and separated into different recycling fractions, for example to wipers, extraction of fibres for use in downcycling applications (e.g. insulation) or for textile-to-textile applications. In manual sorting of the non-wearable garments for textile recycling, the cotton or wool garments are sorted by checking the labels or by hand feel. Due to mislabelling and human error in the feel factor, the quality criteria that are needed for production of textile-to-textile products cannot be achieved today. The quality targets are here quantified as a consistent output of a very high percentage of a particular fibre type, often close or equal to 100%. Uncertainties remain about how good and consistent the quality from manual sorting can be. Moreover, manual sorting is a labour intensive process and the labour costs thus burden the recycled fibres. The manual sorting for textile-to-textile recycling today is therefore often restricted to low wage countries. This emphasises that an economically viable and profitable recycling process needs a highly accurate sorting method to sort for existing textile-to-textile products.
Textile sorting in the future

Chemical recycling of post-consumer textile waste is still in the development stage, but many initiatives are contributing to building and consolidating this industry. The endeavours within the Trash-2-Cash project, focusing on textile-to-textile recycling processes, is one example. The chemical recycling processes (under development within the Trash-2-Cash project) regenerate new fibres from post-production and post-consumer textile of cotton, polyester and cotton/polyester blends. The advantage of chemical recycling over mechanical recycling is that the quality of the regenerated fibres and yarns are expected to be equal to virgin quality. As the chemical textile-to-textile recycling evolves, the need for large volumes of textile sorted fractions with consistent high quality will increase. A highly accurate recognition method is thus needed in order to achieve a consistent high quality of the sorted fractions. Provided that a material recognition technology can sort out fractions for chemical and mechanical fibre regeneration processes, this would be a promising solution for the textile sorting industry. Generally, automated systems are expected to handle large volumes. Combining these aspects (high sorting accuracy and high production rates), automated sorting would then generate higher economic value of the textile-to-textile products. Figure 1 illustrates (in red) where in the sorting process a technological advancement is needed.

Figure 1. The stage of the textile sorting process where an automated process is needed (in red).

Automated sorting technologies

Automated sorting means that a physical process line is built up to handle material streams, where software receives signals from a set of sensors and uses this information to take autonomous decisions on the further fate of each item. This could make it possible to achieve high throughput capacity.
Automated technologies that could be able to sort textile fibre types and composition can be divided into two groups:

- Spectroscopic automated technologies which identify material by its fibre type and colour
- Information-based sorting, such as tagging with code carriers (QR or Radio-frequency identification (RFID)), gives information about fibre type and colour, but also brings necessary information through the whole value chain.

This report will not consider the information-based sorting, and refers to a recent Mistra Future Fashion report by Englund et al\(^1\), which discusses the potential of using this technology for garment sorting. Since spectroscopic technologies are broadly used in many sectors for sorting processes (for instance plastic recycling) they are the first candidates to further investigate for sorting of garments in a near time perspective. Among the spectroscopic technologies, near-infrared (NIR) spectroscopy in one dimensional (1D-NIR) is currently the most developed technology for material recognition and sorting of textiles. Other candidates are Hyperspectral imaging (2D-VIS/NIR/IR) and Raman, but to the author’s knowledge they are not currently in use for textile sorting. A project worth mentioning is the Resyntex H2020 project, coordinated by SOEX\(^2\), which focuses on the generation of secondary raw material from post-consumer textile waste. Among other things, the project is developing an automated sorting technology based on hyperspectral imaging. In the present report, the focus will be on automated NIR spectroscopy sorting.

**Automated near-infrared (NIR) technology**

An understanding of the working principles of NIR technology is necessary when studying its potential and limitations for material recognition. NIR spectroscopy is based on molecular absorptions measured in the near infrared part of the spectrum. The wavelength band employed is approximately 700 nm to 2,500 nm, which falls between the regular mid-IR range of 2,500 and 25,000 nm and the range of visible light, about 390 to 700 nm. The infrared light from a light source is partially and selectively absorbed by the studied surface, and the reflected light creates a characteristic spectrum of each fibre type or blend combination. The spectrum is then compared with a predefined database and thereby it is possible to identify the material composition of the textile material.

A limitation with NIR is that the near-infrared light can only penetrate very thin garments. In most cases the garments are too thick for deep penetration and the collected spectrum covers only the outermost layer of the garment. This means that the side of the garment that is scanned will determine the fibre information. In a fully automated continuous NIR sorting process it is desirable to have a reading distance of 10-20 cm between the NIR scanner and the moving garment. Longer reading distances results in poorer spectra, but also the belt speed has an influence. Ideal spectrum quality is achieved when the garment is in close contact with the NIR scanner for a somewhat longer time.

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\(^2\) Large textile sorting company, www.soexgroup.de
To be effective, fully automated NIR systems require a feed of one single garment at a time. This separation is currently dependent on human intervention, but it is not difficult to envision a future robot aid for this step in the process (automated feeding systems). Instructions from the spectral analysis are sent to the divergence point(s) further down the line. The actual sorting of garments into receiving bin(s) is then performed mechanically or by other means, like jets of pressured air. The NIR scanning of a garment is made in milliseconds, but the overall speed is mainly restricted by the transportation and sorting (blowing) of the garments, one after the other. The number of sorting categories that could be selected per NIR scanner depends also on the overall set-up of the system. There is also the alternative to have a semi-automated system. By semi-automated system we refer to a set-up, where humans are needed in one or more steps in the decision making or handling of the goods.

Outline of the study and limitations

In order to assess the potential of the NIR technology, tests were performed with equipment from four suppliers of NIR systems. These systems were fully automated NIR system, handheld and analytical NIR spectrometer devices. The tests were performed on post-consumer monolayer labelled garments. The term monolayer means a single layer of fabric, as opposed to multilayer which consists of two or more layers. A pre-selection of collected garments was made to obtain a suitable material for the NIR evaluation, with the widest possible range of materials, rather than a representative real scenario of textile waste. Close to half a tonne of textile material was sorted out. Only a limited optimisation was made on the NIR units in the testing period. The test results should therefore be seen as indicative but not final and representative for all practical sorting situations. For a complete understanding of an automated NIR sorting process line for sorting garments it is necessary to test hundreds of tonnes of garments and optimise the models based on the recyclers’ needs. A stakeholder evaluation is needed, but this is beyond the scope of the present report. However, based on the observations from the testing, it is possible to discuss the potential of fully automated NIR technology versus manual sorting for sorting of garments. The comparison will thus be based on the outcome of the NIR testing results and existing knowledge from the textile sorting industry regarding manual sorting.
MATERIALS AND METHODS

Materials

Close to 1.3 tonnes of post-consumer garments and household textiles were collected at SOEX. Labelled garments consisting of monolayer fabrics and maximum three fibre components were sorted from the collected textile waste. Multilayer garments were excluded since NIR is a surface technique and multilayer garments will complicate the evaluation of the recognition results at this early stage. A simplified scheme of the pre-sorting procedure to obtain suitable garments for the NIR testing is illustrated in Figure 2. It should be emphasised that the garments included in the testing are not representing a real non-wearable sorting scenario, since only monolayer garments were included and the sample size was relatively small. Other batches could result in different proportions.

At least one of each pure and blend category was manually picked out as representative garment samples (Figure 3). In total 112 representative samples were used for the testing of the stationary NIR and handheld devices. They were also used as dissemination material for exhibits\(^3\). For the larger scale testing, a bulk material was needed. Approximately half a tonne was picked out from the

\(^3\) Some of the general results and images from the automated sorting tests were presented by University Art of London (UAL) using info-graphical techniques in a series of six cards. In addition, the material samples were prepared and presented, each with their own information card, in three transparent boxes. Together this was the basis of an exhibit, entitled ‘112: textile waste samples’ which was shown at the ‘Making Circles’ textile design exhibition which accompanied the international sustainable textile conference ‘Circular Transitions’ hosted by Mistra Future Fashion and UAL in London, 23-24 November 2016.
included samples for the larger-scale testing. The proportions of each pure and blend category were kept within the half tonne based on the original composition of the included samples.

![Image](71x504 to 141x519)

![Image](71x280 to 228x293)

![Image](76x552 to 295x716)

![Image](300x552 to 519x716)

**Figure 3. Sorting out garments for the test.**

**NIR devices**

Four selected NIR devices, each briefly described below, were included in the testing:

- AUTOSORT from TOMRA SORTING
- FiBERSORT from Valvan
- miRoGun 2.0 from GUT
- UniSPEC2.2USBx from LLA instruments

The testing period was from May 2016 to February 2017. TOMRA SORTING used a fully automated machine for the tests. Valvan used their semi-automatic stand as they build the automated industrial machines for specific customers, and they had no such machine available in their workshop at the time of testing. The devices from GUT and LLA instruments are handheld and stationary NIR devices, respectively. These smaller devices have been included in the test for practical reasons, even if these companies can also provide semi-automated or multiplexed systems used in fully automated lines.

**AUTOSORT (TOMRA SORTING)**

TOMRA SORTING, whose headquarters are based in Norway, is an active company in the development of sensor-based solutions for the food and mining industries and in various types of material recycling. They are involved in the SIPTex project (Swedish Innovation Platform for Textile sorting), where they aim at demonstrating the sorting of non-wearable textiles on a larger scale.

The AUTOSORT unit, a fully automated system (Figure 4) is developed for sorting of a wide range of materials from various waste streams of plastics, paper and organic wastes etc. The items are placed on a moving conveyor belt and transported to NIR and VIS spectrometer sensors. The NIR sensor recognises material whereas the VIS sensor detects colour properties. After recognition with the NIR

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4 SIPTex step 1 (2015-2016), step 2 (2016-2018), funded by Vinnova (Swedish government agency)
scanner, the garment is blown along by pressured air jets to an accept bin if it belongs to the selected category or falls into a reject bin if it does not belong to that category.

**FIBERSORT (Valvan)**

The Belgian company Valvan Baling Systems is developing a fully automated system for garment sorting called the FIBERSORT. The work is partially carried out in a project also bearing the name FIBERSORT, funded by the EU for the period September 2016 –September 2019 and in which a pilot plant for non-wearable textile sorting applications has been produced (Figure 5). During the remainder of the project this pilot plant will be optimised, validated and launched on the global market. In the present study, a FIBERSORT test stand (Figure 5) was used for the testing, since the FIBERSORT line developed in previous projects was not available under the testing period. The test stand includes one NIR sensor and a VIS sensor for colour sorting. The demonstration version has a small moving belt which keeps a certain reading distance between garments and the sensors and it utilizes pressurised air jet technology.

**Figure 5. FIBERSORT test stand to the left and FIBERSORT pilot plant to the right.**

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**mIRoGun 2.0 (GUT)**

mIRoGun 2.0 (Figure 6) is a portable high-speed NIR handheld device, developed by the German company GUT in cooperation with their product development partner IoSys. Besides mobile applications, GUT also provides various stationary desktop or semi-automated systems (sIRoCube) for quality control or sorting of plastic and textile wastes. For the past two years, a customer in Spain have had their semi-automated online system in production for the sorting of textiles. The mIRoGun 2.0 contains models for plastic and textile polymer analysis and can be used to scan pure textile fibres and blends. It can be set up in both ‘triggering’ and a continuous online mode (with no need to press a button every time) for testing a sample. The textile identification model was chosen for the trials.

![Figure 6. mIRoGun 2.0 (GUT).](image)

**UniSPEC2.2USBx (LLA Instruments)**

The uniSPEC2.2USBx is a rapid analytical stationary NIR unit and gives a full NIR spectrum of high spectral resolution (Figure 7). It is developed by LLA instruments in Germany, a company developing analytical spectral imaging process technology, hyperspectral cameras and optical spectrometers for research and development purposes. They are also a partner in the development of sensor-based sorting technology. The uniSPEC2.2USBx is used as an easy-to-transport laboratory scale NIR spectrometer. The multiplexed version of uniSPEC2.2USB (KUSTAx.xMPL) is used as an integrated part in fully automated systems for real-time quality control. It contains plastic, mineral and paper models for various identification applications in plastic, mineral and paper industries.
Procedures

The recognition and sorting procedure was adapted to each NIR system and all software models. It should be recognised that all the devices have different software models and hardware system and the recognition and sorting procedures were adapted to each respective device. The results are not directly comparable. Recognition (identification) by material type was performed with all devices, whereas subsequent sorting was only performed with the TOMRA SORTING and Valvan units. After recognition and sorting into selected categories, the garments were checked by ocular inspection of the labels. Mistakes (error samples) were taken out for chemical laboratory analysis. Fourier Transform Infrared Spectroscopy (FTIR) and chemical dissolution procedures using standard methods were used by RISE and Tekstina to chemically analyse the errors. The analyses determine if the garment was sorted wrongly by NIR or if the garment was sorted correctly by NIR, but categorised wrongly due to erroneous information on the label.

AUTOSORT (TOMRA SORTING)

The testing on the AUTOSORT was performed on the half tonne of garments (Figure 8). Some models already existed and some were prepared for the test. The garments were automated sorted according to the categories: 100 % cotton, 100 % polyester, 100 % acrylic, 100 % wool, ≥ 60 % cotton, ≥ 65 % polyester and residual. Starting with the first category, the garments were manually fed on the conveyor belt. When all garments were recognised and sorted as belonging or not belonging in that category, the following category was chosen and the reject garments were fed manually on the moving belt again. This was repeated for each of the categories. Colour test was also performed on the AUTOSORT to understand the potential of colour sorting.
The testing of the FIBERSORT was performed on the half tonne of garments (Figure 9). Some of the models existed already in the database and some were prepared for the test. The testing was performed in a stationary mode where the garment was in direct contact with the scanning probe and the moving belt function was not used. A screen indicated the suggested sorting categories. After NIR scanning, the garment was placed manually in the suggested bin. Obviously this mode of operation diverges from the industrial version where the initial feeding is manual, but the sorting is made automatically. The selected sorting categories were: 100 % cotton, 100 % polyester, 100 % viscose, 100 % wool, ≥ 80 % wool, 100 % acrylic, ≥ 60 % cotton/polyester blend, ≥ 60 % cotton/other than polyester blend, ≥ 65 % polyester/cotton blend, ≥ 65 % polyester/other than cotton blend and residual. Colour test was also performed to understand the potential of colour sorting.

**FIBERSORT (Valvan)**

The testing of the FIBERSORT was performed on the half tonne of garments (Figure 9). Some of the models existed already in the database and some were prepared for the test. The testing was performed in a stationary mode where the garment was in direct contact with the scanning probe and the moving belt function was not used. A screen indicated the suggested sorting categories. After NIR scanning, the garment was placed manually in the suggested bin. Obviously this mode of operation diverges from the industrial version where the initial feeding is manual, but the sorting is made automatically. The selected sorting categories were: 100 % cotton, 100 % polyester, 100 % viscose, 100 % wool, ≥ 80 % wool, 100 % acrylic, ≥ 60 % cotton/polyester blend, ≥ 60 % cotton/other than polyester blend, ≥ 65 % polyester/cotton blend, ≥ 65 % polyester/other than cotton blend and residual. Colour test was also performed to understand the potential of colour sorting.

**mIRoGun (GUT)**

The testing procedure was performed in two steps and the predefined textile database was used (Figure 10). Based on the pre-defined textile models, the approach for the testing was to use the
mIRoGun as a verification of the label information of each selected category. This means only identification of the fibre types and no sorting was performed. In the first step scanning was performed on the representative 112 samples in stationary mode. The purpose was to identify which fibre types and blends could be recognised. In the second step scanning was performed in online mode on a larger subset of the half-tonne of garments. The selected categories in the second step were cotton, polyester, acrylic and wool. Cotton and elastane blend garments were also scanned in order to evaluate the potential to recognise elastane in a blend.

Figure 10. Testing of mIRoGun (GUT).
**UniSPEC2.2USBx (LLA Instruments)**

The test was conducted in a stationary analytical mode and the samples were in direct contact with the unit during scanning. As a predefined database for different textile fibres and blends was not available, the first step involved scanning of predefined textile fabrics and preparation of algorithms. Thereafter identification of selected pure and blend samples from the 112 representative samples were performed (Figure 11).

![Image](image_url)

*Figure 11. Testing of uniSPEC2.2USBx (LLA instruments).*
RESULTS

Material composition

In the pre-selected post-consumer material used for the NIR evaluation, about 90 different material types were found, where of 14 consisted of pure fibres and 76 consisted of different fibre blends. Interestingly, about 75% of the garments were cotton and cotton blends (mostly with elastane and polyester). This is good news for the Trash-2-Cash technologies which need cotton and cotton polyester blend sources. However, many of the other blends were in different low-volume blend combinations destined for down-cycling processes.

NIR test

Based on the tested NIR equipments, an overall summary of what the NIR technology was able or not able to recognise is presented below.

During the test it was observed that the NIR equipment was able to:

- Recognise garments of pure cotton, polyester, acrylic, wool, polyamide, silk and man-made cellulosic (viscose, modal and lyocell) fibres.
- Recognise cotton/polyester blend.

During the test it was observed that none of the NIR equipment was able to:

- Recognise low content of elastane in cotton and elastane blend.
- Recognise blends in fabrics with different fibre composition on different sides.

Based on some of the NIR equipment test results a limited ability to recognize low content of elastane in other blends (besides cotton blends) or low content of viscose or wool in cotton blends or acrylic blends respectively was also observed. Moreover, it was observed a limited ability to distinguish different wool fibres from each other. Included wool types in the test were merino, cashmere, sheep’s wool, lama, angora, lamb and alpaca. A limitation was also noticed in the ability to discern different man-made cellulosic fibres, i.e. a limited ability to tell apart modal, viscose and lyocell. Some grey and black garments were sorted wrongly and ended up into the residual fraction. This indicates that there could be a limitation in recognition due to the black or grey colour, leading to a possible loss of yield. However, this would be of minor importance since it would not contaminate the pure sorted fractions.

Other observations during the NIR tests were that colour sorting combined with NIR is possible and that a fully automated feeding line is not yet available for garment sorting. Furthermore, an additional outcome of this study was that chemical analysis verified that at least 2% of the garments used for the NIR testing were incorrectly labelled.
DISCUSSION

There are of course even more combinations of fibre blends on the market than the 76 different blends found in the analysed textiles. Although the numbers are not representative for real post-consumer textile waste, since only close to 1.3 tonnes were analysed, the large number of identified blends gives an insight into how complex the input feedstock is for a sorting process to handle and emphasises the technology challenge for material recognition of blends.

Capability of automated NIR technology to improve the quality

The question we want to answer is whether automated NIR technology is a way to improve the sorting quality. This is difficult to assess without having analysed data on quality from a demonstrated automated line. Since an efficient fully automated sorting line using NIR technology has still not been demonstrated by any company yet, a full assessment cannot yet be made. The observed NIR results in the present report should be seen as preliminary observations rather than inherent limitations of the NIR technology. More research is needed to evaluate the capability of NIR to sort for various textile-to-textile products. However, we have tried to look at a scenario for a fully automated NIR system and evaluate which benefits it would provide for two hypothetical recyclers requesting different qualities. Recycler A is requesting 100 % cotton and Recycler B is requesting 100 % polyester garments. The scenario is based on the observations from the NIR recognition in the present study on monolayer garments. It should be pointed out that any process has in practice an acceptable error level and will accept certain contamination. For simplicity in this hypothetical scenario we have chosen that the request is 100% cotton or polyester although we are aware that this is not practically applicable.

Recycler A will get:

- Cotton garments.
- Cotton blend garments (monolayer):
  - Where the other fibre type is in minor component e.g. elastane.
  - With man-made cellulosic (modal, viscose, lyocell) could be present.
  - With polyester or polyamide could be present.
- Garments with multilayer e.g. cotton on the outer layer and other component on the inner layer.

Recycler B will get:

- Polyester garments.
- Polyester blend garments (monolayer):
  - Where the other fibre type is in minor component e.g. elastane could be present.
  - With cotton or polyamide could be present.
- Garments with multilayer e.g. polyester on the outer layer and other component on the inner layer.
Both recyclers will also get:

- Presence of metal, plastic and leather.
- Unknown error due to other reasons, for instance error due to high belt speed rate.

This implies that there will be contamination of the sorted 100 % cotton and 100 % polyester fractions. Seams and plastic details such as pigment prints will certainly stay as impurities in the sorted fractions. The main question will be whether the error generated by the sorting will be smaller than what the recyclers will be able to accept. It is difficult to predict the errors at this early stage of the development, but this is precisely what the FIBERSORT and SIPTex project are aiming to discover. The error frequency as a function of speed is not yet established, but higher speed may cause higher error rates. Moreover, the biggest uncertainties may be during processing of multilayer garments.

**Fully automated NIR sorting process compared to manual sorting**

To the extent it is possible we have assessed the potential of fully automated NIR sorting technology of garments and compared some selected key characteristics. The comparison has been made versus manual sorting of garments and is presented below in Table 1.
Table 1. Comparison of manual and fully automated sorting in terms of key characteristics

<table>
<thead>
<tr>
<th>KEY CHARACTERISTICS</th>
<th>MANUAL SORTING</th>
<th>FULLY AUTOMATED NIR SORTING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material recognition method</td>
<td>Reading labels, hand feel.</td>
<td>NIR spectroscopy.</td>
</tr>
<tr>
<td>Development level</td>
<td>Manual sorting done in textile recycling for more than a century.</td>
<td>Subject to a rapid development. Technology or an efficient working line still not demonstrated by any company.</td>
</tr>
<tr>
<td>Quality of output</td>
<td>Could be high quality, but dependent on the label information. Ability to control impurities by manual removing plastic, metal, leather and other contamination. However, human mistakes and limited ability to detect erroneous labels decrease the quality. Uncertainties remain concerning how good and consistent the quality can be.</td>
<td>The potential of obtaining high quality is at this early stage difficult to assess. Currently seems only suitable for recycling processes with higher tolerance levels to contamination and on larger scales, i.e. works only if further processes could accept the uncertain error due to false recognition (presence of other fibres) or other type of impurities such as plastics, metals and leather.</td>
</tr>
<tr>
<td>Ability to sort by colour</td>
<td>The sensitivity of the human eye is quite enough for most practical current practices. An advantage is the ability to judge whole garments.</td>
<td>It is difficult to assess at this early stage. An advantage could be the ability to distinguish colours that are difficult for the human eye to tell apart.</td>
</tr>
<tr>
<td>Production (capacity)</td>
<td>To manually check labels, make judgement of e.g. colours etc. is time consuming. For larger productions of recyclables not efficient.</td>
<td>Production is higher.</td>
</tr>
<tr>
<td>Costs</td>
<td>Labour intensive, thus labour costs dominate. Sorting of recyclable qualities not economically feasible in high-wage countries.</td>
<td>High investments in complete line installation. Higher installation costs could be compensated if production efficiency is high. A continuous need of maintenance and optimization is also needed. The costs involved are difficult to state at this early stage.</td>
</tr>
<tr>
<td>Job opportunities</td>
<td>Gives plenty of job opportunities, but limits the achievement of economies of scale.</td>
<td>Less staff needed and new and more qualified jobs could be created.</td>
</tr>
<tr>
<td>Challenges</td>
<td>Wrong label information on garments, human errors in the sorting.</td>
<td>Multilayer garments and identification of blends with a low content of a minor fibre constituent.</td>
</tr>
</tbody>
</table>

The essential question is whether fully automated NIR technology could be a better way to improve the sorted quality than manual sorting. The assessment is complicated by the fact that precise numbers have not been established for either manual sorting or fully automated sorting. We can therefore only make an overall judgement based on the quality output aspects mentioned in Table 1. Based on this, the contamination levels are expected to be lower for manual than for fully automated NIR systems.
Possible organisation of future textile sorting lines

At present it is difficult to envisage an optimal future organisation of a textile sorting line. An important question for the future will be: what is the tolerance from recyclers regarding the sorted quality for textile-to-textile recycling applications? The potential of NIR sorting is very large, but a number of unanswered questions remain regarding its ability to meet performance requirements. Recyclers may accept the quality of the output from a fully automated sorting line, and if they do not, it is possible to establish a combination of techniques to improve the quality to an acceptable level. Knowledge about the tolerance levels for impurities would help to steer the development. However, chemical recycling processes are still at the early stages of development for textile waste. A first-hand goal is to get precise tolerance levels of contaminants from chemical recyclers, based on current processes for chemical recycling. In parallel, a further development of dissolution and separation techniques to reach more robust and tolerant processes is highly desirable. Thus, the fulfilment of quality requirements can be met by working from both ends – honing the sorting precision and making the recycling processes more robust and tolerant to foreign materials. Combinations of manual and automatic sorting could be interesting alternatives to increase the quality. This could be accomplished either by a semi-automated sorting system instead of a fully automated system or by humans manually removing particular impurities after fully automated NIR-sorting. The former alternative – a semi-automated NIR system – would generally be restricted to low-cost countries, since manual involvement would be labour intensive in high-cost countries. The latter alternative would imply that more processes are then involved to prepare the raw material, which will increase the production cost and price of the sorted fractions.
CONCLUSIONS

Based on the test observations, following pure fibre types/groups were recognizable with NIR technology: cotton, polyester, polyamide, acrylic, wool, man-made cellulosic and silk. Furthermore cotton polyester blend was identified. However, there were many errors due to false recognitions which contaminated the fractions. In our test results performed on monolayer garments, these errors were partly due to the limited ability of the NIR scanner to detect blends with a low content of a minor fibre constituent (e.g. elastane) and different fibre composition on different sides of the fabric.

At present, fully automated NIR systems for garment and textile sorting are under development but have not yet been sufficiently demonstrated and validated. Fully automated NIR sorting also seems, at present, suitable only for recycling processes with higher tolerance levels for contamination and on larger scales. The potential of NIR sorting is very large, but a number of unanswered questions remain regarding its ability to meet performance requirements. Hence, a simple answer cannot be given to the central question of how NIR technology may improve the sorting quality. A precise figure on the attainable level of manual sorting accuracy and consistency is not possible to establish, but our overall judgement is that the contamination levels are expected to be lower for manual than for fully automated NIR systems. At present it is difficult to outline an optimal organisation of a textile sorting line for textile-to-textile streams. Whether fully automated, semi-automated or fully automated combined with manual sorting are optimal solutions. Quite possibly, NIR technology has a large potential if it is used and integrated properly. An important question for the future will be: what is the tolerance from recyclers and designers regarding the sorted quality for textile-to-textile recycling applications? In other words, the demands of the existing and emerging recycling industry, as well as garment designers and producers, are important drivers in the appropriateness of sorting solutions. Based on the observations from the test, designers need to strive towards designing for circularity, for example by considering the fibre blends during product development.