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Case study report – 10XL

Good practice of circular economy business models

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As part of the TRANSFORM-CE project, several case studies are done to benchmark existing circular economy business models. This document covers the results of the case study conducted at 10XL, based in the Netherlands. A total of 20 case studies will be done, with five cases per country (The Netherlands, Germany, Belgium and the United Kingdom).

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1. Introduction and method

1.1 Goal of case study

TRANSFORM-CE is an international research project which researches amongst others (successful applications of) circular business models, barriers, enablers and needs for circularity, and offers in-depth support for the uptake of recycled feedstock by businesses. A core part of the project is to provide advice to businesses on their way to transition towards a circular economy (CE).
In order to help businesses with developing circular business models (CBM's), it is first important to benchmark existing CBM's of companies. This is done by conducting case study projects with 20 selected businesses throughout North-West Europe. The aim is to provide participating businesses with an in-depth analysis of their current situation and business model, to identify opportunities and provide recommendations for facilitating the transition towards a CBM for these and other companies. The case studies also present an unique opportunity to study barriers, enablers and needs for circularity (and recycling) in more detail.

1.2 Company background

10XL manufactures large format plastic products, by combining additive and subtractive manufacturing into a hybrid system. Their main input material is recycled plastic, whether this comes from industrial waste of the automotive industry, shredded material from their own (returned) products or post-consumer waste. Examples of products that they 3D-print with robot arms range from furniture to sloops and bridges. Products can currently be made up to 6m, with the possibility to print up to 12m in the near future. A short overview of 10 XL is given in table 1.

Table 1: *Overview of company*

Topic	Information
Company name	10XL
Website	www.10-xl.nl
Country	The Netherlands
Size of company (0-10, 10-200, 200-500, 500+ employees)	0-10
Mission/vision	"We want to offer anyone, anywhere and anytime direct access to XL hybrid manufacturing in a full cradle-to-cradle process."
Product category	All kinds of large plastic products, e.g. maritime, furniture, construction, built environment, products for public spaces etc., but not limited to a certain segment.
Production/operational process	3D-printing, milling, tape placements
Used materials	Recycled materials from post-industrial waste, post-consumer waste or products taken back at end-of-life, if needed also virgin or biobased materials. ABS, PP, PLA, PEEK, PA, ASA, HDPE

1.3 Case study process

The case studies are being carried out between September 2020 and December 2021. The case study process is structured in four steps[1], with an iterative approach at the end of each step. The first step (circularity of the business model) aims at creating a general overview of the company, the context and its (circular) business model, to capture how the company creates and delivers value. The second step (circularity in the value chain) involves a circularity assessment of the company and its activities in the value chain. The third step (circularity of operational activities) is focussed on the circularity of the company's operational activities. The last step involves a wrap-up of the results and concludes with the case company's strengths in regards to circularity, an overview of the barriers and enablers for circularity, and opportunities for further enabling circularity. The final result is a case study description, covering the previously established information.

An overview of the case study analysis process is shown in figure 1 on the next page. In order to obtain the results, each of the three steps is divided into four sub steps: 1) desk research and preparation; 2) interview; 3) reporting results; 4) iteration of results. More information about the process and the steps needed for receiving the results can be found in a separate document ('case study methodology') explaining the case study process in more detail. Three interviews are conducted for this case study, with one interview per step and the interviewed persons each having a different function and responsibility within the company. Table 2 gives an overview of the interviewed persons for 10XL.

Table 2: *Overview of interviewed people*

	Interviewed person	Function
Interview 1: Circularity of business model	Gerbert Smits	CEO
Interview 2: Circularity in the value chain	Linda van Hal	CCO
Interview 3: Circularity of operational activities	Joep Grapperhaus	CTO

[1] We make grateful use of insights and methods derived from previous research, in particular the case study method of R2π (2017, 2019), the work of Circulab (2020) and the Ellen MacArthur Foundation (2017, 2019).

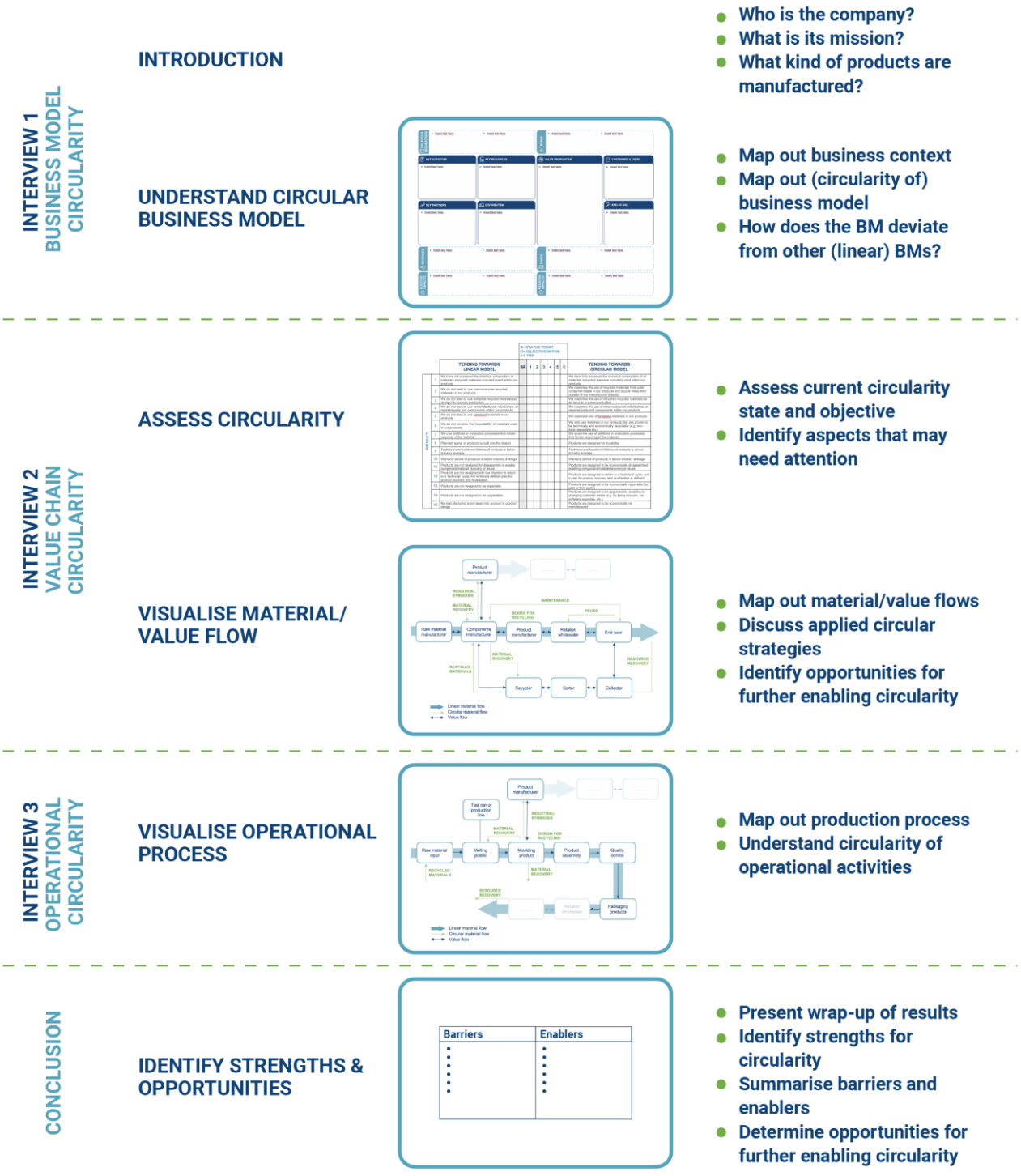

Figure 1: *Overview of case study process*

2. Circularity of business model

The first step aims at creating an overview of the company's business model and the context in which it operates, to capture how the company creates and delivers value (for circularity).

2.1 Circular business model canvas

The circularity of the business model is investigated by using a circular business model canvas (CBMC). This model is created for the purpose of this study and shows how the company creates, delivers and captures value, highlighting circularity aspects of the business. The CBMC of 10XL is visible in figure 2 and a description of each element is given below.

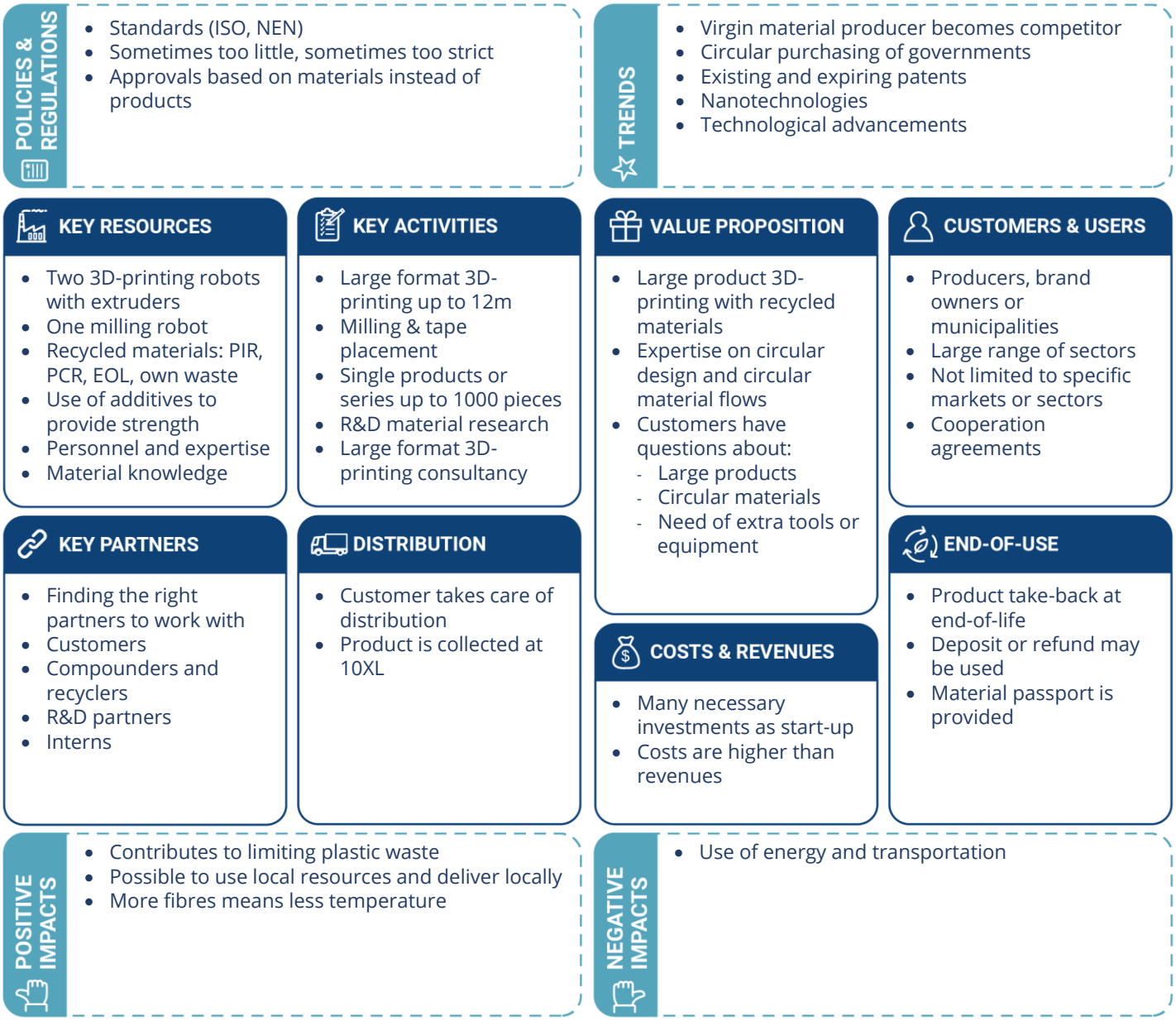

Figure 2: *CBMC of 10XL*

Value proposition

10XL manufactures large format plastic products, by combining additive and subtractive manufacturing into a hybrid system. Their main input material is recycled plastic, whether this comes from industrial waste of the automotive industry, shredded material from their own (returned) products or post-consumer waste. 10XL's customers are often businesses, such as other producers, brand owners or municipalities. They will come with questions about manufacturing large products and the use of circular materials, and are in need of extra tools or equipment.
In addition to their printing facilities, 10XL offers expertise on circular design and circular material flows. This can be in the form of consultancy or as part of the products which the company delivers. This expertise also includes thinking about possibilities of taking up customers' waste streams and finding the right match between a recycled material stream and product.

Customers & users

10XL's customers are often businesses, such as other producers, brand owners or municipalities. They manufacture products for a large range of sectors, which include (but are not limited to): maritime, furniture, infrastructure, construction, built environment, products for public spaces and products for the energy sector. Examples of products that they 3D-print range from sofas and sloops to Cityguards (mini garden around bins) and bridges (see also figure 3). Yet, the company's approach allows all organisations requesting large 3D-printed products made from recycled materials to be its customer. Their customer segment is not limited to specific products and they are willing to explore beyond their current portfolio.
Products are often developed together with customers and knowledge from both parties is combined (e.g. knowledge of bridge building company is combined with 10XL's knowledge of materials and 3D-printing). With most customers a cooperation agreement has been signed, which prevents customers to go to other manufacturers, and 10XL cannot print the same product for other companies. This way, it is not just a product that is delivered, but new products are developed together with the customer.

Figure 3: *Examples of products printed by 10XL (bench, CityGuard and sloop)*

Key activities

10XL manufactures products with hybrid manufacturing, combining additive and subtractive manufacturing into a hybrid system. First, thick layers are 3D-printed (additive manufacturing) and

then a second robot arm is used to smoothen the outside of the printed product and make it more accurately (subtractive manufacturing). Last, tape placements or fibre-reinforcement may be used for strengthening the end product. Hence, manufacturing activities of 10XL consist of large format 3D-printing, milling and tape placements. Depending on the product, one or more of these techniques may be used.
Products can currently be printed up to 6m, with the possibility to print up to 12m in the near future. The required time to print products varies depending on the size of the product. As an example, sloops/boats take about one day to print, whereas Cityguard takes approximately two hours and sofas take about four hours to print. 3D-printing is possible for single products or series up to 1000 pieces. After that, it is not economically profitable anymore and costs for a mould could be compensated for.
Besides manufacturing, 10XL also offers research and consultancy services. They work on R&D projects to improve robot printers and work together with other businesses to research suitable (recycled) materials. They also offer consultancy services for large format 3D-printing. Some businesses may not know which material they want or need, others do know which materials they want, but lack insights of how to manufacture the product.
These activities and services are all part of one process: the first part consists of consultancy and research (choosing the right materials and manufacturing methods), the second step is to design the product and then to manufacture and deliver it.

Key resources
10XL's main resources in terms of machines are its two 3D-printing robots, of which one is a combination of a printing and milling robot. Each of the 3D-printing robots is attached to an extruder. Although these processes still require human supervision (physically or by camera), they would like to be able to print fully automatic in a closed-loop process. This way, various variables can react to each other, without the need of human supervision.
Input materials for 3D-printing may come in the form of granulate or regrind, which will enter the extruder. Their main input material is recycled plastic, but biobased or virgin materials are available on request. Recycled materials may come from industries such as the automotive industry (post-industrial resin, PIR), but may also come from customers that have collected products at end-of-life (EOL), from packaging waste after usage by consumers (post-consumer resin, PCR) or 10XL's own production waste from milling or faulty prints. PCR waste consists of polypropylene (PP) and polyethylene (PE), whilst PIR waste is often made of PP or other materials. 10XL prefers to use only recycled materials, and no 'new' materials from (fossil) fuels, but sometimes they are left no choice to use biobased or virgin materials. If recycled materials are not specifically asked for by customers, 10XL will bring it to their attention and will start a conversation about the possibilities for using recyclate.
The machines also allow for fibre reinforced printing, using additives such as glass fibres, carbon, flax or hennep. For printing products of such a large format (>1m in length) it is important to use additives to strengthen the material and subsequently the product. However, a good viscosity is also necessary to be able to print the product. If material is too thick, the process goes to slow,

which means additional costs. But if material is too viscous, it will not adhere sufficiently and the end product may collapse.

"Recycled materials should be seen as an entirely new material."
- *Gerbert Smits, CEO of 10XL*

When starting a new project, 10XL will look for the right (recycled) material to be used in a product. A strength of 10XL is that they look at recycled materials as an entirely new material, with many possibilities. Their large range of recycled material options to choose from makes it possible to select the right material for the right product, based on material properties and used additives. Because of the need for additives to provide strength, PIR waste (e.g. from the automotive industry) is often used, since additives are already used in this waste stream, so compounding can be avoided.
10XL considers material knowledge to be the most important asset to have. Everyone contributing to material knowledge is regarded to be important for adopting circularity. This goes beyond the used polymer, and also includes, for instance, choice of fibres, their length and how damaged the fibres become (after recycling). Knowing such properties is considered to be more important than the hardware itself. However, most material knowledge lies with virgin producers, who are reluctant to share information for recycling. According to 10XL, the industry is in need of is an independent research institute that solely focusses on recycled materials, not on virgin materials.

"You need to have an insane amount of material knowledge for applying circularity."
- *Gerbert Smits, CEO of 10XL*

Key partners
Customers are regarded to be 10XL's most important stakeholders. Others stakeholders are secondary and include compounders, recyclers (e.g. Stip), R&D partners (preferably independent partners such as PSP, WUR) and interns (from TU Delft). Their business model does not contain any direct relations with consumers, but consists of mutual cooperation with many businesses.

Distribution
Distribution of 10XL's products is arranged by the customer. The 3D-printed product is collected at the production site of 10XL by the customer. 10XL only delivers a product if something goes wrong.

End-of-use
10XL offers customers the possibility to take-back products at end-of-life. A refund may be used as an incentive to ensure product take-back. However, consumers will likely bring the product to a waste station at end-of-life. Hence, it is the responsibility of 10XL's customers to collect products from consumers, otherwise products end up with bulky waste. With Cityguard this process can be more controlled because there is no intermediate involvement of consumers, which makes recollection easier.
Customers may also return products to other companies. For this reason, insights in material properties are provided, for example by providing a 'material passport'. This gives other businesses

the ability to 'know' the material, in order to understand the material that will be dealt with for further (re)processing.
A general collection system for such large products has not been introduced to the market yet. Therefore, solely knowing the material properties does not make much sense if the material stream is not of sufficient volume. Besides, there is also a logistic problem of returning or collecting products. It is not economically viable to drive for the collection of one sofa, nor does this make sense from a sustainability point of view (CO_2-emissions etc.). Hence, until a general method is established, 10XL will act as an intermediate person and offers the possibility to return products to the company.

Costs & revenues
Since 10XL is in its start-up phase, the average costs of resources, equipment, manufacturing and research are higher than the gained revenues.

Policies & regulations
If companies comply with NEN norms, they are usually okay. Regulations or norms that are in place are sometimes regarded to be too little or too strict. Lack of norms can for instance be seen for the use of fire retardants in outside furniture. While fire retardants are not wanted from a manufacturing perspective, they are needed for safety outdoors. If European norms would be introduced, companies could adjust to those. Furthermore, suggestions were also made to ban thermosets and biobased materials, since they will limit recyclability and circularity of materials.
There are also some regulations in place that are regarded to be too strict. For example with testing of products and materials. Currently, material testing is required for each new product. It would be convenient, however, to have a few materials where properties are enough to meet a norm. So instead of doing product tests, material tests could be done which will allow the material to be used in a multitude of products (proven with a material passport).

Trends
The main market trend that 10XL sees is the fact that virgin material producers are becoming competitors, who are reluctant to share their material knowledge. Furthermore, purchasing behaviours of governments are changing to more circular purchasing. For 10 XL this translates to 3D-printing products of recycled materials for public spaces, such as benches and their Cityguard (mini garden around bins). For other businesses purchasing of circular materials is still lacking, except for businesses delivering to governments.
On a technological level, a key trend are existing and expiring patents. Since the past five to six years, more and more patents have emerged. While some patents for 3D-printing may have already expired, there are still many patents for (virgin) materials that stand in the way of circular innovation. Technological developments are seen by the use of nanotechnologies (such as nanocellulose, nanocarbon, nanofibrils etc.), improving material properties. As an example, nanofibrils do not damage during shredding, which has a significant impact on the circularity of the material. Other technological advancements such as tools, programs, controlling machines and more advanced sorting make manufacturing easier.

Positive and negative impacts

Because 10XL largely uses recycled materials for production, its key positive impact is limiting plastic waste. Their circular material sourcing also means that no additional waste is created. Possibilities for local production and delivery also contribute to the company's positive impacts and limit negative impacts of transportation. While the use of energy has a negative impact, 10XL limits the use of energy where possible. Adding fibres as resource input means that less temperature is needed for melting the material/compound (because fibres cannot be melted). High filled compounds are better in that sense, because less electricity is needed for heating. However, too many fibres will make it impossible to print the material and other (additional) activities may be needed, such as mixing/kneading the materials.

3. Circularity in the value chain

After analysing the company's current (circular) business model, a more detailed circularity assessment of the company and its activities in the value chain is made. The material and value flow map is presented, together with its adopted circular strategies.

3.1 Material and value flow map

The ultimate goal of a CE is for resources to flow in circles, with limited leakage out of the system. To evaluate this, it is important to map and visualise the current flow of materials and value within the company's value chain. The material and value flow map of 10XL is presented in figure 4. The value flows (blue) indicate that value is being exchanged between actors, and enables an analysis of the relationships amongst key partners. The circular material flows (green) show where the material comes from, where it goes and how it may return into the cycle.

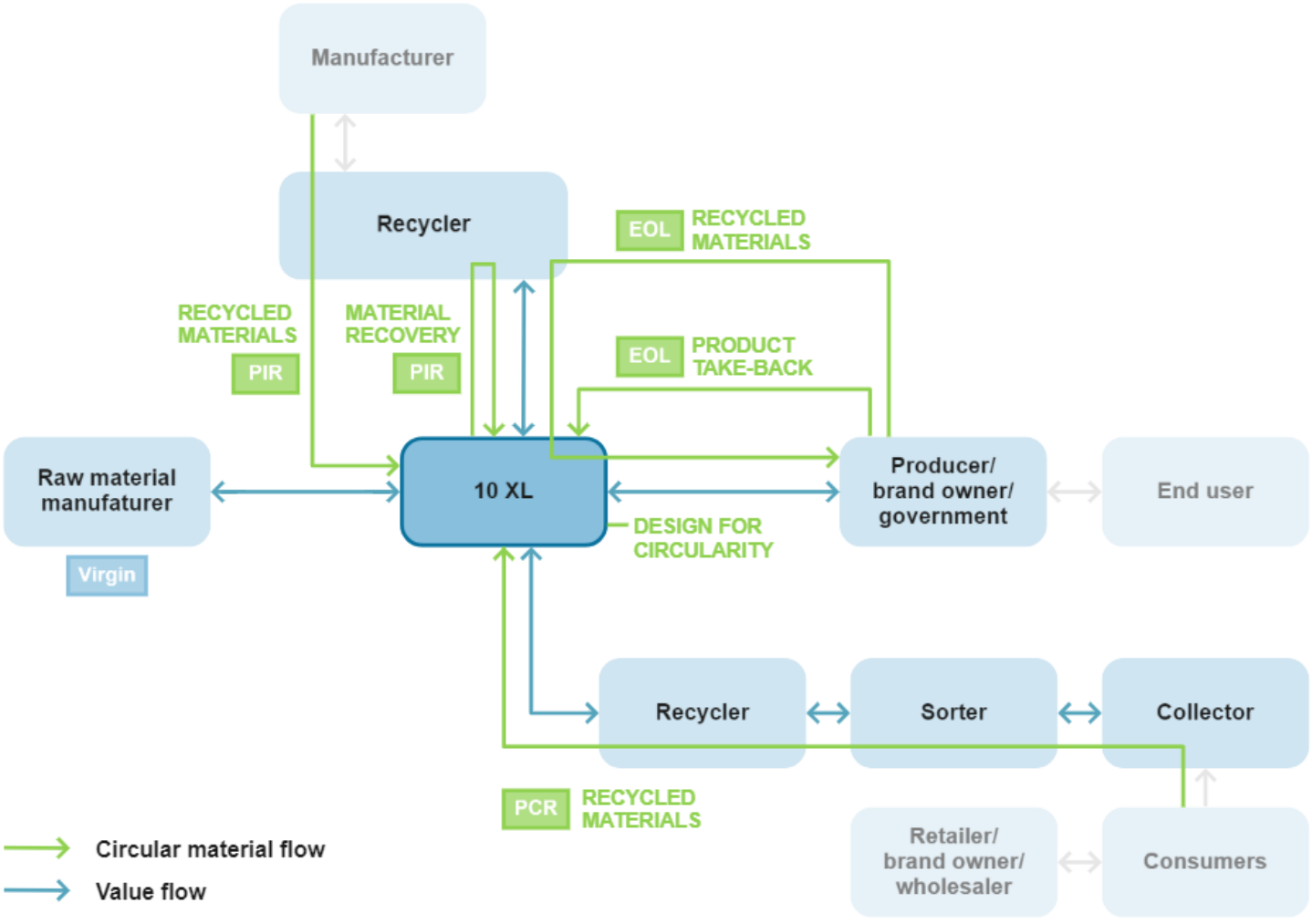

Figure 4: *Material/value flow map of 10XL*
(with PCR: post-consumer resin, PIR: post-industrial resin and EOL: end-of-life materials)

3.2 Circular strategies

As shown in figure 4, 10XL applies multiple circular strategies: use of *recycled materials*, *material recovery* of their own waste, *product take-back* at end-of-use and *designing products for circularity*. Each of the strategies is further explained below.

Recycled materials

10XL's main input material is recycled plastic, but biobased or virgin materials are available on request. If customers do not specifically ask for recycled materials, 10XL will bring it to their attention and will start a conversation about the possibilities for using recyclate.

Recycled materials may come from:

- PIR waste from other industries such as the automotive industry, which passes a recycler before it reaches 10XL.
- EOL waste coming from customers that have large batches of waste from the same product (e.g. chairs from old office) or from product-take back (collected by customers or from 10XL's returned products). 10XL will send this waste to a local recycler for shredding the material.
- PCR waste purchased from a recycler.
- Waste from their own production from milling or faulty prints.

The large products that 10XL manufactures require additives to provide strength and avoid collapsing. Since compounding requires energy and money, 10XL favours the use of materials that already contain glass fibres for material stiffness (PIR) over those that do not (PCR). Moreover, PIR and EOL waste provide better insights in material properties and used additives. For PCR such properties are harder to determine because different polymer types are mixed and input of the recycling process remains unknown. Due to the lack of additives in PCR, this fraction cannot become too large. Approximately 20-30% of PCR can currently be added to products. Hence, products are often a mix of PIR and PCR. 10XL would like to increase the amount of PCR in products if quality and strength of the material will allow it.

Material recovery

Waste from 10XL's production process, coming from milling or faulty prints, is collected and send to a local recycler. 10XL will receive this back as shredded materials in big bags.

Product take-back

10XL offers customers the possibility to take-back products at end-of-life. 'Deposits' are currently used on 10XL's sofas as an incentive to ensure product take-back. This is a predetermined amount of money by 10XL, which equals the difference between costs for recycling and the costs for purchasing other recycled materials. The money is refunded to the customer when products are returned to 10XL. Because the products of 10XL have not been around for that long, proper agreements have not been made yet. Arrangements still have to be made for other products, for example with their Cityguard. Furthermore, customers may return products to other companies. For this reason, material passports are provided.

While the possibility for take-back is offered, it is still a challenge to figure out the best way to implement this in practice. Consumers will likely bring the product to a waste station at end-of-life, and not return it to 10XL's customers.

Design for circularity

Design for circularity by 10XL manifests itself in three ways: *design for recycling*, *design for durability and performance* and *design for disassembly*.

Design for recycling

The used materials by 10XL are suitable for recycling, but how often recycling is possible still needs to be found out by experience. Some larger products from 10XL first have to be cut in pieces before shredding. Moreover, 10XL tries to avoid adding extra additives and rather looks for materials that already contain the necessary additives. Finding the right material for the right product is therefore essential.

To enhance recyclability and uptake of recycled feedstock industry wide, it is important to provide a 'material passport'. This document will provide businesses and recyclers insights in the used materials, their properties and used additives. This way, other companies also have the opportunity to recycle the products, whilst understanding the material and its properties for further (re)processing.

"Knowing the properties of a material is essential for circularity."

- *Linda van Hal, CCO of 10XL*

Design for durability and performance

Products of 10XL are designed in such a way that they will last as long as possible, at least 50 years. Long-fibre thermoplastics are used and the company researches which polymers last the longest. The first thing 10XL looks at when choosing new materials, is to make sure the material is as good and strong as possible, that it is durable and that it matches the required properties for the product. If recyclate can meet these requirements than recycled materials are preferred over the use of virgin materials.

Because the products of 10XL have only been around for a few years, no guarantees can be given of how long the products will last, this still needs to be further investigated and/or learned from experience. An example of research done by 10XL in this field, is the strength of the adhesion between the several layers made with 3D-printing. This is the weakest part of the product and may cause cracks in the material after a few years. 10XL is currently researching how to improve the adhesion of layers by the use of tape placements and fibre reinforcements to strengthen the product in the direction of the layer build-up.

Design for disassembly

Products from 10XL usually consist of just one piece. Customers may add other elements such as a motor (for a sloop/boat) or upholster the product (for a sofa). Hence, products are usually easy to disassemble.

4. Circularity of operational activities

After assessing the circularity of the company's activities within its value chain, a more detailed assessment of the circularity of the company's operational activities is done. A visualisation of the operational process is presented, together with its adopted circular strategies.

4.1 Operational process map

To get a better understanding of how the company's operational activities are affected, an overview of the process is made, see figure 5. This includes circular sourcing of materials, the production process and quality assurance of products. Each of the steps will be further explained below.

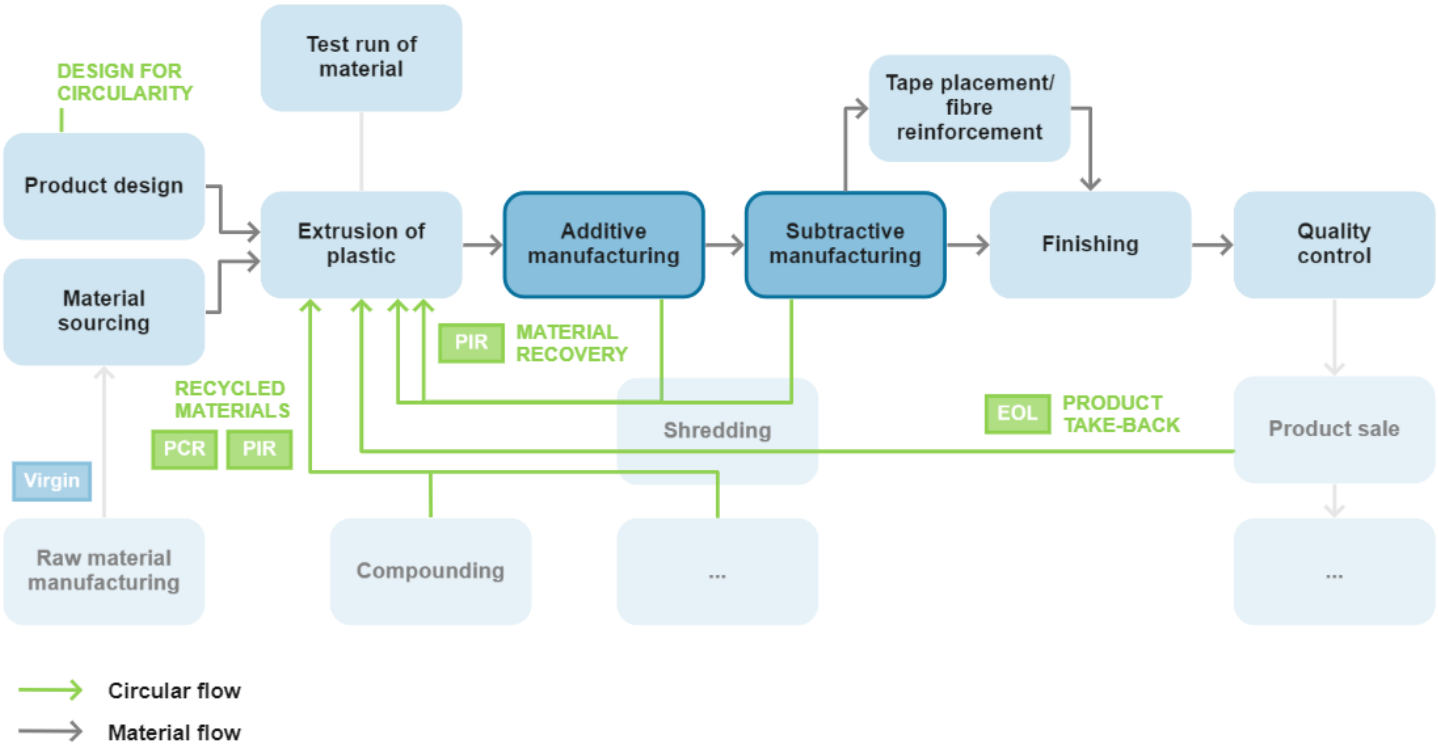

Figure 5: *Operational process map of 10XL*
(with PCR: post-consumer resin, PIR: post-industrial resin and EOL: end-of-life materials)

4.2 Circular sourcing and design

The preliminary process consists of material sourcing, shredding, compounding and designing the product. Advising customers on material sourcing and 3D-printing large products is also part of the operational process of 10XL.

Material sourcing

Recycled material may come from different sources, including waste from other production companies (PIR), consumer waste streams (PCR) or waste from customers at product's end-of-life

(EOL). EOL material from product take-back when products reach end-of-life represents the shortest line. Since 10XL has printed the product material properties are known which eases the manufacturing process. Moreover, the material has been previously selected as a 'printable material' so they know the material is suitable for printing (again).

Due to the wide variety of sources, it is important to find the right material and finding the right partners for supplying materials. Material input used by 10XL includes:

- Batch of PIR and EOL waste that can directly be used
- Mix of PIR with part PCR
- Specific mix from compounders based on PIR or PCR

A strength of 10XL is finding the right material suitable for a specific product. Where the company previously purchased for example PP with glass fibres, they are now purchasing PIR PP with glass fibres. This may not be the perfect material (e.g. colour is not optimal or more or longer glass fibres are desired), but it is still sufficient enough for printing and ensures an acceptable quality of the end product.

"There is a margin between the material and properties you need, and that of what is available."
- Joep Grapperhaus, CTO of 10XL

Based on customer wishes, the following aspects are taken into account with purchasing decisions for materials:

- *Price of the material*: possibility for compounding or using existing streams. If the material costs should be as low as possible, existing material streams are used. Compounding is more expensive and is only possible for large quantities and if customer budget allows it.
- *Desired type of waste*: virgin, EOL, PIR or PCR, and the used percentage of each. Some customers have no interest in recycled materials (e.g. with food applications etc.), some desire the use of PCR and some prefer a mix of materials.
- *Production method*: printing or milling. CNC milling requires other material properties than are needed for printing (e.g. more stability and fibres for milling).
- *Indoor or outdoor use*: outdoor use requires taking into account water (salt or fresh water), erosion, UV resistance etc.
- *Fire retardants*: material should burn slowly, quickly or does not matter.
- *Print settings for product*: which fibres are needed, layer height, texture (rough or smooth), wall thickness, colour etc.
- *Colour options*: changing the colour of recycled material requires more specialised colours, and colours of the recycled material (which is used as a basis) differs per batch. Hence, this may limit colour options and challenges the consistency of colours. It is therefore more convenient if customers are happy with grey colours.

The purity of materials is not always the best, it may consist of pieces of metal or other polymers, vary in colour or have dust or other pieces at the bottom of the bag. Odour may be a problem sometimes (caused by inks, food residues etc.) but this problem is limited in practice. Moreover,

datasheets are currently missing for recycled materials. This is mostly due to testing being too expensive for smaller amounts and it not being economically viable.

Shredding
Materials that 10XL uses often passes a recycler that shredders the material. 10XL may purchase materials from other manufacturers, sorting installations or distributors and then send it to the recycler for the material to be shredded, or they purchase it directly from the company that shredders the material (recycler). Although shredding the material currently includes an external partner, 10XL would like to have their own shredder machine in the future.
With shredding the material is cut into smaller pieces in the form of flakes or powder. This is an important step because advancing technologies may also allow for better sorting of the shredded pieces based on material type, quality, colour or additives. Shredding adds extra value to the material and each extra step comes with extra costs (e.g. second shredding step for smaller pieces, sorting on type or colour etc.).

Compounding
Some materials used by 10XL are purchased from compounders. Compounders mix a specific material based on PIR or PCR waste (consisting of polymers, fibres and/or additives). This way materials can be created with a similar composition to that derived from virgin material suppliers, only now based on recycled materials and customised as desired. Although compounding materials may not be the most sustainable option (kneading, more energy), availability of high quality recycled materials is ensured.
For the use of consumer waste with 3D-printing, compounding is necessary due to lack of required fibres and/or additives in this material stream. Hence if PCR is desired, 10XL looks for a compounder who can make a material according to their preferences and requirements, containing part consumer waste.

Product design
10XL's activities also includes the design of products and creation of 3D-models before manufacturing. The company's expertise on printing large products can be applied here. This step also includes strategies to design for circularity, as previously described by the subdivision in design for recycling, design for durability and performance and design for disassembly.

4.3 Production process

The production process starts with a test run of the material, followed by extrusion of plastic, additive manufacturing, subtractive manufacturing, optional tape placements and finishing of the product.

Test run of material
Prior to printing the final product, the material is tested by printing a test cube. This is done to find mechanical properties of the product and required print settings such as robot speed, layer height, cooling etc. The next step is to optimise the cube as much as possible (e.g. layer density,

temperatures and speed settings). The cube is optimised until satisfied, and certain parts of the cube are extracted for testing the mechanical properties of the material (e.g. tensile strength, bending modulus etc.). Test runs may also be used to see if colour output is as desired.
The difficult part with testing is that the cube itself is consistent (same speed and layer height for each part), whereas complex products have different dimensions (e.g. sofa has parts where double layers are created). For large series of products, products may be optimised for weight and production speed by printing a few test products. However, for smaller series possibilities for optimising will be limited and extra safety margins are applied in the design and settings (e.g. slower printing and/or use of more material).
The material test run is a very important step before starting the printing process. Sometimes a lot of testing is required, however, it also provides the company with new knowledge to be used for advising (new) customers. 10XL has tested a few materials that they often use. They try to operate within a certain framework and keep materials for new products or customers the same as much as possible. Materials may deviate slightly from this (e.g. change from 10% PCR to 20%) , without the need for big adjustments. Production data may also be saved in the future but no procedures for this are applied yet.

"The first time with a new material it is a lot of figuring out, testing and trying, but that knowledge can be reapplied in other projects later on, for different customers or to create new products."

- *Joep Grapperhaus, CTO of 10XL*

Extrusion of plastic
The first step of the production process includes melting and extruding plastic. This step is combined with additive manufacturing.

Additive manufacturing
Additive manufacturing is the part of the production process where 3D-printing of the product takes place. To allow for printing with recycled materials, the printing process and settings are adjusted to the used material. This includes adjustments regarding heating, cooling and printing speed, or the use of a different nozzle. Errors may arise more quickly when recycled materials are used. Moreover, blockages can occur more quickly if very small nozzles are used. This problem can be easily overcome by using a filter in front of the nozzle to prevent blockages.

Subtractive manufacturing
After additive manufacturing, subtractive manufacturing may take place to remove material at certain parts of the product. This process step consists of CNC cutting or milling the product. This step can be applied to a greater or lesser extent, depending on the desired outcome.
A circular strategy that is applied during both additive and subtractive manufacturing is *material recovery*. This means that waste of the production process or misprints are reused again as input for new products. This includes a sub-step of shredding the material by an external recycler.

Tape placement/ fibre reinforcement

Reinforcement fibres are used to ease the printing process and are necessary for providing strength and rigidity to the product (mechanical properties). Hence, printing is always done with a combination of plastic and fibres. It is also possible to apply tape placements on the product after printing. Molten unidirectional fibres are applied to the outside surface of the product to provide strength. The fibres of the tape placement endure the forces of tension and stretch, instead of the adhesion of print layers (which is the weakest part). This process is still new and is not applied extensively yet.

Using fibres for tape placements does not directly influence recyclability of the end product, because it consists of the same material as used for the fibres within the product. However, all fibres become shorter with each recycling cycle and new tape placements will be needed to provide additional strength for new products. After a while, fibres become too short and have a powder-like structure. They will then act as a filler, rather than a fibre providing strength.

Finishing

Finishing the product consists of sanding or polishing the product.

4.4 Quality assurance and product sale

The last part of the operational process consists of quality assurance and sale of the end-product to 10XL's customers.

Quality control

The quality control step mainly consists of a general approval of the end product and results of previous test and prototypes. Sometimes strength calculations are done with the computer. For some products a quality check list is available, which specifies wall thickness, surface accuracy and finishing for a specific product.

Quality is often ensured by dimensions and applying extra safety margins if necessary. Larger products have different (and stricter) quality requirements. In addition to strength, other important quality properties are flammability and discoloration of products (UV protection). Such requirements differ for each industry and product.

The weakest point of the product is usually the adhesion between layers. The layers created by 3D-printing are easier to separate or break, which causes the product to be weaker in the direction of the layer build-up. This also causes the mechanical properties of the product to differ for the printing direction versus the cross section perpendicular to this. Optimal layer orientation is therefore strongly considered when designing products. For this reason, products are often printed in the length of the product (e.g. more strength when sitting on a sofa).

Layer adhesion can be improved by cooling and heating, printing speed, layer build-up, printing in different orientations (with two layers perpendicular to each other), use of fibres (more fibres causes less adhesion, but more mechanical anchoring between layers), use of additional fibre reinforcements and tape placements.

Product sale

After the last quality checks the product is ready for sale and is picked up by the customer. Added to the product is a 'material passport' in the form of a QR-code or nameplate. This material passport allows for better reprocessing the product and its materials at end-of-life, whether used again by 10XL or other manufacturers. The passport describes the material composition and used fibres or additives, and gives an idea of how to process it. However, there is not always a spot on the product for the QR-code and it may wear off after a while.

5. Conclusion and recommendations

Based on the outputs derived from all three interviews with 10XL, strengths of the business model and operational process in regards to circularity are identified, barriers and enablers for circularity are summarised, and opportunities for circularity are described.

5.1 Strengths for circularity

10XL serves customers with questions about the manufacturing of large products and use of circular materials, with the need of extra tools or equipment. This approach allows all large 3D-printed products from recycled materials to be made (up to 12m), not limited to specific markets or sectors. Their business model consists of mutual cooperation with many businesses. They work together with other businesses to research and find suitable (recycled) materials and products are developed together with customers. 10XL's business model is set up in a way that they will always aim to make products of circular (recycled) materials. Even if customers do not specifically ask for recycled materials, 10XL will bring it to their attention and will start a conversation about the possibilities for using recyclate.
10XL's strength lies in finding the right material for the right product. They look at recycled materials as an entirely new material with many possibilities. Within their value chain and network, 10XL is searching for circular materials with the right quality, properties and additives, specified for the product they are willing to make. Instead of using solely post-consumer waste (PCR) (which lacks of additives to provide strength for large products), they often use post-industrial waste (PIR) from the automotive industry because it already contains the necessary amount of additives. Furthermore, waste of misprints and production waste is reused again in new production processes.

The operational process for recycled materials (in contrast to that of virgin materials) mainly differs in the preliminary work. More time is required to find the right materials and finding the right partners for supplying the material. Availability of materials is also uncertain, and in more particular, uncertainties about consistency of quality and colours. Material input used by 10XL consists of batches that can directly be used (PIR or EOL), a mix of PIR and PCR or a specific mix from compounders based on PIR or PCR. When purchasing materials, the following aspects are considered: price of material, type of waste, production method, indoor/outdoor use, fire retardants, print settings for product, and colour options.
Prior to printing the product, material test runs are done by printing a test cube, which is optimised until satisfied. For larger series, prototypes of the end product may also be printed, or safety margins are applied for smaller series (e.g. slower printing and/or use of more material). Knowledge of such material tests may also be used for new projects and advising customers. To allow for printing with recycled materials, adjustments can be made regarding heating, cooling, printing speed, size of nozzle and using a filter to prevent blockages with smaller nozzles.

Products of 10XL are designed in such a way that they will last as long as possible. The adhesion between layers is usually the weakest part of the product. Hence, the use of fibres, fibre reinforcements or tape placements is very important for providing strength in the direction of the

layer build-up. Moreover, different settings for cooling, heating, printing speed, layer build-up and printing orientations can help to improve adhesion between layers.
A general collection system for such large product has not been introduced to the market yet. Hence, 10XL offers customers the possibility to take-back products at end-of-life. Refunds are currently provided on 10XL's sofas as an incentive to ensure product take-back. However, it is likely that consumers bring products to a waste station at end-of-life, and not return it to 10XL's customers. Moreover, material passports are provided to allow for better reprocessing of products and used materials at end-of-life, whether used again by 10XL or other manufacturers.

5.2 Barriers and enablers for circularity

To ensure circularity for 10XL and its value chain, several barriers and enablers can be pointed out. The biggest barrier for 10 XL is not knowing the material properties of recycled materials, and the reluctance of virgin material producers to share information. This requires a lot of testing and trying of materials. Subsequently, knowing such properties (e.g. by providing a material passport) is regarded to be the biggest enabler for implementing recycled materials. Moreover, from a circularity point of view, it is important to look at the bigger picture (e.g. refurbishing old products or make a new one from recycled plastic; awareness for opportunities to use local waste, instead of using recycled materials from far away). Other barriers and enablers have been mentioned and explained before and are summarised in table 3 below.

"Recycling leads to a throwaway culture in which we forget that a lot of effort is needed for making products, even if it is made of waste."

- *Joep Grapperhaus, CTO of 10XL*

Table 3: *Barriers and enablers for enabling circularity at 10XL*

Barriers	Enablers
• Reluctance of virgin material producers to share information • Regulations that are too little (e.g. for use of fire retardants) • Regulations that are too strict (e.g. approvals based on materials instead of products) • Lack of circular purchasing by businesses • Patents on material testing preventing innovation • Additional time for preliminary work (sourcing recycled materials) • Uncertainty of availability of recycled materials • Uncertainties about consistency of quality and colours • Lack of material knowledge for recycled materials	• Developing products together with customers • Start conversation about recycled materials • Circular purchasing of governments • Post-industrial waste that already contains required additives for strength • Finding the right material for the right product • Finding the right partners to work with • Independent research institute for recycled materials • Knowing material properties • Providing material passport • Developments in nanotechnologies • Advancing technologies for better sorting based on material type, quality, colour or additives • Expertise on product design and materials • Test run of materials

• Missing datasheets for recycled materials (material passport) • Shortening of fibres and tape placements with recycling • Finding spot for QR-code (material passport) and wear off • Sufficient volumes for recycling products at EOL	• Filters before nozzle to prevent blockages • Tape placement or fibre reinforcement for providing strength • Applying extra safety margins • Deposit/refund to ensure product take-back • Designing products for durability • Look at the big picture for circularity • Closed loop recycling (use of local waste to create products to be used in the same city)

5.3 Opportunities for circularity

Because the products of 10XL have not been around for that long, there are still some opportunities to enhance circularity by 10XL and the company's activities within the value chain. 10XL also recognises this and is actively working on further researching, discovering and testing options for circularity.

Product take-back and resource recovery

Because 10XL's products are designed to last long, actual effectiveness of product take-back is not sure yet. Nonetheless, it is important to establish a general collection system for large plastic products to ensure circularity of 10XL's products. Such a system is currently missing and products often end up with bulky waste at waste stations. Besides, it is important to achieve sufficient volumes of products from the same material (composition). This includes considering options to design for standardisation, to ensure sufficient volumes of the same material (composition) in order to improve the recycling of products in the future.

On the other hand, it is also possible to further explore options for deposits or refunds (e.g. product is brought back to 10XL and then material is used for manufacturing same product). This can be further developed by using a refund on a wider range of products. Deposits that have been implemented for 10XL's products only apply for returning products from 10XL's customers to 10XL. It does, however, not provide any incentives for consumers to return products to either 10XL's customers or 10XL itself. This is difficult to control because 10XL has no direct contact with the end user. Hence, consumers will likely bring the product to a waste station at end-of-life. Besides, if products are to be returned to 10XL at EOL, logistics also have to be improved since it is not economically viable to drive for the collection of just one product. Options are seen to offer customers or consumers the possibility to return products a few times a year, in exchange for a (small) refund. This should then be further coordinated with customers.

Access

Other options for implementing circular strategies includes product *access*, in which consumers and/or customers only use (access) the product, instead of owning it. 10XL will then stay the owner of the product, which not only helps to ensure product take-back, but will also make them responsible for maintenance and EOL options (e.g. to make sure product actually gets recycled). This could, for instance, be an option for 10XL's own products, such as their sofa and sloops/boats.

Repair and maintenance

Smaller loops of circularity ensure less changes to the product to be made, before reusing the product, parts or materials again. So before diving into options for recycling products at EOL, it is valuable to explore options for circular strategies at the product's end-of-use (when it has not reached EOL yet). Circular strategies such as repair or maintenance are not offered by 10XL yet, though, the company is willing to look into opportunities for repairing products. Knowledge about options for repairing products are still limited because the products have not been around for that long, and they have little experience with the need for repairing products. In the future such a service may be offered to customers or consumers. For example, 'cracks' in the product can be repaired by melting the material around the crack, adding new (melted) material or adding extra tape placements. Maintenance may be offered to customers as part of a service offering or when letting them access the product instead of owning it.

"The most sustainable option is designing something that is timeless and that cannot be broken."

- *Joep Grapperhaus, CTO of 10XL*

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About the project

The problems associated with plastic waste and in particular its adverse impacts on the environment are gaining importance and attention in politics, economics, science and the media. Although plastic is widely used and millions of plastic products are manufactured each year, only 30% of total plastic waste is collected for recycling. Since demand for plastic is expected to increase in the coming years, whilst resources are further depleted, it is important to utilise plastic waste in a resourceful way.

TRANSFORM-CE aims to convert single-use plastic waste into valuable new products. The project intends to divert an estimated 2,580 tonnes of plastic between 2020 and 2023. Two pilot plants will be set up, one in Almere (NL) and one in the UK. The plants will make use of two innovative technologies – intrusion-extrusion moulding (IEM) and additive manufacturing (AM) – to turn plastic waste into recycled feedstock and new products.

Moreover, the project will help to increase the adoption of technology and uptake of recycled feedstock by businesses. This will be promoted through research into the current and future supply of single-use plastic waste from municipal sources, technical information on the materials and recycling processes, and circular business models. In-depth support will also be provided to a range of businesses across North-West Europe, whilst the insights generated through TRANSFORM-CE will be consolidated into an EU Plastic Circular Economy Roadmap to provide wider businesses with the 'know-how' necessary to replicate and up-scale the developed solutions.

Lead partner organisation
Manchester Metropolitan University

Partner organisations
Materia Nova
Social Environmental and Economic Solutions (SOENECS) Ltd
Gemeente Almere
Save Plastics
Technische Universiteit Delft
Hogeschool Utrecht
Hochschule Trier Umwelt-Campus Birkenfeld Institut für angewandtes Stoffstrommanagement (IfaS)
bCircular GmbH
Viridor Waste Management Limited

Countries
UK | BE | NL | DE

Timeline
2019-2023

www.nweurope.eu/transform-ce