# A new system for the recovery and the recycling of thermoplastic polyurethanes (TPU) from ski boot equipment

A. Nanni, M. Colonna, L. Crosetta, M. Parisi, D. Colombo

*SPORT TECHNOLOGY LAB -University of Bologna, Via Terracini 28, 40131 Bologna, Italy*
*RE-SPORT srl via G.Fanin 40131 Bologna IT*

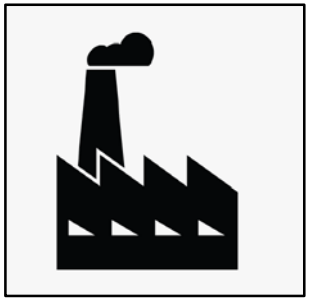
**9th International Conference on Sustainable Solid Waste Management**
**Corfù, Greece,17-06-2022**

**Alessandro Nanni, PhD**
alessandro.nanni18@unibo.it

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DIPARTIMENTO DI
INGEGNERIA CIVILE, CHIMICA, AMBIENTALE E DEI MATERIALI - DICAM

# An ecological problem

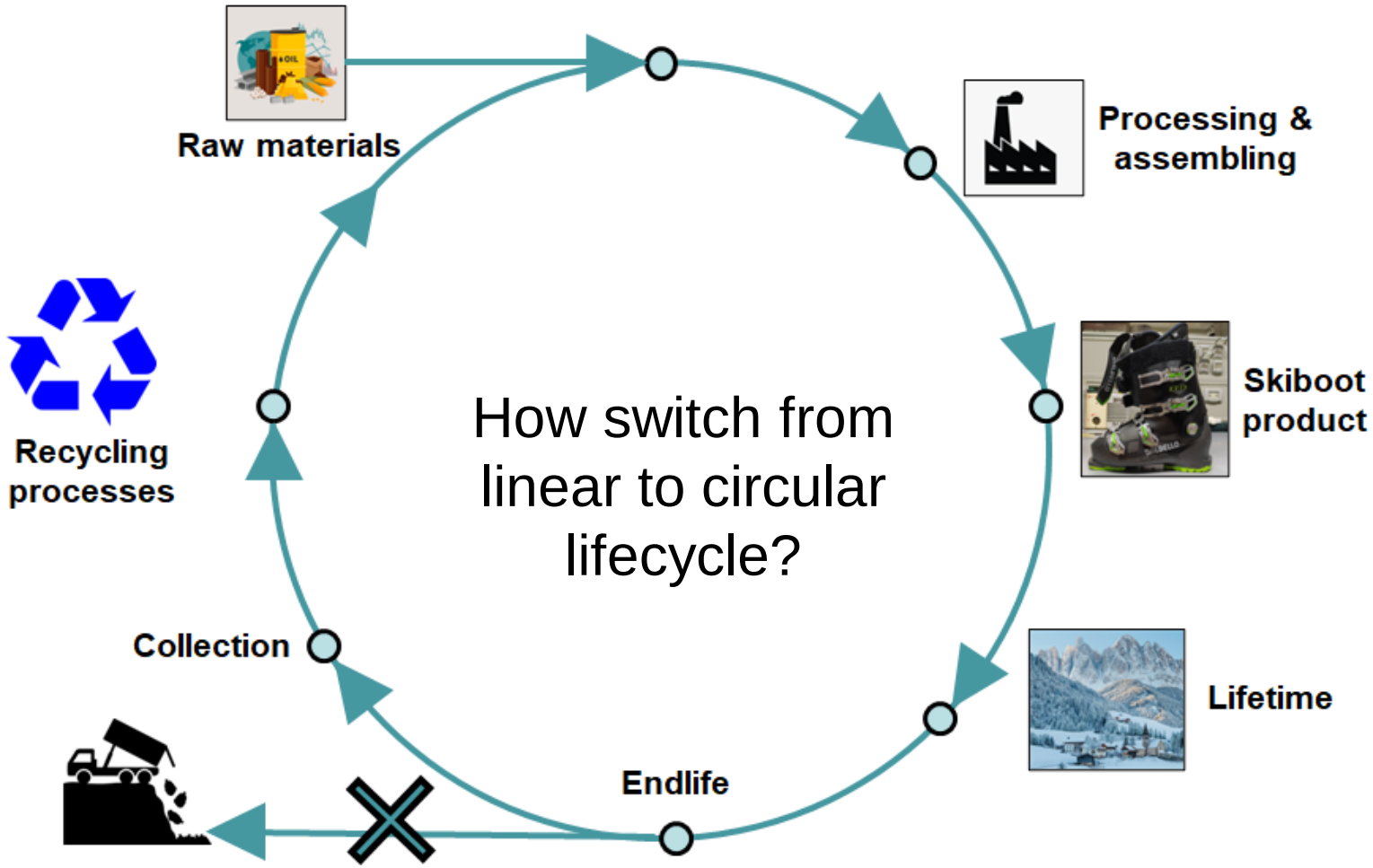

Raw materials | Processing & assembling | Skiboot product | Lifetime | Landfilling

→ **A linear «cradle to grave» economy**

→ **7 million of skiboot are annually destined to landfill and/or incenerinator**

→ **10-15 kton of wastes annually generated**

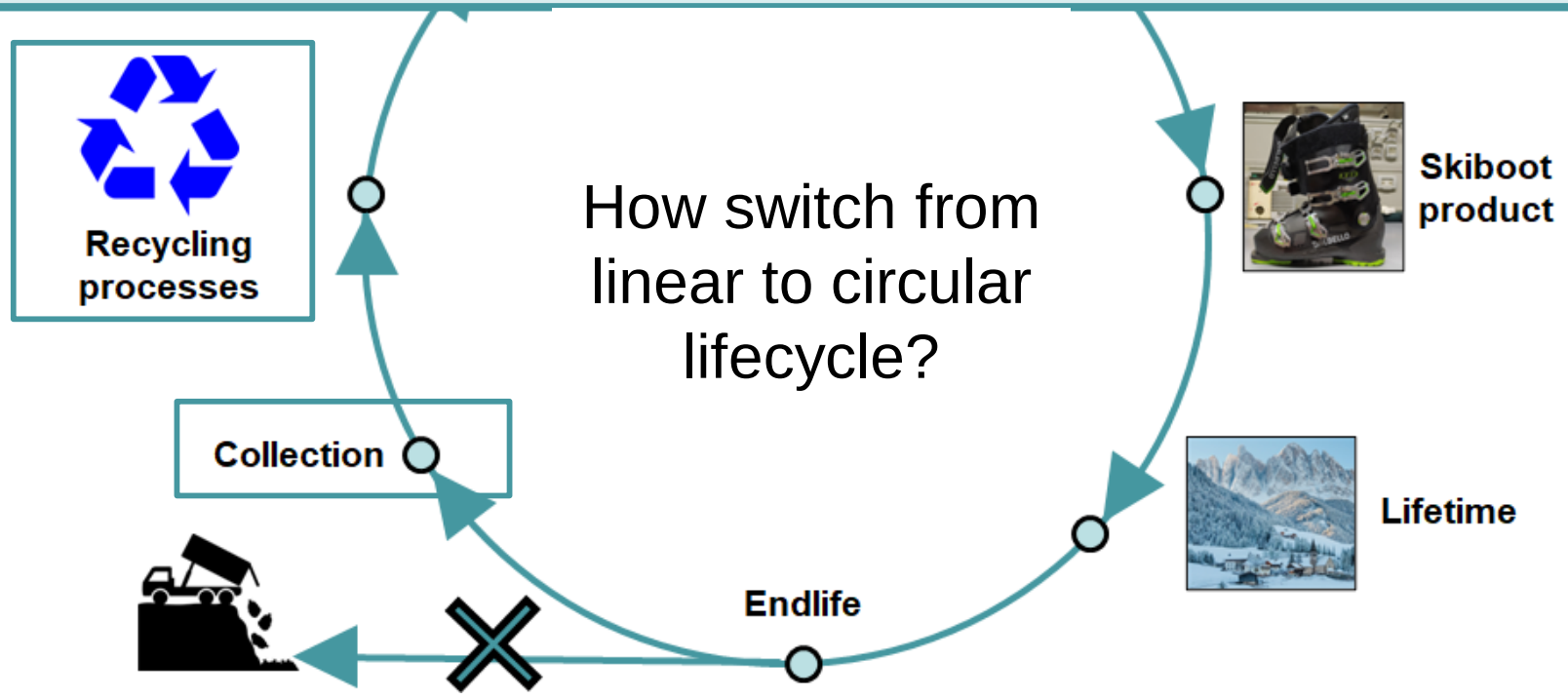
# An ecological transition



# An ecological transition

## The main recycling problems:

- ❑ It is difficult to **collect** the end-of-life skiboots.
- ❑ Skiboots have a **complex and variable** multi-material **composition**



# An ecological transition

## The main recycling problems:

- ❑ It is difficult to **collect** the end-of-life skiboots.
- ❑ Skiboots have a **complex and variable** multi-material **composition**

**COLLABORATION WITH SKI RENTAL SHOOPS**


- They solve the problems of **collection**
- They solve the **variability** of the skiboot composition (entry level/intermediate skiboots)

# Skiboot composition

*(intermediate and entry-level skiboots)*


| | |
|---|---|
| Inner boot (EVA) | **24,9%wt.** |
| Straps (Velcro) | **2,2%wt.** |
| Cuff (TPU) | **22,3%wt.** |
| Shell (TPU) | **30,2%wt.** |
| Buckles (steel and Al) | **12,9%wt.** |
| Sole (TPU) | **4,2%wt.** |
| Insole (PP) | **2,7%wt.** |

**Mtot = 2,256 kg**

**56,7%wt. of TPU**

# Aims of the work

1) Investigating the recyclability of the TPU polymers in terms of:
   - ski-boot's lifetime and state of wear
   - number of the recycling steps
   - weathering ageing

→ **How much is recyclable the sorted TPU?**

2) How can be TPU industrially sorted?
→ *(Not treated here); spoiler: yes*

3) Investigating the techno-economic profitability of the proposed recycling processes
→ **The proposed recycling processes can be scaled-up?**

4) Investigating the environmental impact of the proposed recycling processes
→ (Not treated here here); spoiler: yes

# Scheme of the work
## *(Lab-scale)*


**Ski rental shoops**


- **Virgin (t0)**
- **20 days lifetime (t20)**
- **50 days lifetime (t50)**

Other components

**TPU Cuff and Shell**

**Grinder**

**TPU flakes**

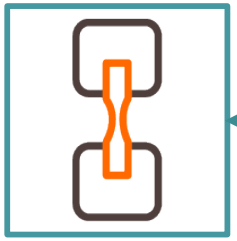
**Injection molding**

**Specimens**

**Recycling loops**

**Weathering**

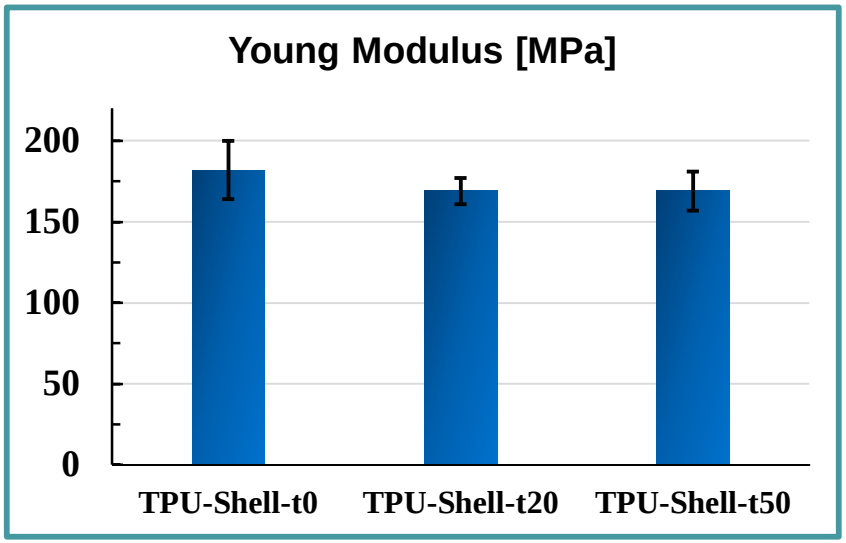
UV
Thermal
Water

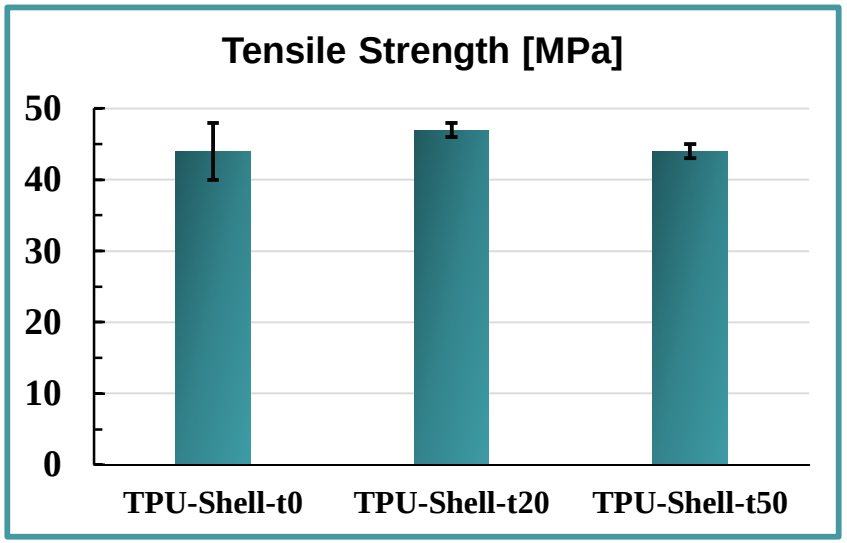


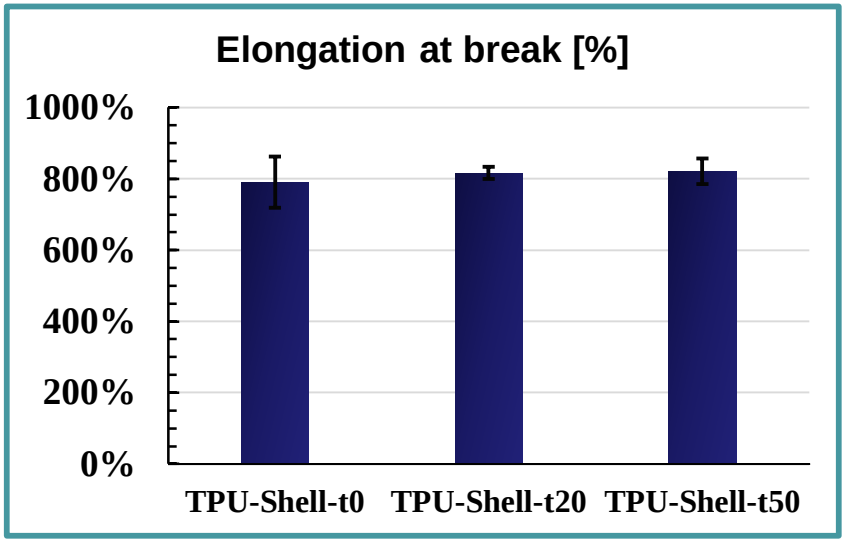
**Testing**

Tensile test
Flexural test
TGA - DSC

# Tensile properties
## t0-t20-t50



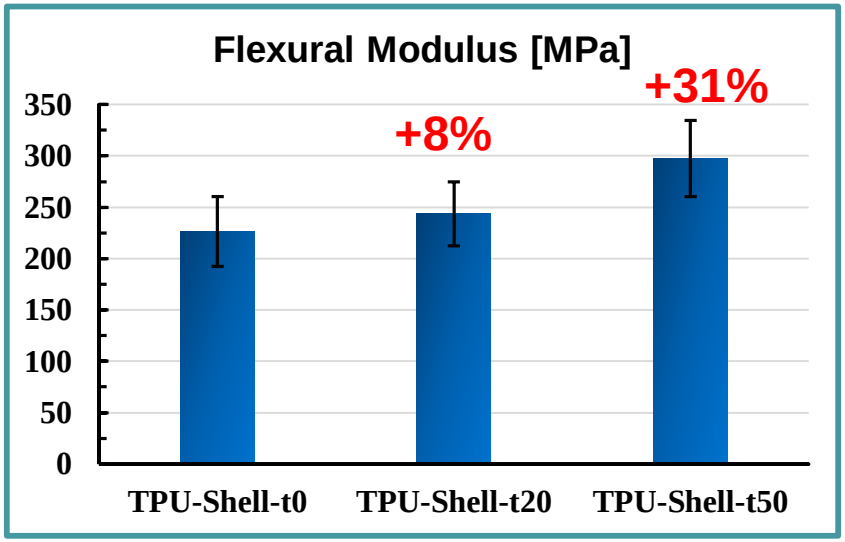



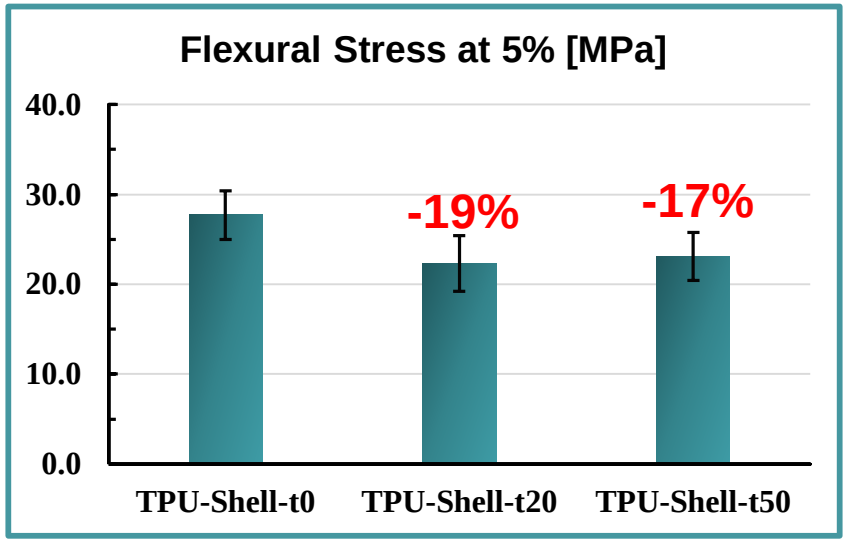



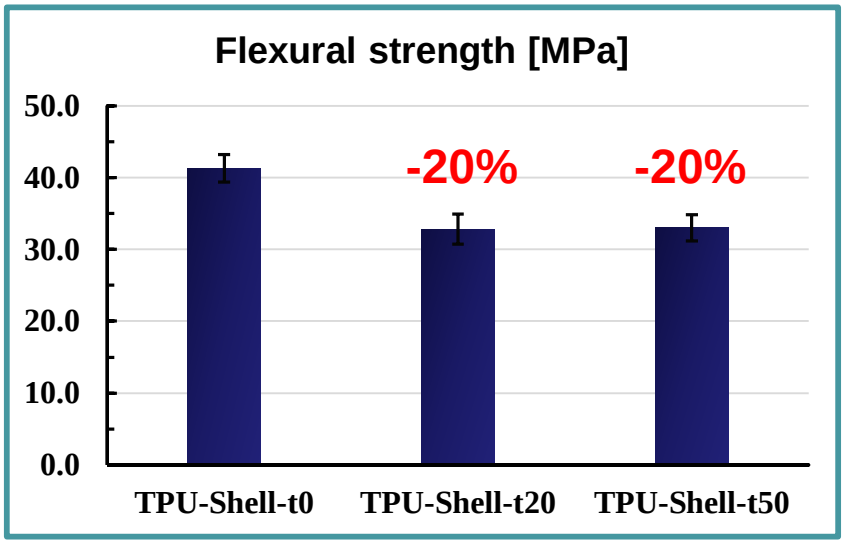

| | E [MPa] | TS [MPa] | e,break [%] |
|---|---|---|---|
| R1-t0 | 182 ± 18 | 44 ± 4 | 791 ± 72 |
| R1-t20 | 169 ± 8 | 47 ± 1 | 816 ± 17 |
| R1-t50 | 169 ± 12 | 44 ± 1 | 821 ± 36 |
| Virgin TPU | 185 ± 10 | 45 ± 2 | 840 ± 20 |

**The lifetime of the skiboot (t0-t20-t50) does not affect the tensile properties**

# Flexural properties
## t0-t20-t50



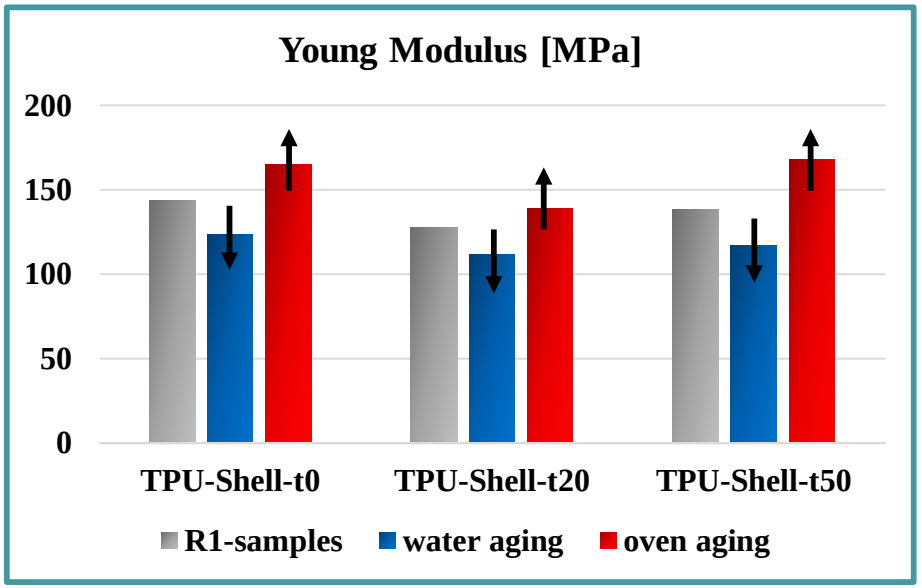



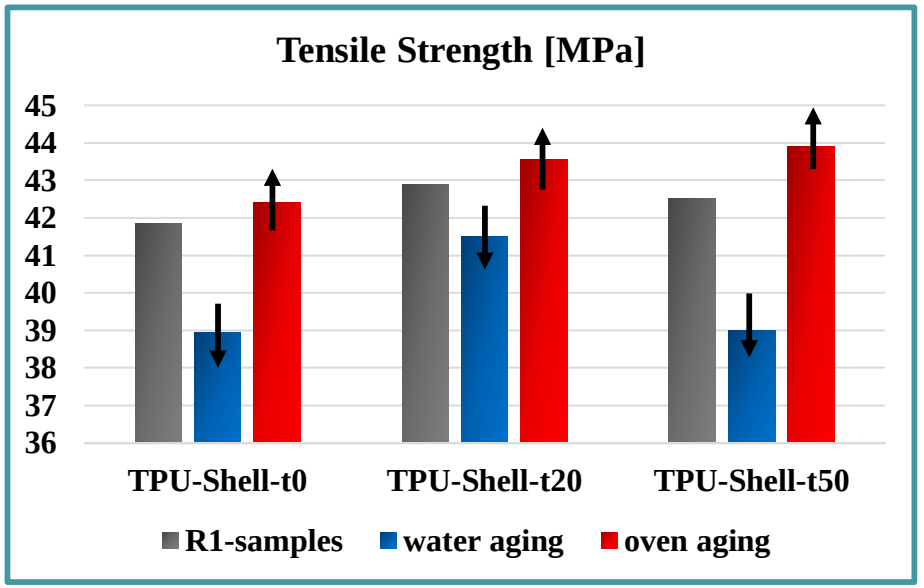




| | Flex modulus [MPa] | Flex stress at 5% [MPa] | Flex strength [MPa] |
|---|---|---|---|
| R1-t0 | 226 ± 34 | 27,7 ± 2,7 | 41,3 ± 1,9 |
| R1-t20 | **244 ± 31** | **22,3 ± 0,4** | **32,9 ± 2,1** |
| R1-t50 | **297 ± 37** | **23,1 ± 0,7** | **33,0 ± 1,8** |

**Used (t20 and t50) recycled (R1) TPUs have reduced flexural properties**

# Aged specimens
## t0-t20-t50



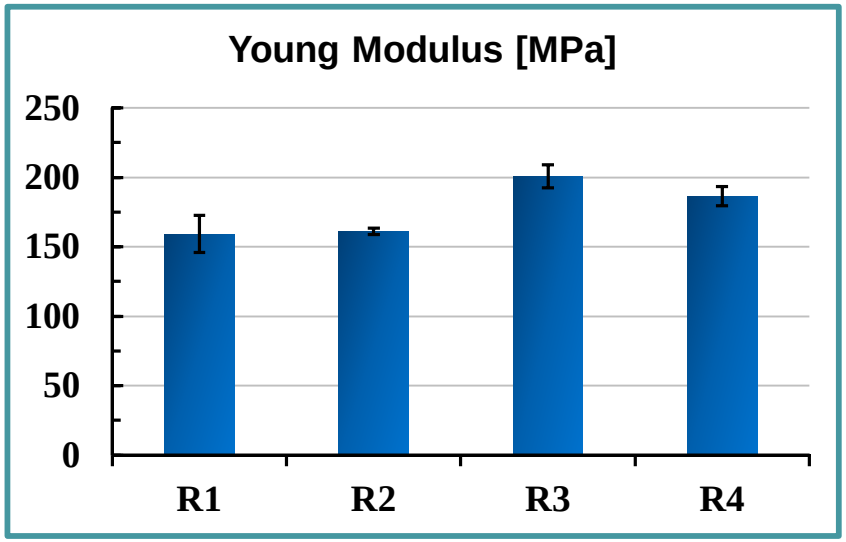

**Water aging** = samples are immersed in water for 24 hours and then frozen to simulate the melting/freezing cycles which ski-boots are subjected in the snow;
→ **plasticizing effect** : water molecules bonded with the ester polymer chains.

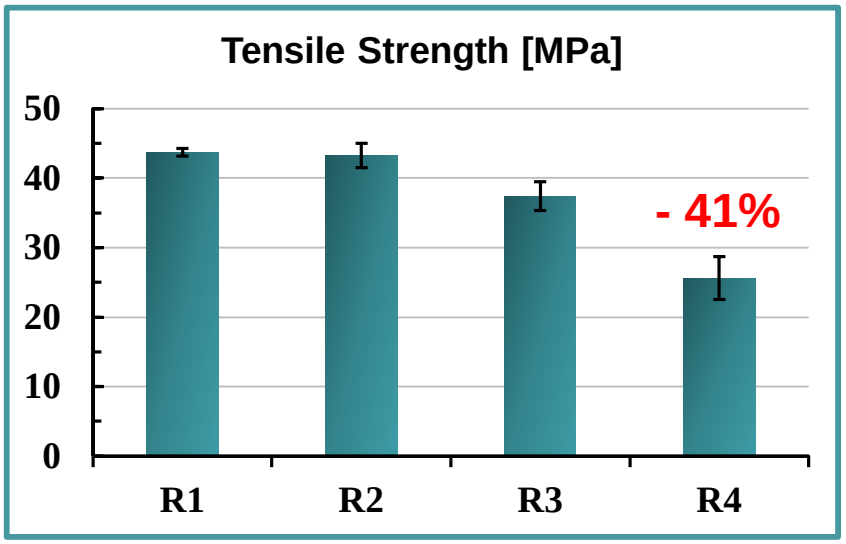
**Oven aging** = samples are placed in oven for 100 hours at 75 °C to accelerate the degradation of the polymer matrix:
→ **hardening effect** samples become stiffer and loose their ductility.

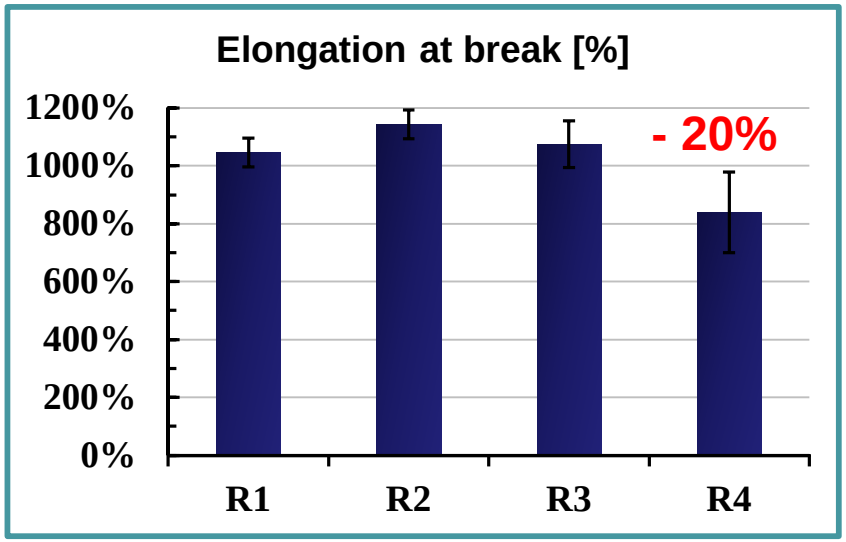
→ Water and thermal aging show opposite counterbalancing effects.

# Recycling loop

## *Recycling of t0*



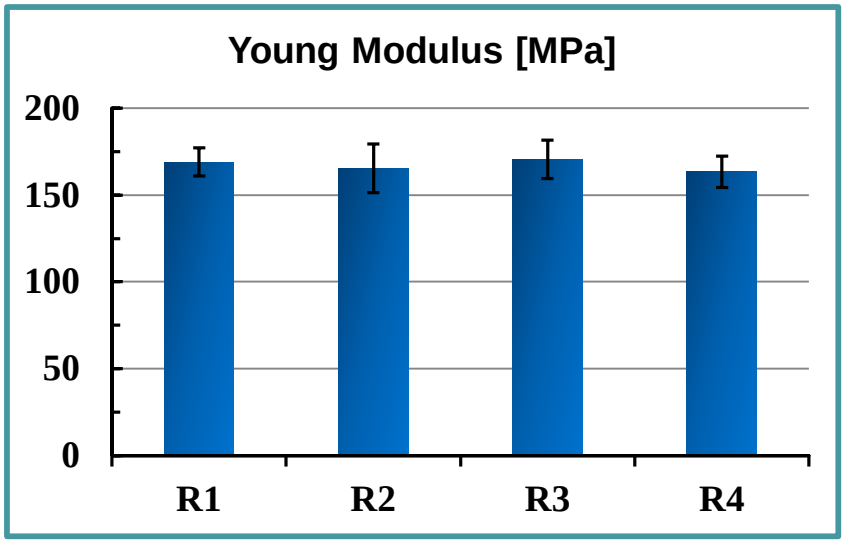



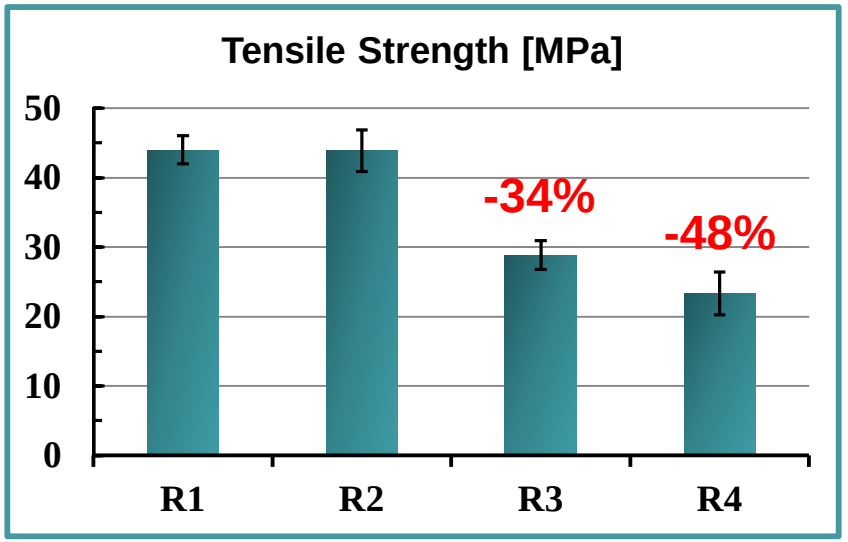

| | E [MPa] | TS [MPa] | e,break [%] |
|---|---|---|---|
| R1-t0 | 159 ± 14 | 44 ± 1 | 1046 ± 50 |
| R2-t0 | 161 ± 2 | 43 ± 2 | 1143 ± 75 |
| R3-t0 | 201 ± 8 | 37 ± 2 | 1075 ± 80 |
| R4-t0 | 186 ± 7 | **26 ± 3** | **840 ± 139** |

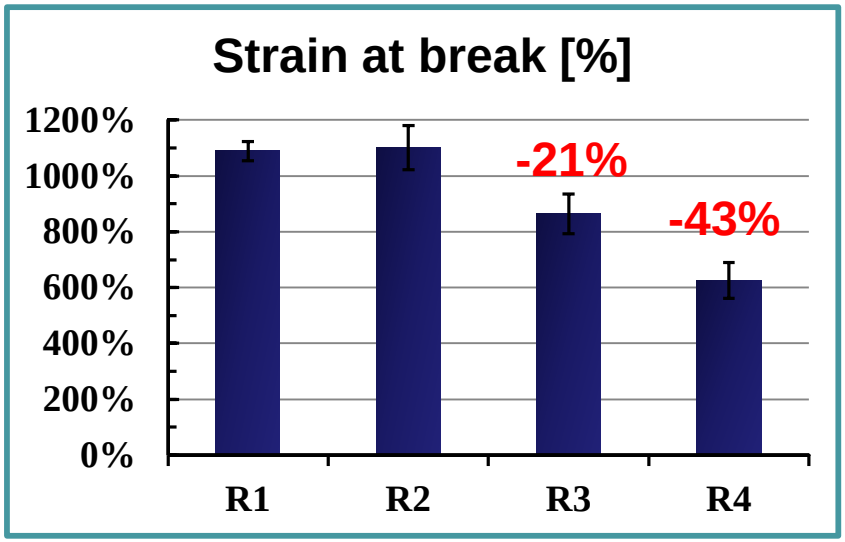
**t0 skiboots are recyclable up to three times**

# Recycling loop

## *Recycling of t50*




| | E [MPa] | TS [MPa] | e,break [%] |
|---|---|---|---|
| R1-t0 | 169 ± 8 | 44 ± 2 | 1089 ± 35 |
| R2-t0 | 165 ± 14 | 44 ± 3 | 1101 ± 80 |
| R3-t0 | 170 ± 11 | **29 ± 2** | **865 ± 71** |
| R4-t0 | 163 ± 9 | **23 ± 3** | **626 ± 64** |

**t50 skiboots are recyclable up to two times**

# Conclusions

1) Tensile properties are not affected by the lifetime of the skiboot, while flexural properties are (slighthly).

2) Accelerated weathering aging modify the mechanical behaviour of the TPU polymer but the overall properties result similar to untreated TPU as oven and water aging show opposite counterbalancing effects.

3) **Among the different contributes (lifetime usage, weathering and recycling), the reprocessing is the one that most affect the mechanical properties of recovered TPU.**

4) However, the properties of recycled TPU were **overall satisfactory** up to the 2th recycling step.

# Techno-Economic Analysis

Collection

T

- €

Grinder

- €

*Triboelectric*

Sorting

- €

Other component

wastes

- €

*n=93%*

EVA

+ €

*n=97%*

TPU

+ €

vTPU

- €

T

- €

Extrusion

- €

+ €

Total polymers recovered = **78%wt.**

**Approach 1**: direct sell of sorted TPU flakes– no extrusion
**Approach 2**: extrusion of sorted TPU flakes with vTPU

# Techno-Economic Analysis

**Grinder**

- PC = 103 k€
- **Productivity = 100 kg/h**
- Consumption = 80 W/kg
- Labor = 1 pers./machine

**Sorting**

- PC = 350 k€
- **Productivity = 500 kg,in/h**
- Consumption = 3'150 W/kg
- Labor = 2 pers./machine

**Extrusion**

- PC = 195 k€
- **Productivity = 150 kg/h**
- Consumption = 400 W/kg
- Labor = 1 pers./machine

**The plant is able to recycle up to 300k ski-boots for years (677 ton)**

- Selling price of r-EVA = 1,5 €/kg
- Selling price of r-TPU = 3,0 €/kg
- vTPU content = 0-50%wt.
- vTPU cost = 4,0 €/kg
- Depreciation time = 10 years

- Electricity cost = 0,1984 €/kWh
- Waste tax = 0,3 €/kg
- Transports cost = 0,32 €/(ton*km)
- Labor cost = 18 €/h
- Taxes = 24%

# Techno-Economic Analysis

- **Total Investment Cost (TIC)**

$$\boldsymbol{TIC}\ (€) = Direct\ Fixed\ Costs\ (DFC) + Working\ capital + Start\ up\ \&\ validation$$

→ Required expenses needed to build-up the entire new recycling plant

- **Net Profit (P)**

$$\boldsymbol{P}(€) = Revenues\ - Annual\ Operating\ Costs\ - Taxes + (Depreciation)$$

→ P indicates if , a part from the TIC, the recycling processes are profitable or not

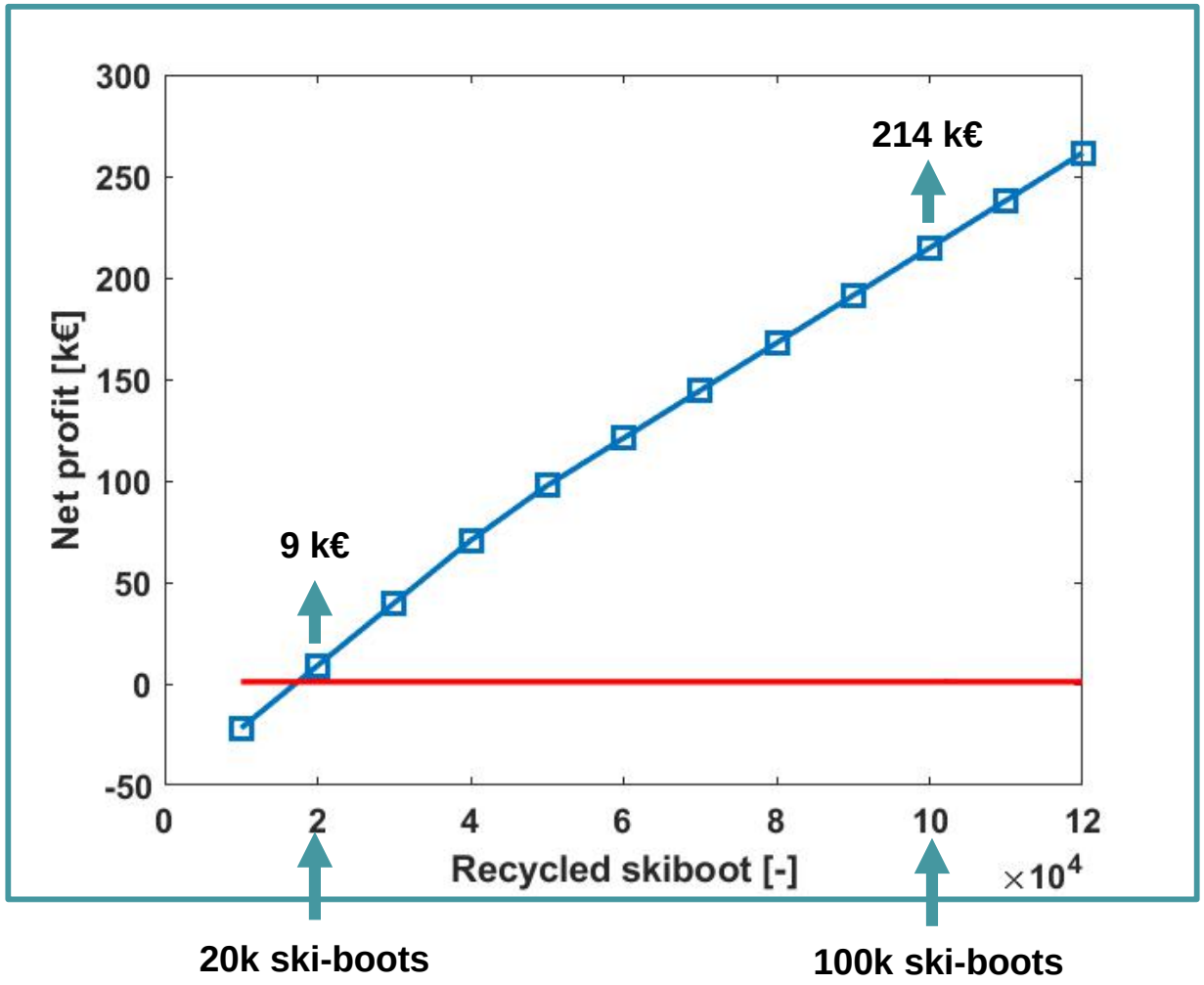
- **Net Present Value (NPV)**

$$\boldsymbol{NPV}\ (€) = \sum_{2}^{10} \frac{\boldsymbol{P_t}}{(1+d)^t} - \boldsymbol{TIC} \qquad d = discount\ rate = 7\%$$

→ NPV inditicates if the **new recycling plant** is profitable in 10 years

# Techno-Economic Analysis

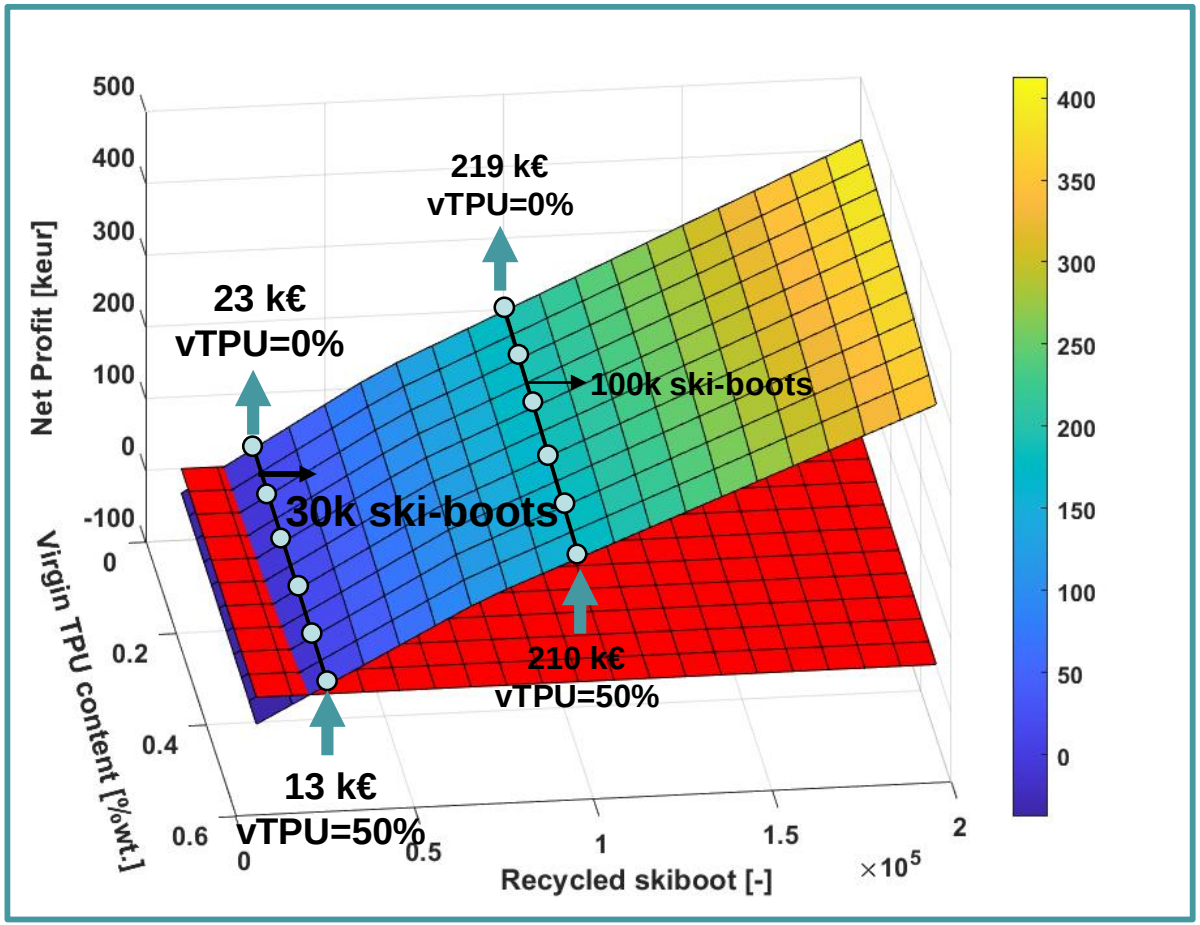
## Net Profit (processes)- No extrusion




- The recycling processes are profitable when **20k ski-boots** (0,3%) are recycled
- When 100k ski-boots are recycled (1,4%), the net profit is of 129k€

# Techno-Economical Analysis

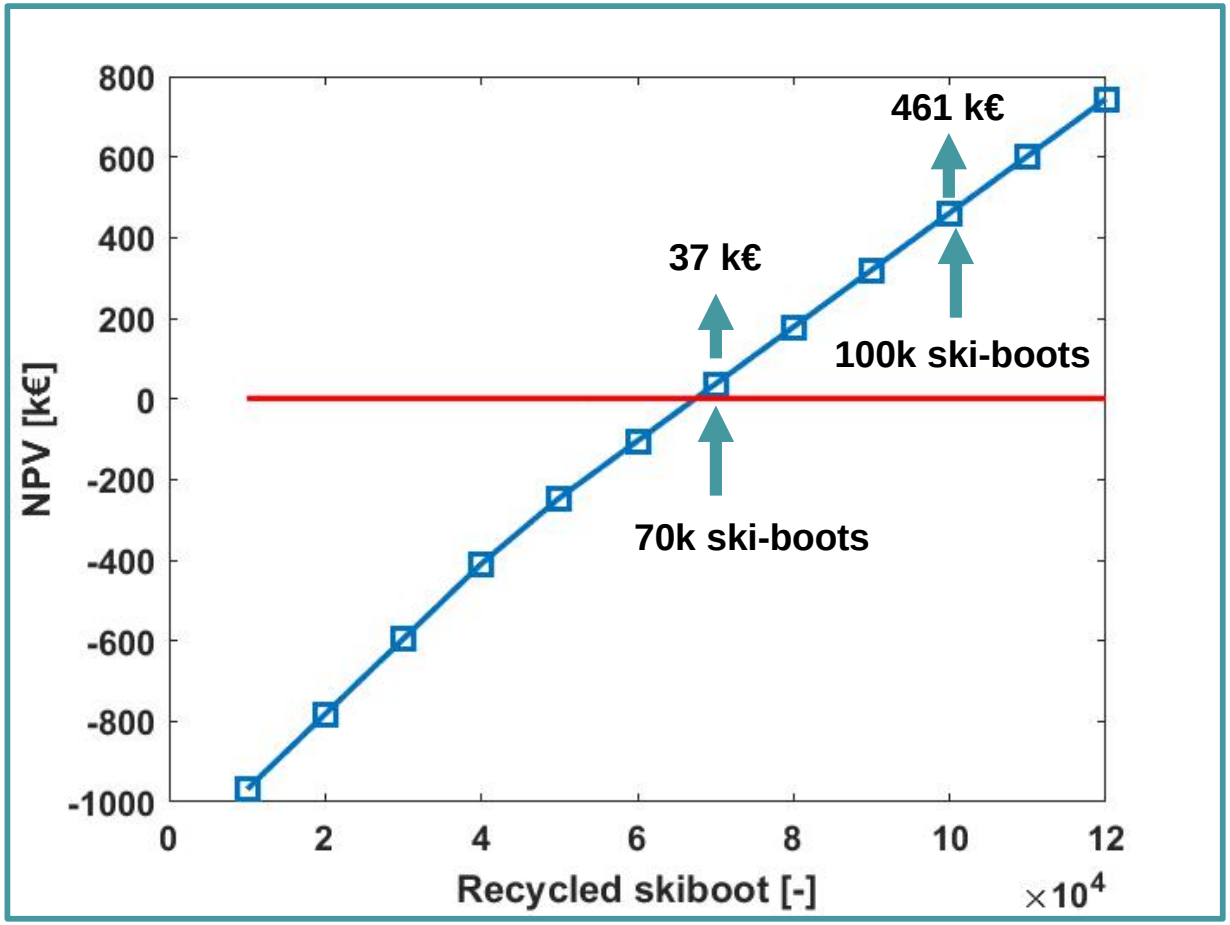
## Net Profit (processes) - Extrusion with vTPU




- The recycling processes are profitable when **30k ski-boots** (0,3%) are recycled and P ranges between 13 k€ (vTPU=50%) and 23 k€ (vTPU=0%)
- When 100k ski-boots are recycled (1,4%), the net profit ranges between 210 k€ (vTPU=50%) to 219 k€ (vTPU=0%).

# Techno-Economical Analysis

## NPV (plant) - No extrusion

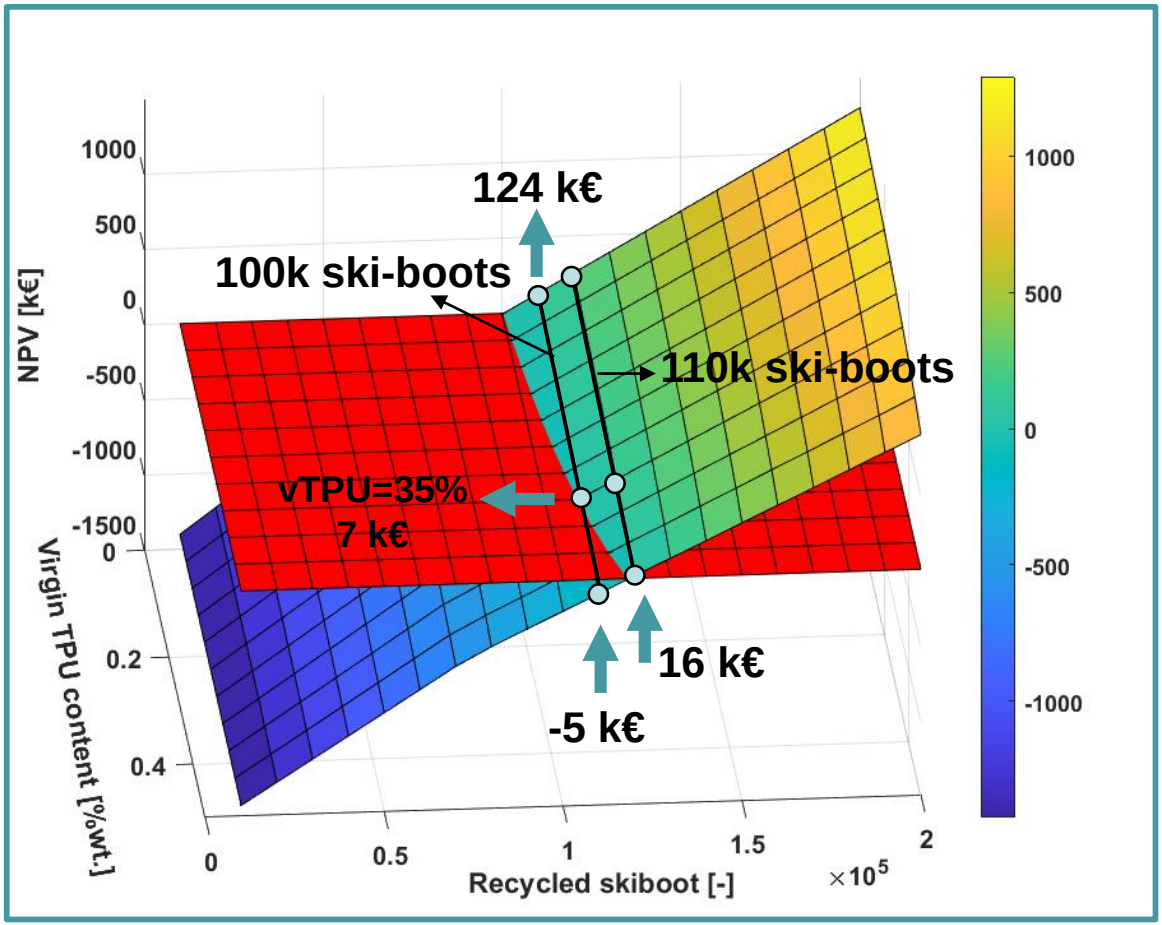



- The recycling plant is profitable when **70k ski-boots** (1,0%) are recycled

**Total Investment Cost ≃ 1,0-1,2 M€**

# Techno-Economical Analysis

## NPV (plant) - Extrusion with vTPU




- The recycling plant is profitable when **100k ski-boots** (1,4%) are recycled and vTPU is <35% or when **110k ski-boots** (1,6%) are recycled and vTPU is >35%.

**Total Investment Cost ≃ 1,2-1,5 M€**

# Conclusions

The number of recycled ski-boots (input raw material) affects the economic profitability much more than the use (or not) of vTPU

Recycling processes become profitable when **20-30 k** ski-boots are collected (**third-part processes**) but an apposite recycling plant should be build-up only when at least **70k** (in case of direct sell of rTPU) or **100-110 k** ski-boots (in case of extrusion of rTPU with vTPU) are collectable.

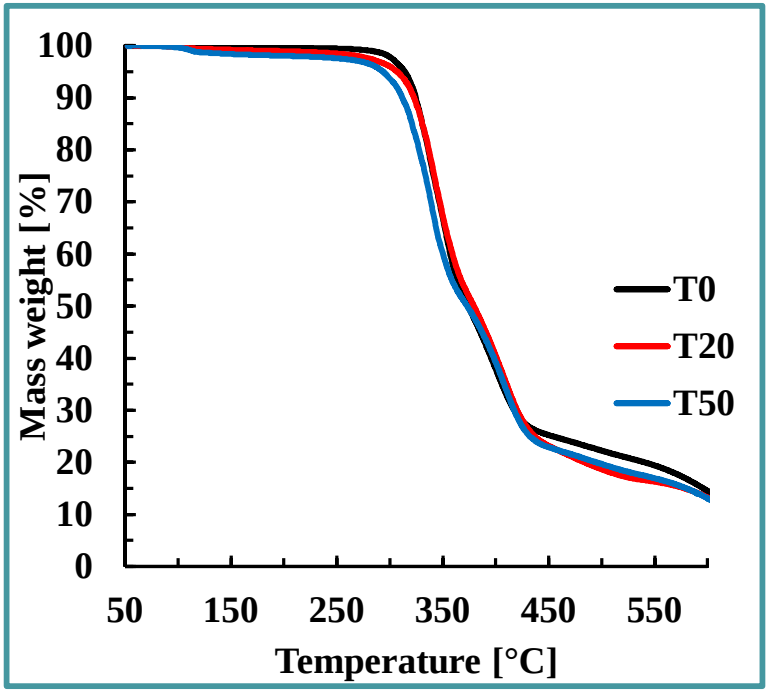
**Alessandro Nanni, PhD**
alessandro.nanni18@unibo.it

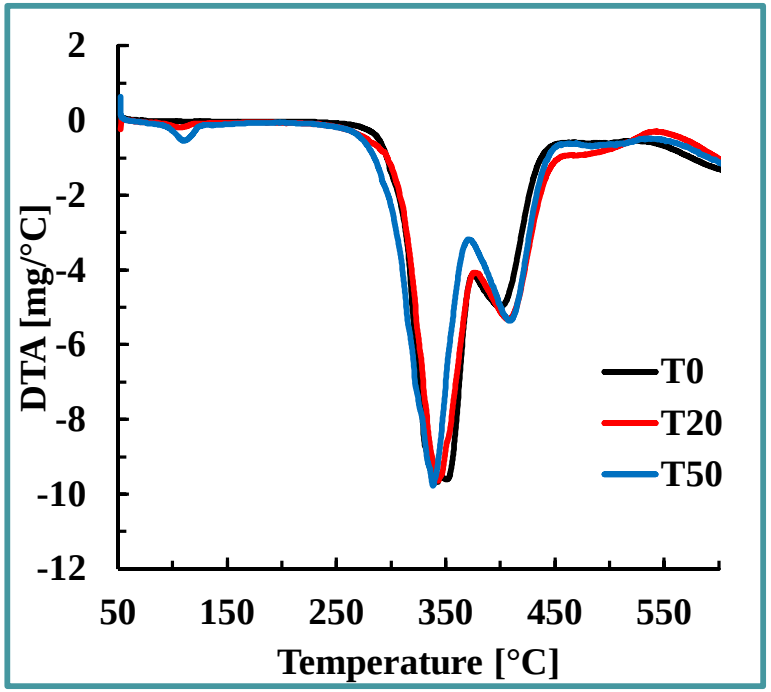

LIFE19 ENV/BG/000059

# LIFE RESKIBOOT

# ThermoGravimetric Analysis

## t0-t20-t50

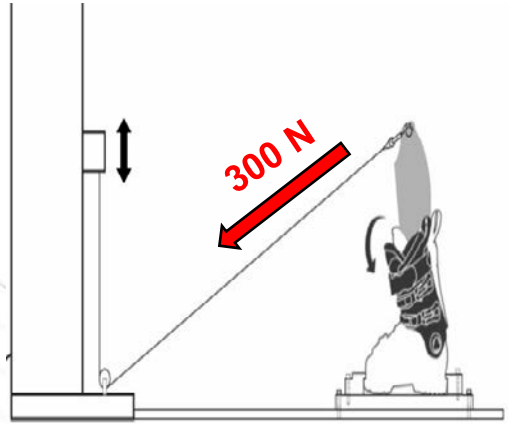



| | T5 [°C] | T10 [°C] | T15 [°C] | R600 [%] | Tpeak [°C] |
|---|---|---|---|---|---|
| R1-t0 | 314 | 325 | 331 | 14 | 342 |
| R1-t20 | 307 | 323 | 331 | 13 | 343 |
| R1-t50 | **294** | **312** | **321** | 13 | **338** |

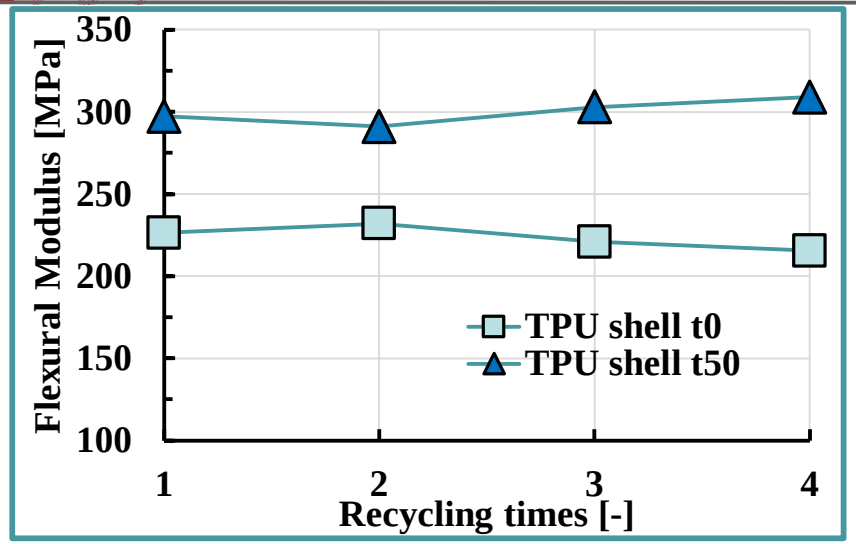
t20 and t50 have the TGA curve left-shifted of 5-10 °C as consequence of possible degradative phenomena

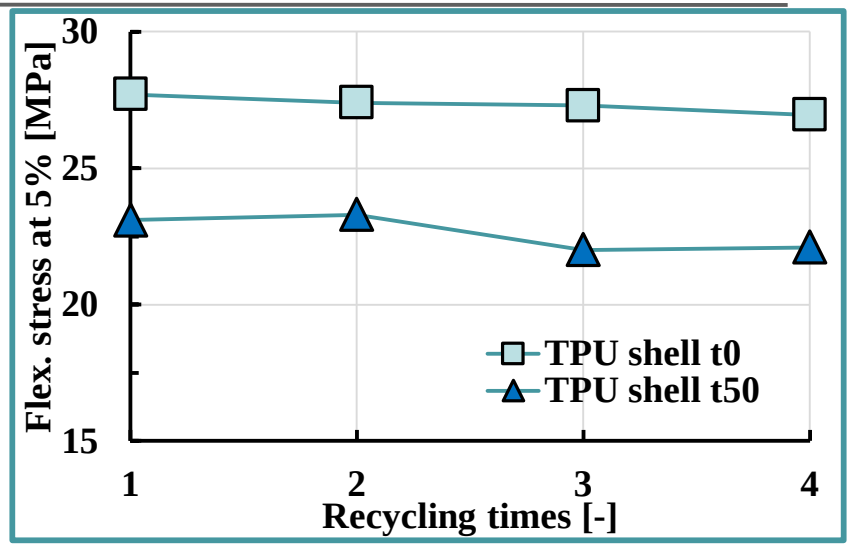
# Flexural tests
*(t0-t20-t50)*

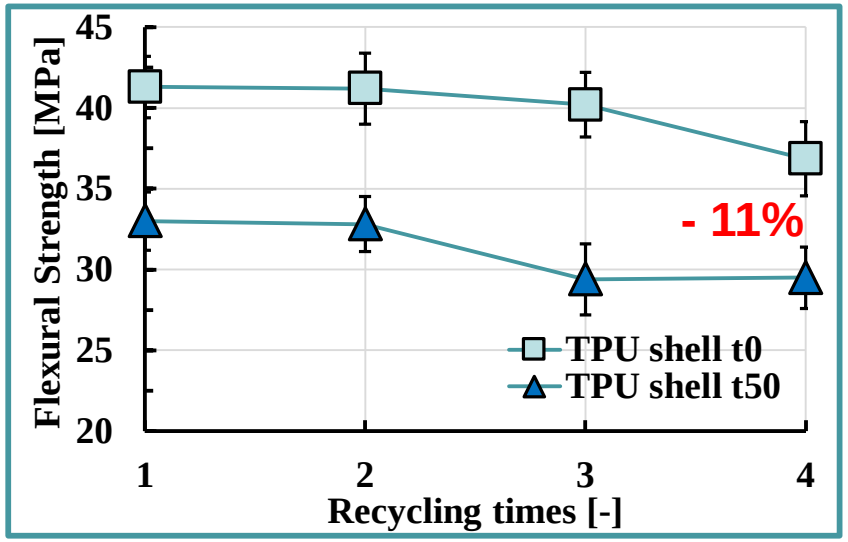


# Flexural properties

## Recycling of t0 and t50



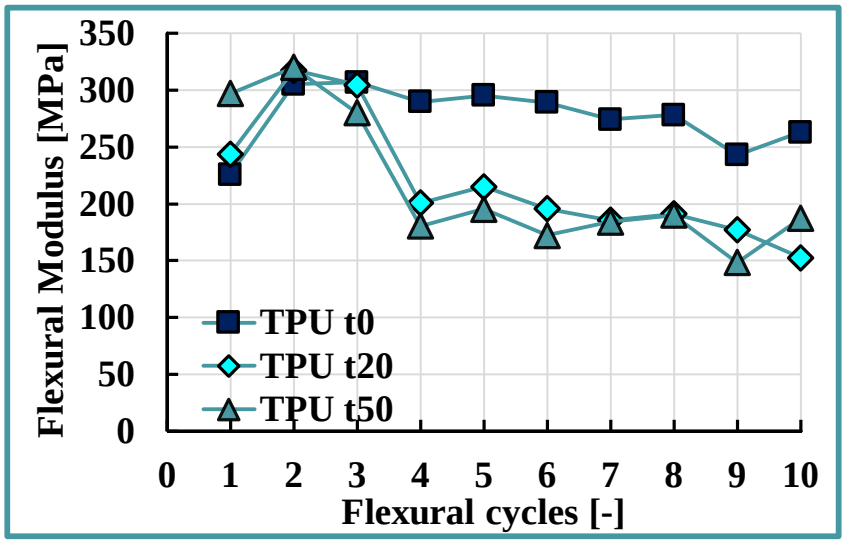



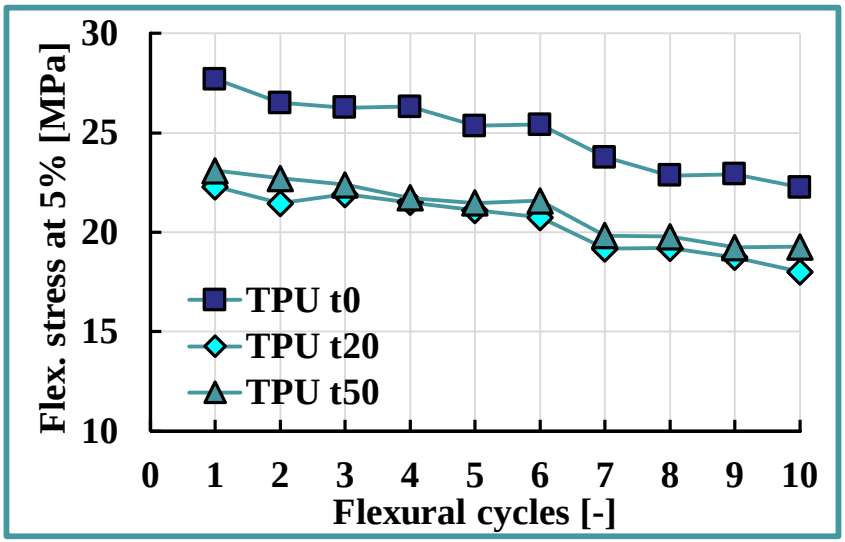



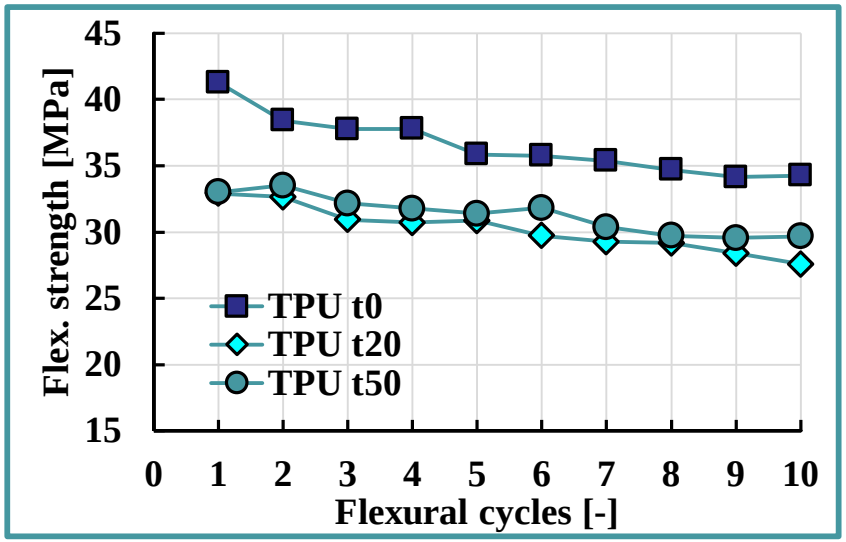

**Flexural properties do not significantly decrease with the number of recycling steps.**

# Flexural properties

## Flexural consecutive cycles t0-t20-t50



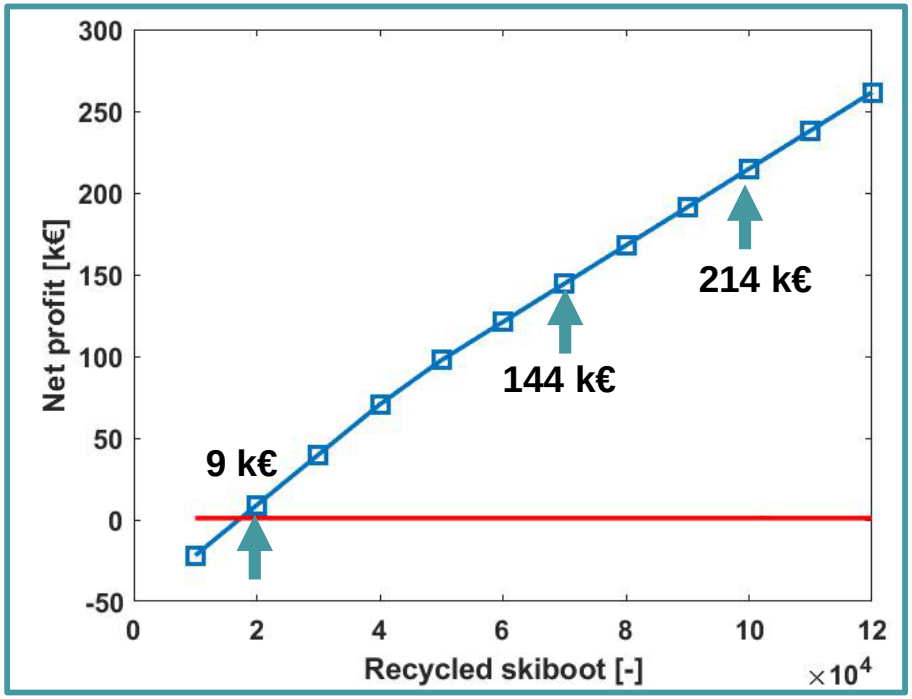



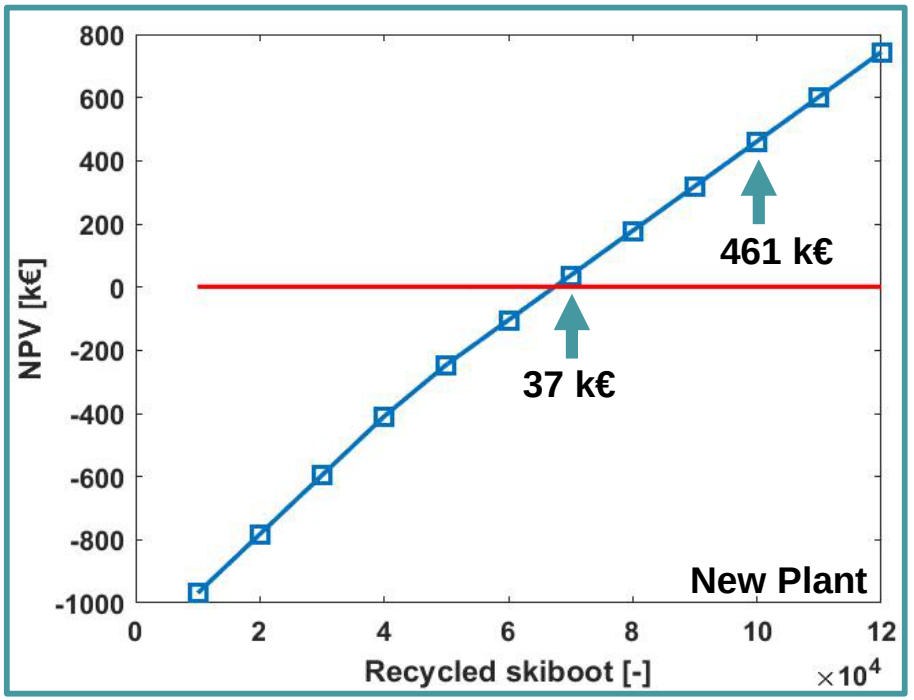

**During the first 3-4 cycles TPU became stiffer and then it starts to lose flexural properties**

# Techno-Economical Analysis

## Approach 1: No extrusion

**Total Investment Cost ≃ 1,1 M€**




The Net Profit:

- >0 when 20k ski-boots (0,3%) are recycled
- =144k€ when 70k ski-boots (1%) are recycled
- =214 k€ when 100k ski-boots (1,4%) are recycled

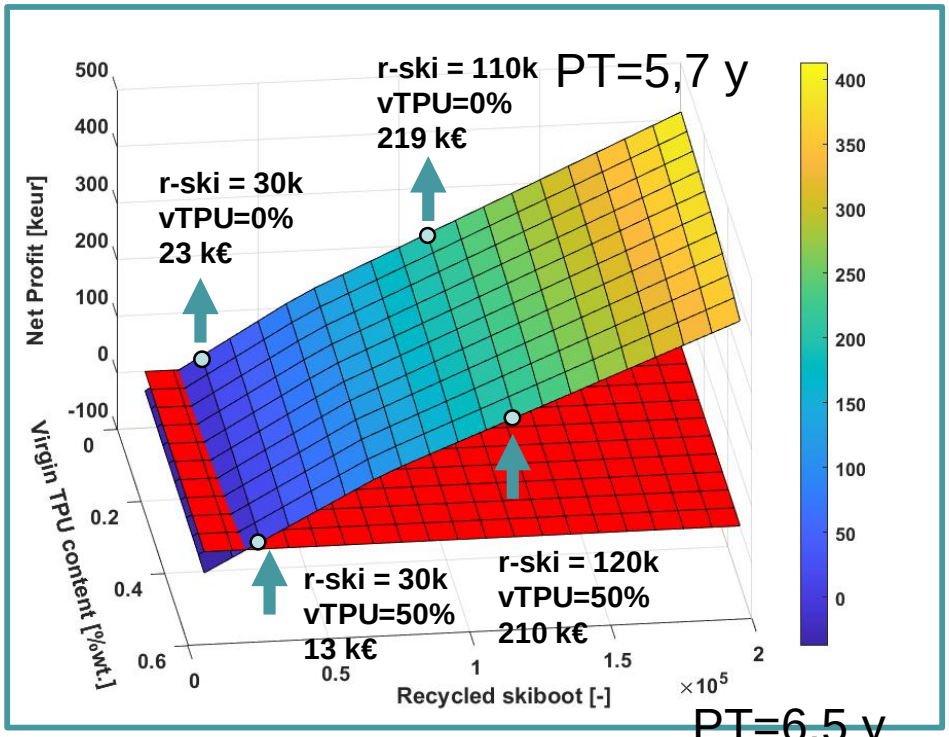
The NPV:

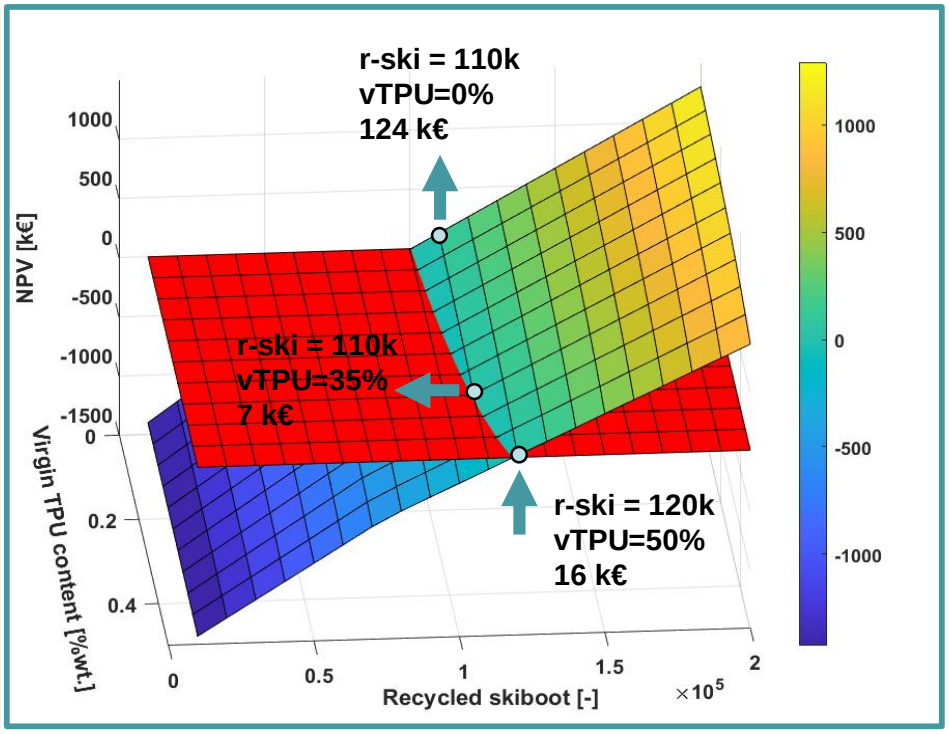
- =37k€ when 70k ski-boots (1%) are recycled
- =461 k€ when 100k ski-boots (1,4%) are recycled

# Techno-Economical Analysis

## Approach 2: Extrusion of vTPU

**Total Investment Cost ≃ 1,2-1,5 M€**




The net profit:

- >0 when 30k ski-boots (0,4%) are recycled
- =144k€ when 70k ski-boots (1%) are recycled
- =214 k€ when 100k ski-boots (1,4%) are recycled

The NPV:

- >0 € when 110k ski-boots (1,6%) are recycled and vTPU<35%
- =461 k€ when 100k ski-boots (1,4%) are recycled

# An ecological transition


Raw materials

Processing & assembling

How switch from linear to circular lifecycle?

Recycling processes

Skiboot product

Collection

Lifetime

Endlife