A Design for Circularity Case Study: Replacing PVC in temporary information carriers

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Abstract

Short-lifetime information carriers are printable surfaces like roll-up banners or temporary panels. Typically, these carriers are made out of PVC, as this material is cheap and easily printed upon. However, when PVC ends up in mixed plastic waste, it is known to have a very negative impact on the recyclability of such commingled plastics. As such, currently these carriers are at best incinerated after their short lifetime. Within this research, it was investigated if PVC carriers could be replaced with more sustainable PP alternatives. The carriers were successfully tested for printability and user experience, after which their mechanical recyclability was investigated. To be able to send the material to a closed-loop application, successful de-inking of the printed layer was achieved.

LCA was conducted, comparing the base PVC and PP (1 lifetime, incineration) scenarios as well as a closed-loop (including de-inking) and two open-loop mechanical recycling scenarios for PP. It was found that in all cases, PP is more sustainable than PVC. One of the open-loop scenarios was revealed to be the overall most sustainable option, due to the larger impact of the de-inking process required for closed-loop recycling.

Keywords: plastics, circular economy, mechanical recycling, LCA

1. Introduction

This case study focuses on improved circularity for two types of indoor temporary information carriers: the roll-up banner and the rigid plastic panel, shown in Figure 1.

Figure 1: examples of the case products: a temporary rigid information panel (left) and a roll-up banner (right).

Such products are typically used for a short period of time, like a multi-day event or an advertisement campaign. They are most commonly made in polyvinyl chloride (PVC), which is then printed upon. PVC is cheap, robust and easy to print upon. Takeback schemes for these products are extremely rare. After their short lifetime, they are either disposed as mixed waste (for incineration) or end up in mixed solid plastic waste (SPW). It is known that in the (mechanical) recycling of such mixed SPW streams, the presence of PVC will be detrimental to the properties of the regenerated plastic, due to the development of HCl (Brebu et al., 2004)(Paci and La mantia, 1999). Therefore, for the information carriers to achieve any kind of circularity, a replacement material needs to be found for PVC in this application. This substitute materials must be as easy-to-use (robustness and printability) as PVC, allow for the same type of user experience and be recyclable through existing or nascent collection schemes.

In the current research, we have conducted a market study of potential – commercially available – replacement materials for PVC as a temporary information carrier. From the market study, mono-material polypropylene (PP) alternatives were selected for evaluation. As a rule, monomaterials can be recycled to a higher quality level than multilayered products (Ragaert et al., 2017). Moreover, PP is one of the most ubiquitously used and recycled polymers (Al-Salem et al., 2009), which would allow these products to join existing recovery schemes for PP. The PP alternatives were tested for mechanical properties, mechanical recyclability ('as is' and after de-inking) and evaluated in life cycle analysis (LCA). As a reference for all properties, they were compared to the currently used PVC products.

2. Material and methods

The general flow of the research is shown in Figure 2. Selected PP alternatives for banners and panels were measured in terms of composition and mechanical properties. Printed versions were subjected to user experience evaluation and sent to mechanical recycling, which comprised shredding, (optional) de-inking and further processing. Processing via extrusion to sheet was considered representative for closed and semi-closed loop recycling, injection moulding of test bars (after pelletizing via extrusion) was considered representative for open loop recycling. Resulting products were evaluated for tensile properties and all results were fed into an LCA, for comparison to the conventional PVC alternatives.

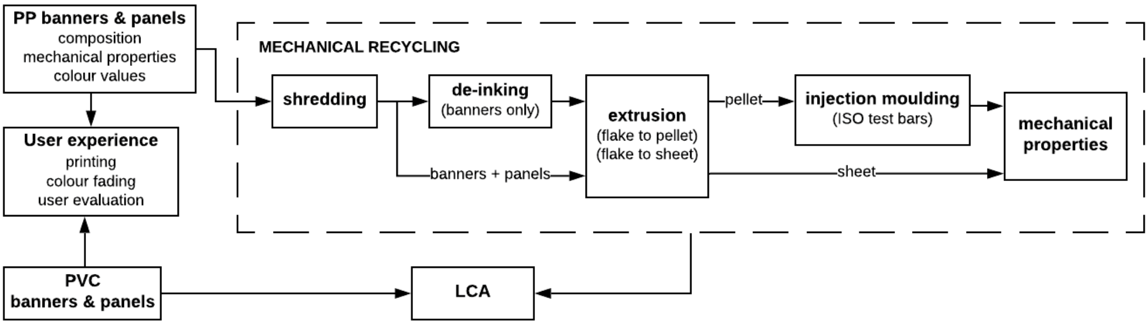


Figure 2: flow of the research

2.1 Information carriers and printing

Out of 22 temporary information carriers, selected as potential candidates for ecological solvent digital printing, a rigid panel and a non-silverback banner were chosen as representative test specimen for indoor information carriers. Both were advertised as monomaterial PP. As reference materials for the user experience experiment a classic PVC banner and panel are chosen. All evaluated products are summarized in Table 1.

Table 1: Overview of the used materials.

product	Tradename (supplier)	Thickness (µm)	Surface mass (g/m²)	Description
PVC banner	D-line Frontlit 510 (Frontlit)	400	510	Internal mesh by weaving and covered with cast PVC
PP banner	Solvent PP Film 220 (Emblem)	220	183	Cast film with universal coating
PVC panel	FOREX Lite (Thyssenkrupp Plastics)	8000	4800	foamed flexible PVC panel with glossy surface
PP panel	Kibo-X (Infinex)	8000	2000	Sandwich panel: full outer layers with x-shaped internal spacer structure

All materials were acquired by the printing company Karakters (Ghent, Belgium) and kindly donated to Ghent University by them. UV cured inkjet printing was performed on a HP Latex 570 Printer with water based latex ink (HP 831/871 Latex Inks). Standard base colours were printed on 40 m of the PP banner virgin for testing, followed by a visual inspection of the print quality.

2.2 Composition

The exact material composition of the PP banner and of the PP panel was determined using FTIR (Tensor 27, Bruker), DSC (Polyma 214, Netzsch), density measurement (mass replacement method ISO 1183: 2011, Precisa) and scanning electron microscopy (SEM) (Phenom table top G1, Phenom).

2.3 User experience

For the panels, a user poll was set up during a local festival (Gentse Feesten 2018, Ghent), using a three-question list and 200 respondents, testing the public perception on perception-of-quality, willingness-to-pay and on the importance of sustainability in the city,

for the PP panel, compared to a common PVC panel. The PP panel served a temporary public signalling function.
For the banners, colour values of printed (PP and PVC) surfaces are measured using the D65/10° method on Colorflex EZ (Hunterlab) for banner samples before and after UV radiation in a 'worst case' scenario: for 211 hours, which is the equivalent for 10 weeks of outdoor sunlight. Colour values before and after are given as Lab values.

2.5 Mechanical recycling

All materials are reduced to flakes on a Piovan type RSP15/30 shredder (Piovan group, Italy) with sieve diameter 8 mm. Part of the banner materials were subjected to a proprietary de-inking process to obtain clean white flakes.
Prior to further processing all shredded material is dried in a hot air dryer (Farragtech card 40E, Austria) at 80 °C for 3 h. Sheet extrusion and pelletizing was performed on a single screw extruder (Brabender 19 Plasticorder) with a 150*0.7 mm^2 slit die and a 2 mm (diameter) round filament die respectively. For sheet extrusion, screw speed was set at 70 rpm and the barrel temperature profile at 170-185-200-210-210 °C. Further injection moulding of testbars with the pellets was performed on an injection moulding machine with 280 kN clamping force (ENGEL 28T), using a ISO 527-type 1A test-specimen mould. The barrel temperature profile was set at 230-230-220-210 °C with an injection speed of 125 mm/s, injection pressure of 800 bar, 4 s of holding pressure (200 bar) and 20 s of cooling time at 25 °C.

2.6 Mechanical characterization

Tensile testing was performed on the injection-moulded test bars and on die-cut ISO tensile test bars for the new products as well as the sheet-extruded recyclates.
All samples were conditioned at 23 ± 1°C in 50 ± 10 % relative humidity and tested according to ISO 527-1:2012 on an Instron 5565 tensile apparatus with Bluehill 2.0 software.
Results are reported as the mean ± standard deviation for at least seven measured specimens.

2.7 LCA

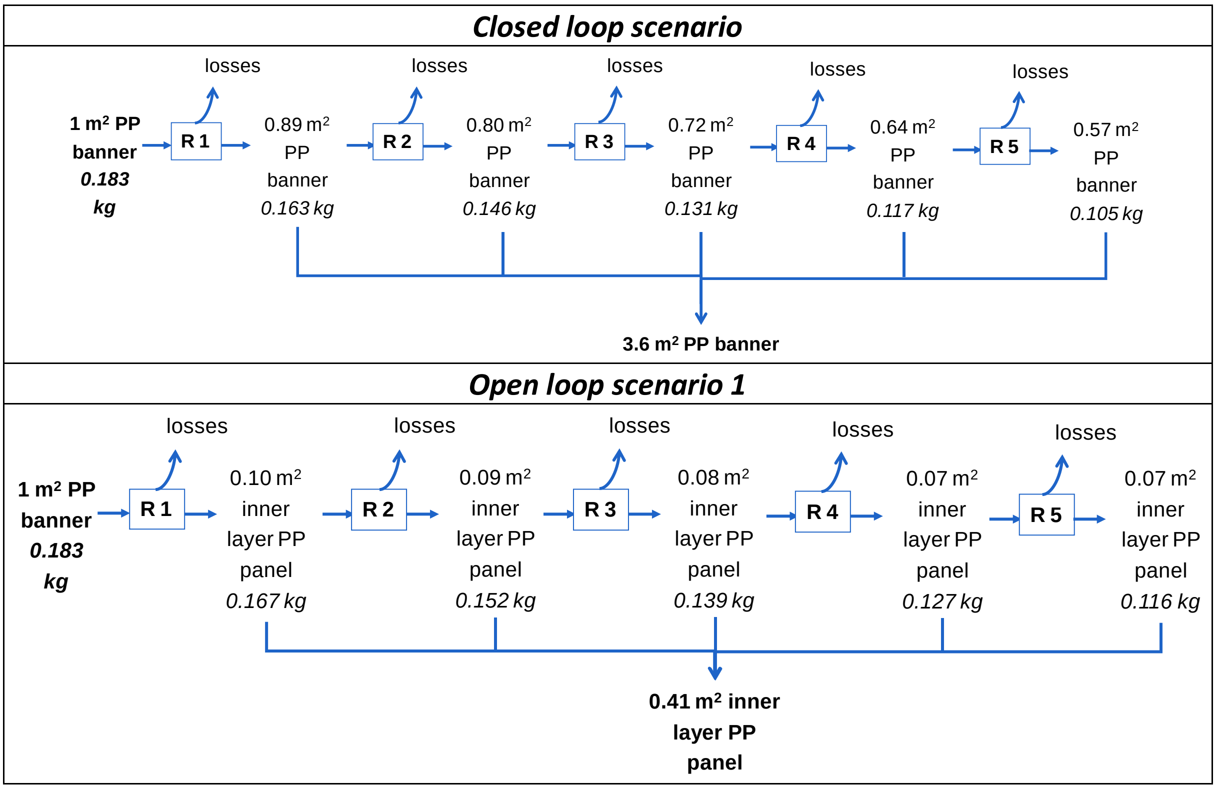
Several recycling scenarios are defined for the PP banners and panels. For the recycling scenario's, the number of recycling loops is set at five. The scenarios are:

- PP scenario: the products (banners/panels) are produced from virgin PP and disposed as the PVC alternatives (i.e., incinerated);
- Closed loop scenario: the banners/panels are produced from virgin PP and follow several recycling loops which involves shredding the banners/panels, de-inking, extrusion into pellets and extrusion into new product (banners/panels). When all the recycling loops are completed, the products are incinerated;
- Open loop 1: the banners/panels are produced from virgin PP and are recycled without de-inking to produce the inner layer of twin-wall panels. The produced panels are themselves recycled to produce the inner layer of new panels. When all the recycling loops are completed, the panels are incinerated;
- Open loop 2: the banners/panels are produced from virgin PP and are recycled as garden furniture. At the end of its lifetime, the furniture is incinerated.

Data inventory was made in collaboration with The Center for Polymer and Material Technologies (CPMT) and the Laboratory of Industrial Water- and Ecotechnology (LIWET) of Ghent University. The Ecoinvent database (v3.3) is used to model the background processes. The impact on Climate Change and Resource use are assessed based on the IPCC GWP 100 method (IPCC, 2013) and the Cumulated Exergy Extraction from the Natural Environment (CEENE) version 2013 method (Alvarenga et al., 2013), respectively.

The mass flow of two of these scenarios is illustrated in Table 2.

Table 2: Mass flow and associated product area produced along the recycling loops (R) of the Closed loop and Open loop 1 scenario of the banners.



3. Results and discussion

3.1 Composition of the PP alternatives

While both the banner and panel are advertised as being pure PP, composition analysis reveals that neither of them is. FTIR and DSC analysis (not shown) of the banner showed that it is coated with a top layer of PMMA, most likely to improve printability of the surface. This top layer makes up 11 m% of the whole. The banner was likewise coated with a thin PPMA layer, which made up only 1 m% of the whole (thicker, heavier) product. PMMA is typically used in thin films such as banners as an anti-reflecting coating layer with a good adherence of water based latex ink (Hamdy, 2016).

Density values of 1.050 ± 0.004 g/cm³ for the PP banner virgin and 0.950 ± 0.006 g/cm³ for the PP panel virgin are significantly above those values typical for PP and just the PMMA top layer cannot account for this. SEM images (not shown) clearly revealed the presence of scaled plates of talcum, most likely in combination with much smaller calcium carbonate spheres. It is safe to state that the PP of both the panel and the banner are filled with talcum and/or $CaCO_3$, both of which are common and cheap fillers for PP (Leong et al., 2004). An adverse effect to recyclability is expected from the immiscible PMMA, especially in the banners, where it makes up a significant part of the overall composition.

3.2 User experience

User evaluation

Out of the 200 respondents, over 60% expressed that they did not see any difference between the PP and PVC panels, whereas about 25% considered it more beautiful and 10% less beautiful than the PVC version. When asked, a staggering 98% of the respondents would choose a more expensive but recyclable alternative (the PP panel) over the cheaper non-recyclable PVC panel. Moreover, over 70% of the people in the user poll regarded a municipality's commitment to sustainability as (very) important, while remaining sceptical about the cost of a transfer to more green alternatives.

Loss of colour over time

For both PP and PVC printed banners, a light, bright and dark colour were evaluated before and after UV treatment (Lab values shown in Table 2). Typically, the appearance of the colour yellow is associated with degradation within polymers and the discoloration of light colours towards the yellow region is perceived by the public as a loss of colour persistence/quality.

Table 3: Lab values and observations of the banners before (PP and PVC) and after (PP_UV and PVC-UV) UV treatment.

	Light colour				**Bright colour**				**Dark colour**			
	PP	**PP_UV**	**PVC**	**PVC_UV**	**PP**	**PP_UV**	**PVC**	**PVC_UV**	**PP**	**PP_UV**	**PVC**	**PVC_UV**
L	85,3	84,8	86,9	84,5	61,7	63,1	83,6	85,0	11,4	15,5	14,1	17,5
a	0,8	-0,5	-1,9	-2,8	-35,6	-31,0	-3,7	-4,6	0,1	0,0	0,0	-0,2
b	-3,6	2,2	-5,7	0,1	44,6	36,5	-12,0	-7,8	-2,0	-2,7	-0,7	-1,0
	More black, more yellow				More white, less yellow		More white, less blue		More white, more blue			

The PP and the PVC banner materials showed a similar discoloration pattern for light and dark colours, with L values moving towards the black region and b values moving towards the yellow region for light coloured banner materials, whereas L values showed a loss in blackness and an increase in blue colours for the dark banner materials. PP and PVC banners in bright colours both regressed into lighter regions upon UV exposure, whereas the b values decreased for the PP banner and increased for the PVC banner. In general, the changes in colour, expressed by Lab-values, due to UV exposure can be considered similar for both PP and PVC banner material. The same trend was present for PP and PVC panels (results not presented).

3.3 Mechanical recycling

De-inking of the banner materials proved successful to obtain clean white flakes, as shown in Figure 3. Furthermore, the PMMA top layer was delaminated (for both banners and panels) by this treatment, thus delivering a purer PP, for which improved recycling quality is expected.

Figure 3: banner flakes before, during and after de-inking.

Figure 4 shows the mechanical properties of the banners before and after recycling; for both de-inked and 'as is' recycled flakes. It must be noted that sample preparation is different between these samples: the properties of the printed banners were tested on ISO bars die-cut from the banners. The samples for the extruded recycled sheets were likewise die-cut. Note that the extruded sheet has a much larger thickness than the banner. The test bar samples were injection moulded and had a thickness of 4 mm.

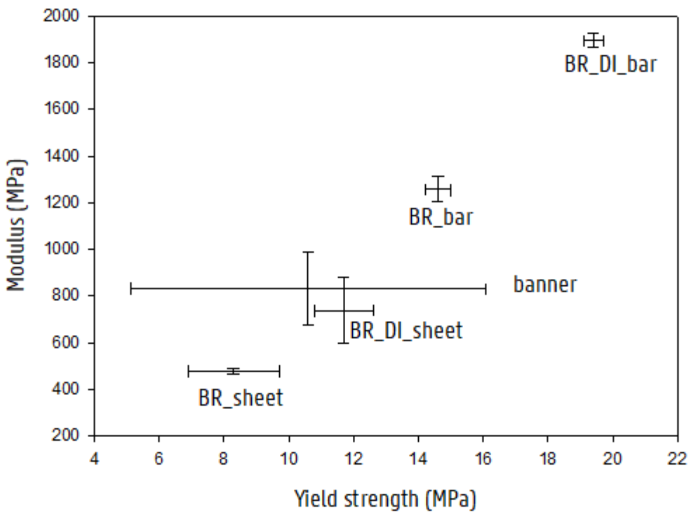


Figure 4: Tensile mechanical properties of the different banner materials: as delivered printed banner (banner), recycled banner material into extruded sheet (BR_sheet) or injection moulded test bar (BR_bar), recycled and de-inked banner material into extruded sheet (BR_DI_sheet) or injection moulded test bar (BR_DI_bar).

In Figure 4, it can be observed that the variations on the base results are quite high for the printed banner (with the top layer), most likely due to uneven straining behaviour between the two polymers PP and (far stiffer) PMMA. Once the materials are blended in the recycling step, PP is expected to become the matrix, in which the immiscible PMMA will be dispersed (Paul, 2009). We can observe a negative effect on mechanical properties for the extruded sheets (BR_sheet), despites PMMA being a strong and stiff material in comparison to PP. This leads us to believe that the PMMA is not contributing to the material's deformation behavior and acts as voids instead. The de-inking procedure, having removed not only the inks but also the PMMA top layer, causes a significant improvement on the modulus for the extruded sheets (BR_DI_sheet).

Results for injection moulded recycled materials are remarkably better than for extruded sheets. This is attributed to two elements: (1) Injection moulding is a high-pressure processing technique in a closed cavity, allowing for more packing of material in the parts and (2) the recycled flakes were repelletized via extrusion prior to injection moulding, thus allowing for better homogenization of the compounds. Furthermore, it may be observed that for the moulded bars, the de-inking process has an even stronger beneficial effect, leading to mechanical properties of high-quality PP. However, even by processing ‘as is’, typical properties for virgin PP are achieved by injection moulding, leading us to expect that this regranulate could be sold easily as PP regrind, only requiring the de-inking when colour neutrality is required.

Figure 5 shows the mechanical testing results for the panel materials. Once more, there is a large variation for the as delivered printed panel. The effect of the second PMMA/ink layer is expected to be smaller here, as the relative layer thickness is much lower than for the banners. However, the samples did need to be cut so as to include only a full outer layer of the panels, which leaves room for variations due to the manual cutting. Note that the PP used for the panels is most likely not the same as the one used for the banners, as these come from entirely different processes. Therefore, comparison between both product types are not relevant for the mechanical properties.

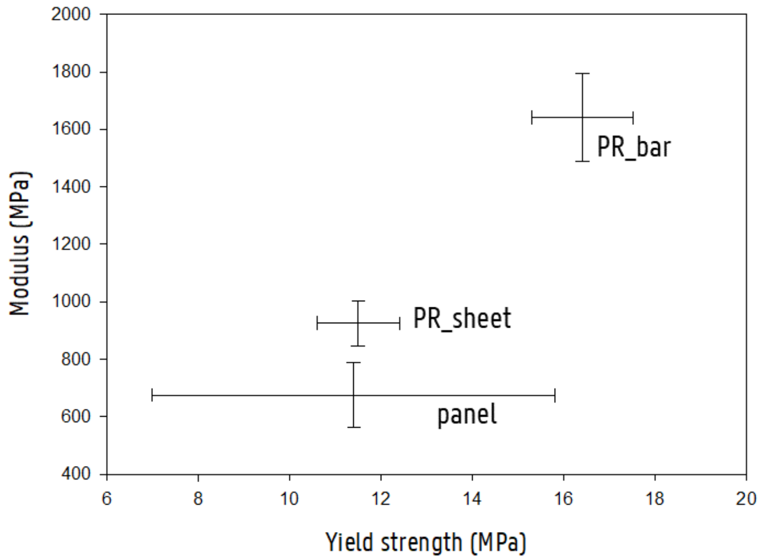


Figure 5: Tensile mechanical properties of the different panel materials: as delivered printed panel (panel), recycled panel material into extruded sheet (PR_sheet) or injection moulded test bar (PR_bar).

As with the banners, it can be observed that injection moulding yields significantly better properties than extrusion. Even without de-inking, the panel material can be processed into products with properties alike to high quality PP.
It may be concluded that the technical quality of the recycled materials is sufficient for re-use in new applications.

Figure 6 shows the visual quality of injection moulded parts with the (not de-inked) banner and panel materials.

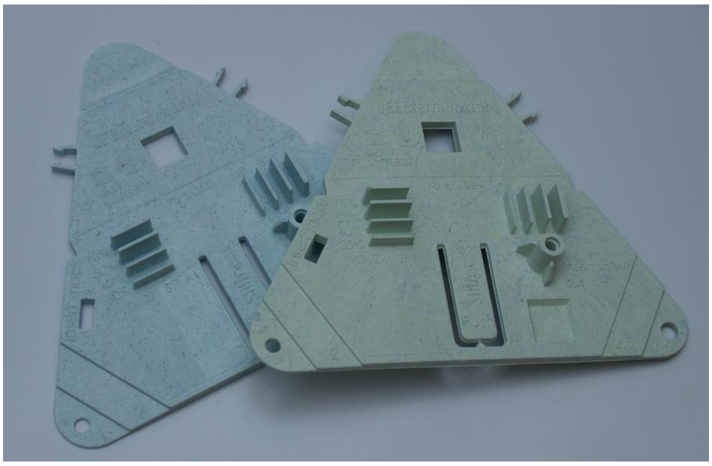


Figure 6 (left): Injection moulded parts with (left) recycled banners and (right) recycled panels.

Figure 7 (right): granulate and extruded sheet from de-inked banner material.

The colour effects are visible, but well homogenised. Depending on the application, these may very well not pose an issue at all. Such would be the case for the open loops scenarios, allowing them to avoid the environmental cost of de-inking, which would only be required for closed-loop recycling. The visual quality of the de-inked material is shown in Figure 7.

3.4 LCA

Banners

The results of the impact of the banners on Climate Change are presented in Figure 8.

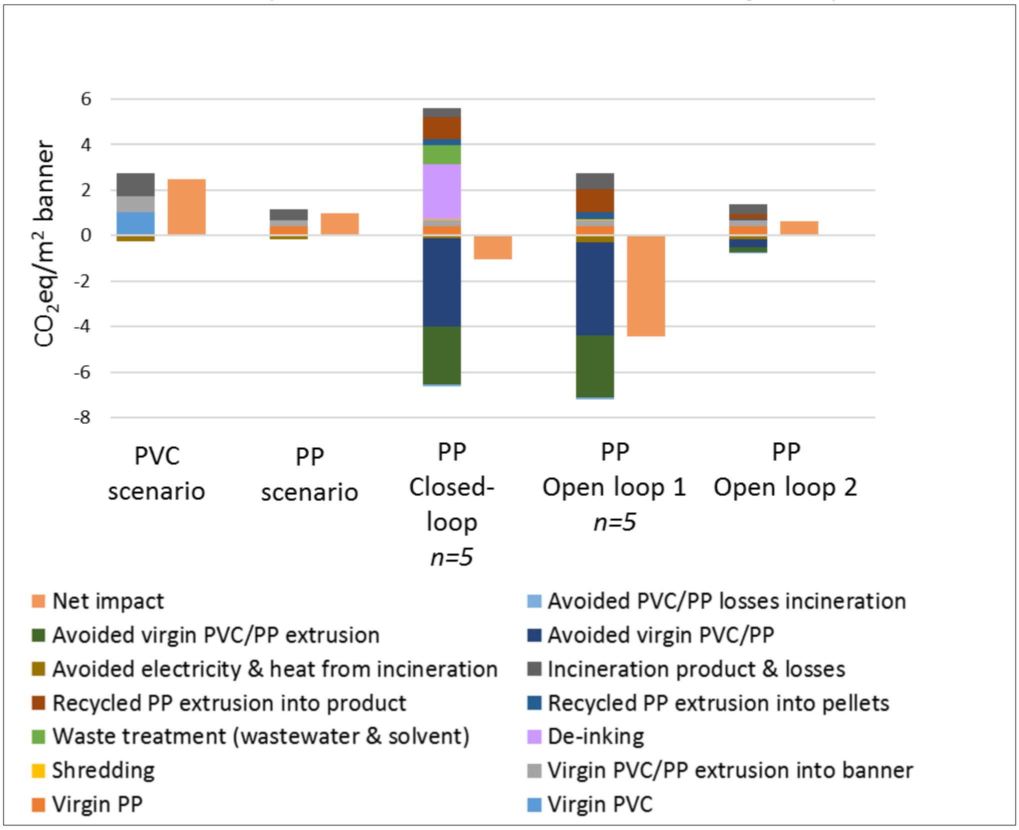


Figure 8: Global Warming impact of the five banners scenarios.

The main contributors of the PVC scenario are the production of virgin PVC (38%), the incineration of the product at the end-of-life (37%) and the extrusion of the PVC into banners

(25%). The main contributors of the PP scenario are similar, the first contributor being the incineration of the product (42%), the production of virgin PP (35%) and the extrusion of the PP into products (23%). The net impact of the PVC and PP scenario are 2.5 and 1.0 kg CO_2eq m^{-2} banner, respectively. These two scenarios have the highest net impact, as the closed loop, open loop 1 and open loop 2 scenarios have an impact of -1.0, -4.4 and 0.6 kg CO_2eq m^{-2} banner. However, it shows that simply replacing PVC by PP in single use banners has the potential to decrease by more than 60% the impact of the banner on climate change. This is due to the lower density of PP compared to PVC, which results in the use of less material in the PP banners (0.19 kg m^{-2} PP banner against 0.49 kg m^{-2} PVC banner).

The Closed loop scenario is the scenario with the highest positive impact (5.6 kg CO_2eq m^{-2} banner). The main contributor is the de-inking process (2.4 kg CO_2eq m^{-2} banner), mainly due to the drying step (50% of the de-inking impact) and the production of the solvent (37%). The following main contributors are the extrusion of the PP into new banners along the five recycling loops (17%) and the disposal of the solvent (15%). This positive impact is outbalanced by the avoided impact (-6.6 kg CO_2eq m^{-2} banner), 58% of which is due to avoiding the production of virgin PVC from the recycling of the PP banners into new banners. 38% of the avoided impacts is due to the avoided extrusion of this PVC. The net impact of the Closed loop scenario is -1.0 kg CO_2eq m^{-2} banner. This negative number does not mean that the banners represent a sink of emissions: it means that compared to the benchmark scenario (i.e., the production of PVC banners), the recyclable PP banners have a lower impact on Climate Change.

The Open loop 1 scenario shows the lowest net impact (-4,4 kg CO_2eq m^{-2} banner). While there is no impact from de-inking, the avoided impacts have the same order of magnitude than in the Closed loop scenario, which makes the net impact lower.

The Open loop 2 scenario has a net impact of 0.6 kg CO_2eq m^{-2} banner, making it the least preferable scenario among the closed and open loop scenarios. This lower environmental performance is due to the low avoided impact from avoiding PP instead of PVC in the two other scenarios. This conclusion might change if the recycled plastic-based furniture is assumed to replaced aluminum or wood-based furniture. However, recycled plastic-based furniture is more likely to displace the production of plastic-based furniture chosen by consumers because of its particular properties (e.g., lightness and easiness to clean).

Panels

The analysis of the panels considered the same scenarios as for the banners as well as an additional scenario which considers the option to produce cardboard panels. The results for Climate Change impact are presented in Figure 9. The order of magnitude of the results for the panels are higher than for the banners because panels require much more material per squared meter (-13.9, -43.4 and 5.4 kg CO_2eq m^{-2} panel for the Closed loop, Open loop 1 and Open loop 2 scenarios, respectively). However, the results profile of the PVC, PP, Closed loop, Open loop 1 & 2 scenarios is the same as for the banners. Therefore, the hotspot analysis of these scenarios is not further detailed here. The cardboard scenario appears to be the one with the lowest net impact (-61.1 kg CO_2eq m^{-2} panel). The Closed loop and Open loop 1 scenarios emit more greenhouse gases during the production process than the cardboard scenario. It is important to stress the fact that data for cardboard panels are taken from the ecoinvent database, which corresponds to processes developed at industrial scale. The efficiency of the recycling process, still at lab scale, is expected to increase when implemented at larger scale and when choices of industrial scale processes will have to be made, e.g., the replacement of batch deinking (current situation) by a continuous process.

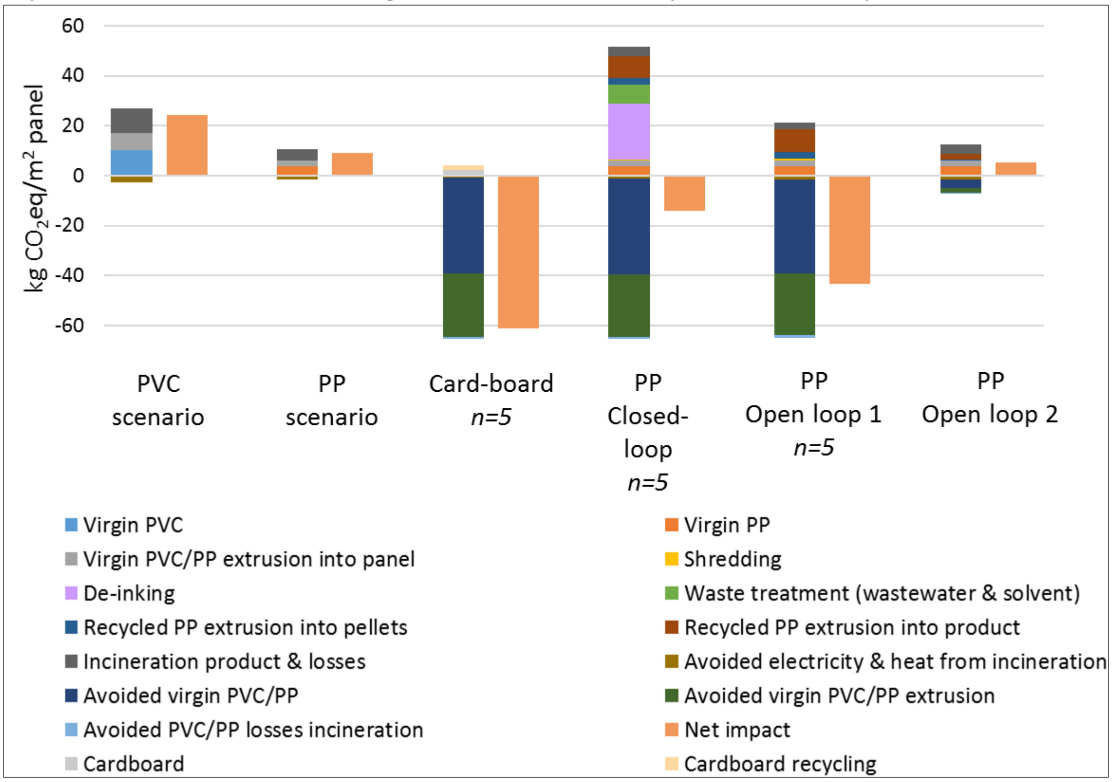


Figure 9: Global Warming impact of the six panel scenarios.

The comparison with the cardboard panels showed that from a pure environmental perspective, cardboard is a more interesting material than PP. However, the data used in the analysis were at industrial scale for cardboard and at lab scale for the panels. Therefore, the potential of efficiency improvement of the recycling processes should be further investigated to estimate its potential performance compared to cardboard. Moreover, cardboard is known to be less durable than plastic (folding of corners, fraying of edges…) and could never be used in an outdoor application, whereas PP is quite weather resistant.

4. Conclusions

PVC banners and panels were successfully replaced with PP alternatives. User testing showed that consumers find them (at least) equally attractive to current PVC carriers and that discoloration due to UV exposure is expected to be no worse than that of those PVC carriers. These alternatives were found to be suitable for mechanical recycling towards closed or open loop applications. De-inking was possible and improved recyclate quality but needs to be balanced against the increased environmental cost of the de-inking process.

The impact on Climate Change was assessed and compared with benchmark scenarios. First, the results show that simply replacing PVC by PP in a single use product (no recycling loop) decreases the impact by more than 60%. Secondly, the open loop 1 scenario appears to be the most promising option among the three recycling scenarios. The Closed loop scenario is the second preferred option, due to the high impacts related to the de-inking process, especially due to the drying of the flakes and the use and disposal of the solvent. The recycling of the banner and panel into garden furniture is the least interesting option.

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