Heat-Pressure Lamination

Design exploration and fabrication with recycled polyethylene-foil, aka shopping plastic bags

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Abstract. Fabrication techniques and design potential of up-cycling plastic bags by heat-pressure lamination are explored. The material properties are tested and put into a digital design system. The main performance criteria is structure. Two design prototypes are being discussed. The first one is using a set of modular molds and a second one a techniques of inflated cushions resulting in shapes closely matching these in curved folding.

Keywords. Digital-low-tech; fabrication; up-cycling; structural analysis; curved folding; design exploration.

INTRODUCTION

This paper explores heat-pressure laminating techniques for recycled plastic bags in freeform construction. It looks at up-cycling waste material by creating raw plastic sheets form used polyethylene (PE) carrier bags. New fabrication techniques specific to the chosen material are proposed and its design potential is been explored. This process includes benchmarking the material properties and mapping out possible architectural applications by means of material testing, simulation and design exploration addressing architectural and furniture scale (Figure 1).

Plastic bags are widely used, hardly reused, and often they don't find their way into the recycling chain. In the developing world they are one of the cheapest building materials found in shanty towns (The Economist, 2012). The EU is planning to ban plastic bags, as only 50% of the material is recycled, bans are already in place in Australia and San Francisco (Robin Wood Magazin, 2010).

Their potential for up-cycling seems to be limited due to their relative small size and tendency to tear and puncture. Laminating layers of used PE bags into larger and thicker sheets creates the raw material for new fabrication techniques. These allow for an application to a wide range of forms at a comparatively low cost of material and production. In this paper two forming techniques are being explored. Firstly by a modular system of truncated blocks leading to faceted forms and secondly by a technique that features PU-foam inflated pockets resulting in forms very similar to curved folding.

THE MATERIAL

Plastics play an essential and ubiquitous role in our everyday life, for what the approximately 71 plastic
bags used in Germany per inhabitant in 2011 are just one example (Umweltbundesamt, 2013). Most plastics are polymer plastics. They are typically synthetic materials, most commonly derived from petrochemicals. The biggest share in all plastic products with 39.4% is allotted to packaging products. Therefore it is no surprise, that the six most used plastics are polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polystyrene (PS) and polyurethane (PUR), which are all – amongst other applications – processed to packaging materials. Together these account for around 80% of the overall plastics demand in Europe. Out of these six, polyethylene is with a share of 29% the most demanded plastic in Europe (PlasticsEurope, 2012). PE is class-divided into high-density polyethylene (HDPE), low-density polyethylene (LDPE) and linear low-density polyethylene (LLDPE). HDPE is used for products such as milk jugs, detergent bottles, margarine tubs, garbage containers and water pipes. Furthermore one third of all toys are manufactured from HDPE. LLDPE is used for cable covering, toys, lids, buckets, containers and pipes as well as in packaging; particularly film for bags and sheets. The majority of all plastic film applications such as plastic bags and film wrap are though from LDPE. The European demand of LLDPE and LDPE in 2011 was together 8.000.000 tons (PlasticsEurope, 2012).

The standard plastic shopping bags used as source material in this research are almost without exception made of low-density polyethylene (LDPE). They come in thicknesses of 50, 70 and 100µm. The melting point is between 135° - 140° C at which the material starts to bond well to many other materials and especially to other layers of the same material [1]. This property is used to melt layers of plastic bags into thicker sheets by applying heat and pressure at the same time. Experiments showed that the

Figure 1
Backdrop for an installation at NODE13.
application of only heat caused the material to curl and crimp. Therefore the shrinkage has to be countered by a flat tool, resulting in a smooth material build-up.

Shopping plastic bags come in various sizes and thicknesses. The developed technique of heat-pressure lamination can compensate this variety in source material since one can construct a specific area either from multiple smaller bags or less bigger bags and a specific thickness either from many thin or few thicker bags. Nevertheless very thin bags, like those one gets for fruits and vegetables in a supermarket, tend to tear much faster during the process of lamination and therefore the produced sheet material becomes perforated.

Another factor that influences the processability of the plastic bags are their typical prints. Some colours, particularly those that build a rather thick layer on the plastic bag, reduce the ability for layers of multiple plastic bags to bond together and form a continuous material build-up.

**TESTING HEAT-PRESSURE LAMINATION**

Initial test with a household flat iron proved already to be successful on smaller samples provided a non-adhesive paper was applied to protect the heat source from bonding with the molten material. Depending on the ground a second non-adhesive layer was placed between the sheets of PE-foil and the working surface. Up to four layers of material could be laid-up in one pass. With fewer layers the lamination process took less time, with more layers a smooth material build-up was not accomplished. The heat of the household iron turned out to be not sufficient for more layers per course. With each new course more layers can be added to a sheet, there are theoretical no limitations in thickness.

The thickness of the build-up is almost directly proportional to the layers used. A sample with 40 layers of 50µm thick PE-foil that should have been 2.00mm thick was 1.40mm to 2.00mm. A sample with 80 layers of 50µm thick PE-foil was 2.50mm to 3.80mm, whereby calculative it should have been 4.00mm thick. This shows that the imprecision increases with the amount of layers due to the increase in manual work courses.

The new material behaved at around 10 layers is like leather, and from 20 layers onwards like plastics sheets of a similar thickness. The sample with 80 layers showed board-like characteristics and didn’t resemble the source material any longer in haptic regards.

The material was laminated onto a range of forms, where tessellated convex shapes showed to be the most promising. All these forms required an adequate mold or counterpart to be laminated onto. On all curved or double curved surfaces the heat and pressure distribution with a flat iron or any other flat heat source is only linear or punctual respectively and therefore less efficient. Concave, curved moulds below a certain radius are not accessible with a flat heat-device at all.

**STRUCTURAL TESTING, SIMULATION AND BENCHMARKING**

First structural test were done on a sample strip of 50mm x 50mm of differently thick build-ups of 1, 2, 4, 8, 16 and 24 layers of 50µm PE-foil. These physical tests were assessing the bending behaviour. The flexing of the material under dead-load was tested. A sample with only 1 layer of 50µm, fixed horizontally, did sag entirely vertical within 0.5cm distance from the fixation, with no horizontal zone. A sample with 2 layers of 50µm cantilevered ca. 0.3cm horizontally and sag to a 30° angle only. A sample with 16 layers of 50µm – which means a material build-up of 0.8mm – showed only 0.3cm deflection over 5.0cm cantilevering and a sample with 24 layers of 50µm – which means a thickness of 1.2mm – didn’t show any deflection under dead-load with a cantilevering of 5.0cm (Figure 2).

Stretch-tear test were done as well, which proved that the application of heat and the build-up in layers didn’t change the material characteristics namely the Young’s-modulus. For these test samples of 100mm x 100mm with 1, 2 and 4 layers respectively were fixed linear on two opposing sides
and stretched in 5cm steps. The two non-fixated sides bent inwards but on all three samples with the almost identical shape. Only the force needed to stretch the samples increased according to the samples thickness (Figure 3).

Different formal features such as folds and curvature were physically and digitally tested to increase structural performance. In a second analysis cycle the physical test helped to calibrate the digital analysis. This was done with the linear dynamics engine Scan and Solve [2]. The process allowed for evaluating the structural performance of a digital 3d modelling, taking into account the actual material thickness. In an iterative procedure an object of a specific size and thickness – here 1575mm x 630mm with a thickness of 0.7mm or 14 layers of 50µm PE-foil – was tested, additional folds where created, the new geometry was tested again and results were evaluated against each other. The Figure below shows three instances of the geometric advancement whereby the last is used as one part of the backdrop partition wall described later. Comparative physical test proved the increase in rigidity implied by the reduction of total displacement exhibited in the digital Scan and Solve model. The load
case illustrated below denotes horizontal- or wind-
loads perpendicular to the longer side of the geom-
etry (Figure 4).

This was further developed into an optimization
cycle where the designer could locally optimize for
the number of layers put into the material in order to
enhance structural behaviour. Eventually it was de-
cided to work with just one thickness, i.e. the same
number of layers throughout the entire object. The
thickness had to be sufficient for the area with the
highest stress level. This way the fabrication process
undertaken by a group of seven students was kept
simple and fewer instructions had to be communi-
cated. With a CNC driven fabrication process – with
a robotic arm doing the heat-pressure lamination
as well as sheets cut with as laser-cutter – one could
have gone for a rather sophisticated differentiation
of material thicknesses.

**TOOLING**
The initial tooling of a flat heat source limited the
production to single curved convex forms. As the
heat is only applied at a small part at the time it is
possible to move the mould forward as the fabri-
cation progresses. Thus allowing for a continuous
change of curvature even when using set limited
number of modular moulds.

Several non-adhesive materials, such as tracing
paper, aluminium foil, standard baking paper and re-
usable baking paper, were tested to prevent the heat
source from bonding with the molten material. Best
result were achieved with an industrial Teflon- or
PTFE-coated reusable baking paper or better glass
fibre fabric that comes in various width as bulk stock.
Thus it allowed the preproduction of raw material
with the needed amount of layers with a rotary iron.

It was tested to sort and flatten the collected
used plastic bags automatically but for the circum-
stances and the amount of bags dealt with a hand
sorting proved to be more reasonable.

The use of a laser-cutter was tested on the fin-
ished build-ups and again the behaviour was in-line
with that of pure LDPE, exhibiting sharp cuts. LDPE
of the thicknesses (0.2mm to 2.0mm) dealt with can
be cut with high speed and little energy. A sample
of 0.5mm PE-foil was cut for example with a 70watt
laser at maximum power with a speed of 100mm/s.

**PROOF OF CONCEPT (USING A MODU-
LAR MOULDING SYSTEM)**
The design potential was tested in an exhibition
design for the multimedia programming festival
‘NODE13 - Forum for Digital Arts’ that took place
February 11th - 17th 2013 in Frankfurter Kunstverein,
Frankfurt, Germany. The proposed design was based
on a modular moulding system of a cube and trunc-
cated versions of that cube which could be assem-
bled into larger tessellated formations. The geometry
of the moulds is an abstraction from the NODE13’s
visual corporate identity. From the four shapes –
cube, ramp, chamfer and pyramid – countless geom-
metries can be assembled, connected with wingnut
screws and used as one mould (Figure 5). Once the
layering is done the moulds can be removed and
placed in a new position for further layering.

Three different types of objects were developed
out of which two were fabricated for the exhibition:
  • a series of projector housings fitted into a grid-
ded light ceiling (prototyped but not build for
  the exhibition)
  • a backdrop partition wall to house a projection
art-piece

Figure 4
instance of a digital model
analyzed with linear dynamics
engine ‘Scan and Solve’. 
• a series of cable trays which could be clusters to form sculptures

In the case of the projector housing only a limited set of moulds with maximum dimensions of 0.315cm x 0.315cm each was used to fabricate an object of 1.26cm x 1.26cm x 0.63cm. To achieve this, some moulds where moved when a certain area was completed for further lamination on the same piece (Figure 6, 7). The big advantage of this technique is to build structures of theoretically unlimited size entirely seamless. The prototyping however showed, that a lot of precision got lost in the step of moving the moulds into a new position. Furthermore the elements got almost too big for transportation and on-site fabrication wasn’t an option.

Therefore the fabrication technique was slightly adjusted for the wall-like element of 2.50m height and 4.50m width, that served as a backdrop for a projection mapping on a rotating NODE logo (Figure 1). The overall shape was subdivided into nine parts of which each could be fabricated with the moulds given.

For aesthetic reasons the installation facing the side of the backdrop had to be black. Painting was avoided by manufacturing the final layer of the backdrop from black garbage bag, which is made from LDPE-foil as well. On the backside the recycled plastic bags are exposed.

In the case of the CableTrayClusters, the wooden (MDF) moulds were kept to provide the necessary rigidity. During the daily workshops, the CableTrayClusters provided electricity to the workshop participants at all desks and in the evening they could be piled up and turned into sculptures during exhibition hours (Figure 8).

SCALING OF PRODUCTION
For the fabrication of the exhibition design the production had to be scaled. Main improvements were made by using a larger heat roll press to build material sheets of up to 4 layers before applying larger pieces to the formwork. The geometry and formwork was adjusted for the shrinkage of the material at larger scale, whereby the PE-foil could be wrapped around corners in each direction to counter the slight shrinkage during cooling of the piece. Details were developed to allow for off-site production and assembling transportable parts onsite.

Figure 5
Layout optimization for modular moulding system.

Figure 6
Projector housing fitted in light ceiling.
A major bottleneck became the sourcing of material. The proposed design and prototyping required 3000+ plastic bags. This was tackled by initiating local crowd sourcing strategies. First of all students and employees of the Städelschule were approached personally, via email and posters to bring their ‘bag full of bags’ that almost everyone has at home to allocated drop-off stations. Furthermore local businesses were approached as well as offices with relatedness to the Städelschule Architecture Class. The eventually most successful initiative was an event called ‘more bags more beer’ organised in cooperation with the organizers of NODE13. During the party an algorithm linked the beer-price with the amount of plastic bags collected with the beer price live changing above the bar and the amount of plastic bags collected shown at the entrance. All guests were asked to bring plastic bags which led to a price drop from 4,00€ per bottle at 8:00pm to 1,22€ per bottle at 5:00am and more than 1200 plastic bags collected.

DETAILING
Due to the variable thickness of the material and the welding process during fabrication there is a wide range of detailing options available. Textile features such as pockets, zip fasteners, snap fasteners are used when the material is relatively thin. To weld-ons are used when the material is thicker. Two characteristics exhibit a great potential for design opportunities firstly the possibility to create variable thickness throughout the construction and secondly to weld it seamless into a very large pieces in almost any direction.

The detailing option of creating pockets during the lamination process was further explored in a second design approach.

SECOND DESIGN APPROACH (USING INFLATED CUSHIONS)
In a second approach the possibility of building pockets into the material as it was layered up was tested. In regards to fabrication, layers of non-ad-
hesive material are placed between layers of PE-foil during lamination. These pockets are then filled with additional structural members such as concrete or granular material – PU foam was used for prototyping. Thereby the pockets turn into cushions and increase the structural capacity since envelope and contents act as one structural unit.

Furthermore this technique allows turning the flat material-system into a three-dimensional structure. By varying the number of layers on each side of the cushion the PU-foil bends around the cushion, creating a fold. The angle of that fold depends on the ratio of layers on the respective sides. With the same amount for layers on each side, i.e. the same material thickness above and below the cushion, the resulting angle is 180°, or no folding is happening. By increasing the material thickness on one side, the radius of the rounding between the cushion and the neighboring, non-inflated PE-foil on the thicker side grows compared to the transition from cushion to non-inflated surface on the thinner side. This causes the material to bend around a linear cushion in towards the thinner side. With double the material thickness on one side compared to the other (ratio 2:1) the result was an angle of approximately 90°. By increasing the ratio to 3:1 and higher, the resulting angle had around 75°. An acute angle of less than 70° couldn't be achieved in any test.

The bending-angle also depends on the level of inflation, whereby less pressure causes less bending. In all physical tests PU-foam was used as a filling material, which produces the maximum inflation and creates a nearly circular cross-section of the cushion. The further elaboration on this material system focused on the play with varying material thicknesses than on the level of inflation of the cushions.

A range of different diameters for the cushions was tested in physical and digital models, which all showed the same bending behavior with the same ratio of material thickness. Thereby it was proved, that the folding-angle only depends on the level of inflation – constant in case of the physical models – and the quotient of layers on each side.

**INFLATION-SIMULATION VS. FOLDING-SIMULATION**

To execute more tests with different cushion geometries – linear, curved, multiple parallel and orthogonal cushions – a digital physic-simulation definition was set up incorporating material properties and material behaviour using the live physics engine Kangaroo for Grasshopper by Daniel Piker [3]. This first computational simulation reproduces the inflation of a cushion and the material stiffness of a specific material thickness on each side and that way the bending of the sheet material around the cushion. Despite the fact that this simulation works very accurate, the benefit of the generated digital models is limited since the setup lacks flexibility. The mesh-geometry for each simulation can be prepared with further Grasshopper tools, such as Weaverbird, but any layout more complex than a simple rectangular cushion involves some Rhino-modelling [4]. Therefore this simulation approach can't be integrated in any iterative evaluation or optimisation cycle.

To increase simulation-performance the systems behaviour was abstracted. Only taking into account the essential geometric performance of the material-system, the folding. The contraction of the sheets in the area of cushions where no bending is happening were neglected. This physic-simulation again is using Kangaroo as well as the Kangaroo based curved folding simulation plug-in KingKong by RoboFold / Gregory Epps [5]. The setup of each layout for this folding-simulation is less time consuming than the preparation of the mesh-geometry for the inflation-simulation and – more important – could be parameterized and automated. Moreover the folding-simulation takes only a fraction of the time of the inflation-simulation described before. For a setup with a square sheet and a cushion or fold describing a line between the middle of two neighbouring sides via the centre of the sheet the inflation-simulation takes around 10 seconds whereas the folding-simulation needs only 10ms to compute (Figure 9). Thus a multiplicity of iterations can be executed out of only the fittest are then simulated with the inflation-simulation setup.
STRUCTURAL- AND PERFORMANCE- ANALYSIS

The folded three-dimensional sheet geometry was analysed in regards to its structural capacity using Karamba, an interactive, parametric finite element program for shell and beam structures, which works as a plug-in for Grasshopper [6]. Simple load-cases with even distributed vertical loads, i.e. dead load were simulated and their deformation evaluated. The evolutionary solver component Galapagos for Grasshopper allowed running multiple iterations within a short time [7]. With each iteration the crease and therefore the three-dimensional folded geometry was changed parametrically. Taking design constraints into account the variation of any crease layout was changed only within a specific range and if required only at certain segments of individual folds.

Areas with the least deformation where then localized within the most structurally sound geometry where material can potentially be removed. This changed shape with openings was then analyzed once more and evaluated in structural regards against its equivalent with uniform material thickness – minor impairment was accepted.

The material-system of heat-pressure laminated PE-foil with integrated structural cushions, which turn the flat build-up into a three-dimensional structure when inflated is used for an architectural proposal of a spatial landscape. This design scheme will facilitate an environment for co-working spaces, student- and other low-cost-housing as well as flexible event spaces. The proposed structure shall provide areas for seating, bridge levels, partitions and encloses spaces. To evaluate different design proposals in regards to movement patterns and ergonomics, an agent-based simulation is used. Agents behave different depending on various geometrical conditions. They move slower on steeper slopes, reverse when inclination tends wall-like or rest at areas where geometry corresponds with the criteria defined as geometry that people can sit on.

FURTHER RESEARCH AND POSSIBLE RANGE OF APPLICATIONS

There are three main areas of further development: a) The sourcing of the material; this only makes sense if one could start activating the 50% of material which are finding their way into the recycling process at the moment. b) Understanding better the energy involved to source prepare and fabricate in the proposed fashion and possibly finding ways to optimize the process towards minimized energy. c) To explore design opportunities which match the materials characteristics and its value as a up-cycled product.

REFERENCES

