Color Reproduction Consistency and Capability of Tree-free Copy Paper

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According to the American Forest and Paper Association, paper manufacturing is responsible for the third-largest consumption of fossil fuels worldwide and the single-largest industrial use of water per pound of finished products (Garner, 2002). Awareness of these sustainability issues, paper manufacturers are making efforts to explore alternative fibers to provide paper choices for consumers. This new generation of paper is being produced from plant fiber or mineral powder to provide tree-free alternatives. Plant-fiber paper usually requires fewer chemicals, takes less energy to process, and also tends to have higher potential in relation to bio-refineries. Mineral-based paper requires no chemical bleaching, uses much less water during processing, and when disposed it degrades back to the base component of mineral powder. This paper studied sustainable development and use of tree-free copy paper for the laser printer. The color reproduction capability and process capability of tree-free paper were evaluated in terms of optical density, print contrast, and color gamut.

1. Introduction

Terms such as “Going Green” and “Green Graphic Design” have become hot topics these days as sustainability issues arise in industry. Anna Carlile, principle and founder of Viola Eco-Graphic Design, stated that (Sherin, 2008):

> *As global citizens, we have a duty to ensure that our work practices are sustainable, whatever the industry. In simple term, it’s about ensuring that the actions of today do not compromise the needs of future generations.*

The life cycle of print starts with paper choices. Specifying environmentally preferable paper products can reduce the effect that printing has on the planet. Over the past two centuries, wood has been the primary raw material in paper manufacturing. However, wood-based paper carries a significant “ecological shadow” of energy consumption, bleaching chemicals, and water used in its production. In its 2010 report, United Nations Environment Program (UNEP) identified pulp and paper industry as one of the largest direct contributors to human toxicity. The substances from paper and paperboard mills that contribute most to human toxicity impact are mercury (II) ion, beryllium, and hydrogen fluoride (Hertwich et al, 2010). Motivated by legislation, consumer pressure, and the desire to become more resource and energy efficient, the pulp and paper industry in the United States has invested in new technologies and processes that reduce its environmental impact. Using tree-free fiber in production is one way to minimize or eliminate the environmental impacts (Sherin, 2008).

1.1. Sources of Tree-free Fibers

Tree-free paper is made without the use of tree fiber. There are a variety of alternative fibers that can be used to make paper and reduce the demand on forests. Basically, tree-free paper can be divided into two main categories: organic and nonorganic (Dougherty, 2008; Sherin, 2008; Fiedor & Gray, 2005; Carver & Guidry, 2010).

Organic tree-free paper uses fibers derived from plant sources such as residues from agricultural crops, or plants grown specifically for papermaking.

- Agricultural residues (also called agri-fiber or agri-pulp) are left over materials from the harvesting of agricultural crops such as wheat, rice, cotton, flax, rye and sugarcane bagasse. These fibers, typically treated as a waste product, are considered the most preferable materials to be used for paper production because it makes the most of a waste material and doesn’t require dedicated agricultural land.
- Purpose crops listed in Table 1 are tree-free crops grown specifically to make paper.

Non-organic paper made of minerals, a novel type of paper manufactured from calcium carbonate (also known as stone paper), uses little to no water in their production processes, releases fewer emissions, and uses just under half the energy of wood-based paper production. They are durable and water resistant, and considered recyclable. However, since recycling facilities are not widely available for these materials, books made

Purpose Crops	Characteristics
Hemp	• Fiber yield is roughly twice that of pine • Reaches heights of 1.8 to 5 meters in 70 to 100 days • Contains a mixture of both long and short fibers • Strong and durable fibers require minimal bleaching due to their naturally light coloration • Low in lignin, can be broken down more quickly with fewer chemicals • Can be blended with ling fiber post-consumer waste to add strength • Not widely embraced in industry due to high costs and regulatory problems
Kenaf	• Fiber yield is roughly 3–5 times higher than pines • Reaches heights of 3 to 5.5 meters in five months • Contains a mixture of both long and short fibers • Great papermaking characteristics use fewer chemicals, and less heat and time in the pulping process (contains only 9% lignin)
Bamboo	• Grows faster than wood • Can be regrown from established roots without replanting • Comes from Asia and requires long distance transportation
Cotton	• Two types of fibers used in papermaking: textile scraps and cotton linters, used in high-end papers for many years • Processed with minimal chemicals

Table 1: Purpose crops used to create paper. [2,3]

from mineral alternatives have a high risk of ending up in landfills. As a tree-free alternative, its recyclability and eco-friendly feature are still questionable (Dougherty, 2008; Sherin, 2008; Fiedor & Gray, 2005; Carver & Guidry, 2010).

1.2. Challenges of Tree-free Fibers

Tree-free fibers have advantages of producing paper with fewer chemicals, less energy, and less water than wood, offering farmers alternative crop options, promoting biodiversity by relieving pressures of deforestation, and taking advantage of readily available fibers not being utilized. On the other hand, some studies indicate that the use of purpose crops may require more frequent doses of fertilizer and pesticides, but do not necessarily support the substitution of these fibers for wood pulp. Most environmental groups even argue that annual crops do not provide the secondary benefits of tree plantations, including wildlife habitats and carbon trapping (Kinsella, 2004; Sherin, 2008).

Today, agricultural residues are being used in some parts of the world. In North America, however, no major paper manufacturer has made a big commitment to these fiber sources. Increasing the market share of non-wood fibers is difficult due to a lack of production facilities for tree-free papers. In most cases, tree-free fiber is more expensive, not available in large quantities, and faces challenges in manufacturing because mills may have to be redesigned or retrofitted to accommodate these new materials in the papermaking process (Fiedor & Gray, 2005; Kinsella, 2004).

So far, the applications of tree-free paper are focused on stationery and office copy paper use. Several kenaf and hemp products mixed with recycled paper fibers and tree-free paper manufactured from agricultural residues (such as coffee, mango, lemon, and banana) used to produce quality stationery, add different elements to design. These products have made it to market, but none have been a big success so far. Tree-free paper made from sugar cane bagasse, on the other hand, has made some inroads in the North American office paper market. It biodegrades faster than wood-based paper, and can be recycled with paper made from trees.

2. Experimental Design

In order to study the color reproduction and process capability of tree-free copy paper, three commercially available tree-free papers sugarcane copy paper A, B, and C were selected and tested, with a wood-based copy paper as reference. Table 2 shows characteristics of tested tree-free copy papers. Like wood-based copy paper, tree-free copy papers use optical brightener agent (OBA) to bring up the desired brightness.

The color reproduction capability of tree-free paper was evaluated in terms of optical density, print contrast and color gamut. A Xerox DocuColor 250 laser printer with toner-based inks (profiled as a CMYK device) was used in the study. Fifty samples of each substrate were collected and measured with an X-Rite i1iO spectrophotometer. ICC profiles were generated for the digital printers by using ProfileMaker 5.0.10. ICC profiles were then loaded into CHROMiX ColorThink Pro 3 software and the gamut volumes of the ICC profiles were determined. The optical densities and print contrast of tested tree-free papers were measured using an X-Rite 530 SpectroDensitometer.

The color reproduction consistency and capability of tree-free papers were discussed. One of indices used to measures process capability is Cp index. It is defined as the ratio of the designated specification range to the individual paper type process range, for optical density, print contrast, and color gamut parameters. Cp index is calculated as (upper specification limit - lower specification limit)/(6*Sigma). In other words, this ratio expresses the proportion of the range of the normal curve for each paper type that falls within that specification limits (Montgomery, 1997).

For this study, a relative specification range was determined based on data for the selected paper types and used to calculate the Cp indices, as described below.

3. Color-related Attributes

Table 3 lists color-related attributes for the wood-based and sugarcane paper samples from the laser printer. Color density and print contrast values are shown for yellow (Y), magenta (M), cyan (C), and black (K). The average optical density measurements of tested tree-free copy paper are lower than those of wood-based copy paper. Although the wood-based copy paper yielded higher average optical densities, it tended to have larger color reproduction variability. The wood-based copy paper had higher average print contrast, with the exception of black. The sugarcane C copy paper had lower print contrast with larger variability. It also shows that the wood-based copy paper produced a wider color gamut with smaller color reproduction variability, while sugarcane B copy paper having larger color reproduction variability.

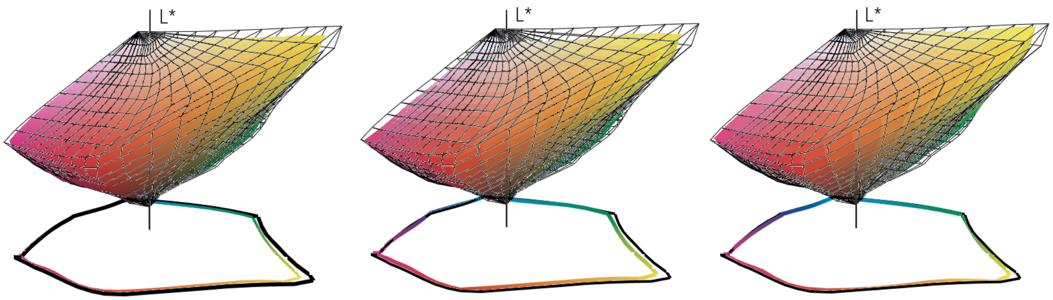
Figure 1 illustrates the color gamut comparison for the wood-based and sugarcane copy papers. Note the black projection line represents the color gamut of the wood-based paper reference. The color gamut of wood-based copy paper is larger, especially in the yellow regions. Microscope images of tested copy papers (black line) are shown in Figure 2, at 40x magnification. It shows that wood-based copy paper tended to produce a smoother, sharper edge.

Paper	Paper Weight	Brightness	OBA	Paper White		
				L*	a*	b*
Wood-based	20#	92	Y	95.53	1.94	-6.54
Sugarcane A	20#	93	Y	92.64	4.3	-10.05
Sugarcane B	22#	92	Y	93.17	3.95	-10.25
Sugarcane C	20#	92	Y	93.94	2.25	-7.46

Table 2: Characteristics of tested tree-free copy papers

		Wood-based		Sugarcane A		Sugarcane B		Sugarcane C	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Optical Density	Y	0.85	0.02	0.84	0.01	0.84	0.01	0.82	0.02
	M	1.10	0.02	1.06	0.02	1.08	0.02	1.05	0.02
	C	1.22	0.03	1.17	0.02	1.20	0.02	1.16	0.02
	K	1.61	0.03	1.58	0.03	1.60	0.04	1.58	0.06
Print Contrast	Y	19.09	2.28	18.29	1.56	18.69	1.53	16.48	2.51
	M	32.11	2.38	30.57	1.67	30.97	2.29	29.04	1.95
	C	25.25	1.70	24.29	1.11	23.54	1.30	22.42	1.69
	K	39.69	1.86	41.13	1.23	40.91	1.89	40.47	2.41
Color Gammut		336.358	3.712	312.351	3.414	308.103	10.248	312.096	5.365

Table 3: Color-related attributes of tested copy papers. Note: S.D. represents Standard Deviation (Sigma).

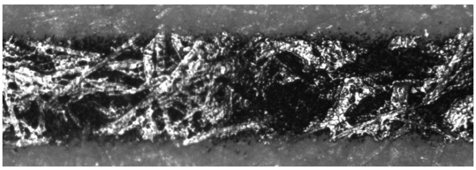


(a) Sugarcane A (true color) v.s. wood-based (wireframe)

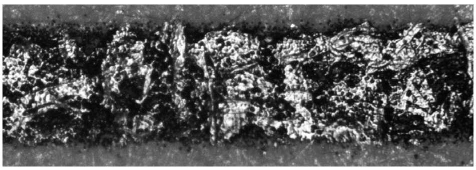
(b) Sugarcane B (true color) v.s. wood-based (wireframe)

(c) Sugarcane C (true color) v.s. wood-based (wireframe)

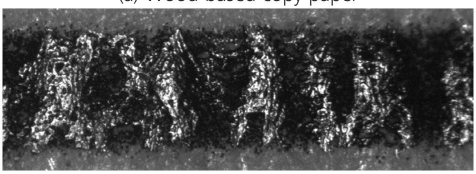
Figure 1: Color gamut comparison for the copy paper



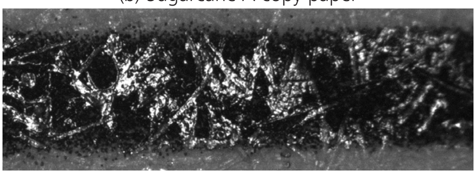
(a) Wood-based copy paper



(b) Sugarcane A copy paper



(c) Sugarcane B copy paper



(d) Sugarcane C copy paper

Figure 2: Microscope images (@ 40x magnification)

4. One-way ANOVA Analysis

One-way Analysis of Variance (ANOVA) statistical procedure was employed to determine whether the differences in optical density, print contrast, and color gamut of tested copy paper were significant. The significant level (α) was set at 0.05 for all tests. Appendix I presents One-way ANOVA tests on the color-related attributes difference among the tested copy papers.

For the optical density, it shows that the significant value of p is $0.000 < 0.05$ (α) for observed optical densities yellow, magenta, and cyan (with $p = 0.001$ for black), that is, at least one pair of the mean optical density values is significantly different at 0.05 levels. The 95% confidence intervals of measurements are also exhibited in the lower part of tables. It shows that Sugarcane B copy paper and wood-based copy paper have similar optical density values for yellow (as their 95% confidence intervals of measurements are overlap with each other). Sugarcane A and C copy papers have similar optical density values for black.

As for the print contrast, as shown in Appendix I, the significant value of p is $0.000 < 0.05$ (α) for observed print contrast yellow, magenta, and cyan (with $p = 0.001$ for black), in other words, at least one pair of the mean print contrast values is significantly different at 0.05 levels. According to 95% confidence intervals of measurements, wood-based and sugarcane A & B copy papers have similar print contrast values for yellow. The average print contrast value of sugarcane A copy paper is close to that of sugarcane B copy paper. It also shows that sugarcane copy papers have similar print contrast values for black.

One-way ANOVA test on the color gamut difference among the tested copy papers shows that at least one pair of the mean color gamut values is significantly different at 0.05 levels (the significant value of p is $0.000 < 0.05$ (α)). Based upon 95% confidence intervals of measurements, the color gamut of wood-based copy paper is significantly different from that of sugarcane copy paper. The average color gamut value of sugarcane A copy paper is close to that of sugarcane C copy paper.

5. Capability Analyses

The tools within the Minitab 16.0 software used to analyze the consistency for optical density and color gamut measurements are individual control chart (I chart), moving range charts (MR chart), and capability analysis. Individual control chart (I chart) and moving range charts (MR chart) were used to remove the outlier data. The capability analysis tool was used to calculate Cp index for each paper type. In order to do the capability analysis, lower specification limit (LSL) and upper specification limit (USL) are required input parameters. However, due to lack of historical parameters of LSL and

Cp value		Wood-based	Sugarcane A	Sugarcane B	Sugarcane C
Optical Density	Y	1.07	1.02	**1.39**	0.73
	M	0.91	0.99	0.93	**1.23**
	C	0.83	1.07	**1.83**	0.76
	K	1.20	**1.26**	1.20	0.65
Print Contrast	Y	0.88	1.23	**1.39**	0.75
	M	0.84	1.15	0.85	**1.30**
	C	0.84	**1.13**	1.07	1.01
	K	1.08	**1.80**	0.93	0.68
Color Gammut		1.06	**1.65**	0.54	0.84

Table 4: The relative PCR (Cp value) for the tested copy papers

USL for color-related attributes of paper, relative specification limits were determined using test data. After eliminating all outlier points, revised Sigma (the process standard deviation) was calculated for each paper type and the average Sigma was computed from the Sigmas of wood-based and sugarcane papers. The relative LSL and USL (Appendix II) were obtained by subtracting and adding the appropriate average 3*Sigma value from each individual paper type mean, respectively.

Using LSL and USL values in Appendix II, the relative Cp indices were calculated. Results for color attributes are shown in Table 4. A higher Cp index indicates more capable or more consistent results from the printing process. As shown in Table 4, the sugarcane B had the largest relative Cp index for optical densities yellow (Cp = 1.39) and cyan (Cp = 1.83). The Sugarcane A copy paper had the largest relative Cp for the print contrast cyan (Cp = 1.13), black (Cp = 1.80), and color gamut (Cp = 1.65). Overall, sugarcane A was the most capable copy paper for delivering consistent results in print contrast and color gamut. The sugarcane C copy paper, on the other hand, was the least capable paper for delivering consistent results in optical density and print contrast, with exception of magenta.

6. Conclusions

Achieving uniformity of printing and obtaining good color reproduction performance are crucial in the print production. This study investigated the copy paper application of sugarcane alternatives. It was found that, sugarcane A copy paper was competitive with wood-based copy paper in terms of color reproduction consistency. Although wood-based copy paper yielded higher optical density, print contrast, and color gamut, sugarcane A was the most capable copy paper for delivering consistent results in color-related attributes. The sugarcane C copy paper, on the other hand, was the least capable paper for delivering consistent results. Users can choose sugarcane A copy paper as alternative when consistency is the highest priority.

Sugarcane alternatives do represent new opportunities for increased choice in environmentally preferable materials and can be explored as a potential way to reduce the rate of hardwood deforestation. These types of paper could also support economic development in developing countries where they currently burn crop residue. With significant consumer demand by publishers and consumers alike, these alternative fiber options may become more accessible alternatives in the future.

Appendix I: One-way ANOVA Analysis

One-way ANOVA test on the optical density of yellow

Source	DF	SS	MS	F	P
Factor	3	0.016390	0.005463	25.83	0.000
Error	196	0.041450	0.000211		
Total	199	0.057840			

```
                                    Individual 95% CIs For Mean Based on Pooled StDev
Level         N    Mean   StDev    -------+---------+---------+---------+--
Wood-based   50  0.84600  0.01552                               (-----*----)
Sugarcane A  50  0.83600  0.01400                  (----*----)
Sugarcane B  50  0.84320  0.01115                            (----*----)
Sugarcane C  50  0.82260  0.01688   (----*----)
                                    -------+---------+---------+---------+--
                                        0.8240    0.8320    0.8400    0.8480
```

One-way ANOVA test on the optical density of magenta

Source	DF	SS	MS	F	P
Factor	3	0.058212	0.019404	43.41	0.000
Error	196	0.087620	0.000447		
Total	199	0.145832			

```
                                   Individual 95% CIs For Mean Based on Pooled StDev
Level         N   Mean   StDev    ---+---------+---------+---------+------
Wood-based   50  1.0980  0.0238                                   (---*---)
Sugarcane A  50  1.0644  0.0206             (---*---)
Sugarcane B  50  1.0770  0.0221                      (---*---)
Sugarcane C  50  1.0518  0.0176   (---*---)
                                  ---+---------+---------+---------+------
                                   1.050     1.065     1.080     1.095
```

One-way ANOVA test on the optical density of cyan

Source	DF	SS	MS	F	P
Factor	3	0.089698	0.029899	55.15	0.000
Error	196	0.106252	0.000542		
Total	199	0.195950			

```
                                   Individual 95% CIs For Mean Based on Pooled StDev
Level         N   Mean   StDev    --+---------+---------+---------+-------
Wood-based   50  1.2160  0.0280                               (--*--)
Sugarcane A  50  1.1738  0.0223          (--*--)
Sugarcane B  50  1.1986  0.0170                      (--*---)
Sugarcane C  50  1.1616  0.0244    (--*--)
                                  --+---------+---------+---------+-------
                                  1.160     1.180     1.200     1.220
```

One-way ANOVA test on the optical density of black

Source	DF	SS	MS	F	P
Factor	3	0.02691	0.00897	5.39	0.001
Error	196	0.32598	0.00166		
Total	199	0.35289			

```
                                  Individual 95% CIs For Mean Based on Pooled StDev
Level         N   Mean   StDev   ----+---------+---------+---------+-----
Wood-based   50  1.6084  0.0377                     (------*-------)
Sugarcane A  50  1.5798  0.0277  (------*-------)
Sugarcane B  50  1.5980  0.0348             (------*-------)
Sugarcane C  50  1.5828  0.0570    (------*-------)
                                 ----+---------+---------+---------+-----
                                   1.575     1.590     1.605     1.620
```

One-way ANOVA test on the print contrast of yellow

Source	DF	SS	MS	F	P
Factor	3	198.25	66.08	16.27	0.000
Error	196	795.85	4.06		
Total	199	994.10			

```
                                 Individual 95% CIs For Mean Based on Pooled StDev
Level        N   Mean  StDev   -+---------+---------+---------+--------
Wood-based   50  19.087  2.276                           (-----*----)
Sugarcane A  50  18.285  1.563                  (-----*----)
Sugarcane B  50  18.690  1.526                       (-----*-----)
Sugarcane C  50  16.483  2.508  (-----*----)
                               -+---------+---------+---------+--------
                               16.0      17.0      18.0      19.0
```

One-way ANOVA test on the print contrast of magenta

Source	DF	SS	MS	F	P
Factor	3	241.61	80.54	18.38	0.000
Error	196	858.65	4.38		
Total	199	1100.26			

```
                                 Individual 95% CIs For Mean Based on Pooled StDev
Level        N   Mean  StDev   ---+---------+---------+---------+------
Wood-based   50  32.106  2.383                           (----*---)
Sugarcane A  50  30.576  1.675              (----*----)
Sugarcane B  50  30.973  2.287                (----*----)
Sugarcane C  50  29.036  1.952  (----*----)
                               ---+---------+---------+---------+------
                                 28.8      30.0      31.2      32.4
```

One-way ANOVA test on the print contrast of cyan

Source	DF	SS	MS	F	P
Factor	3	214.35	71.45	33.04	0.000
Error	196	423.88	2.16		
Total	199	638.24			

```
                                 Individual 95% CIs For Mean Based on Pooled StDev
Level        N   Mean  StDev   +---------+---------+---------+---------
Wood-based   50  25.253  1.699                               (----*---)
Sugarcane A  50  24.288  1.110                       (---*---)
Sugarcane B  50  23.537  1.299             (---*---)
Sugarcane C  50  22.425  1.687  (---*---)
                               +---------+---------+---------+---------
                               22.0      23.0      24.0      25.0
```

One-way ANOVA test on the print contrast of black

Source	DF	SS	MS	F	P
Factor	3	60.37	20.12	5.61	0.001
Error	196	702.84	3.59		
Total	199	763.21			

```
                                 Individual 95% CIs For Mean Based on Pooled StDev
Level        N   Mean  StDev   -+---------+---------+---------+--------
Wood-based   50  39.693  1.859  (-------*-------)
Sugarcane A  50  41.127  1.228                        (-------*------)
Sugarcane B  50  40.914  1.890                     (------*-------)
Sugarcane C  50  40.465  2.409               (------*-------)
                               -+---------+---------+---------+--------
                               39.20     39.90     40.60     41.30
```

One-way ANOVA test on the color gamut

Source	DF	SS	MS	F	P
Factor	3	24967644624	8322548208	209.06	0.000
Error	196	7802567760	39809019		
Total	199	32770212385			

```
                                   Individual 95% CIs For Mean Based on Pooled StDev
Level        N   Mean    StDev     -------+---------+---------+---------+--
Wood-based   50  336358   3712                                        (-*--)
Sugarcane A  50  312351   3414           (-*--)
Sugarcane B  50  308103  10248     (-*-)
Sugarcane C  50  312096   5365          (-*-)
                                   -------+---------+---------+---------+--
                                       312000    320000    328000    336000
```

Appendix II: The LSL and USL for each attribute

		Wood-based		Sugarcane A		Sugarcane B		Sugarcane C	
		LSL	USL	LSL	USL	LSL	USL	LSL	USL
Optical Density	Y	0.80	0.89	0.79	0.88	0.80	0.89	0.78	0.87
	M	1.03	1.16	1.00	1.13	1.01	1.14	0.99	1.12
	C	1.15	1.28	1.11	1.24	1.14	1.26	1.10	1.22
	K	1.49	1.73	1.46	1.70	1.48	1.72	1.47	1.70
Print Contrast	Y	12.54	25.65	11.73	24.84	12.20	25.31	9.93	23.04
	M	25.51	38.71	23.98	37.18	24.37	37.57	22.34	35.54
	C	21.01	29.49	20.05	28.53	19.29	27.78	18.25	26.74
	K	34.58	44.80	36.01	46.22	35.80	46.02	35.35	45.57
Color Gamut		322,602	350,114	298,595	326,107	294,533	322,045	298,340	325,852

References

[1] Carver, J.; Guidry, N. (2010): Rethinking Paper & Ink: The Sustainable Publishing Revolution. Portland, OR, .

[2] Dougherty, B. (2008): Green Graphic Design. New York, NY, Allworth Press.

[3] Fiedor, A.; Gray, C. (2005): Exploration of Sustainable Printing. California Polytechnic State University.

[4] Garner, J.W. (2002): Energy Conservation Practices Offer Environmental and Cost Benefits. Pulp & Paper, vol. 76, no. 10, pp. 53-56.

[5] Hertwich, E.; Van der Voet, E.; Suh, S.; Tukker, A.; Huijbregts M.; Kazmierczyk, P.; Lenzen, M.; McNeely, J.; Moriguchi, Y. (2010): UNEP Assessing the Environmental Impacts of Consumption and Production: Priority Products and Materials. A Report of the Working Group on the Environmental Impacts of Products and Materials to the International Panel for Sustainable Resource Management.

[6] Kinsella, S. (2004): The Environmental Paper Listening Study, Chapter Four: Tree Free Paper, Retrieved January 6, 2012, from http://conservatree.org/paperlisteningstudy/TFExecSum.pdf.

[7] Montgomery, D.C. (1997): Introduction to statistical quality control (3rd ed.). New York, John Wiley & Sons, Inc.

[8] Sherin, A. (2008): Sustainable: a handbook of materials and applications for graphic designers and their clients. Beverly, MA, Rockport Publishers.

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