Received: 17 Januruy 2019 Accepted: 20 February 2019
DOI: 10.1002/amp2.10012

RESEARCH ARTICLE

ADVANCED MANUFACTURING ••oPROCESSING WILEY

Life cycle comparison of carpet dyeing processes

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Carpet manufacturing continues to adopt advanced technologies and new processes. One important process is central to the carpet product, dyeing for the color and beauty of patterns derived for modem carpets. Carpets and fibers are dyed by a variety of different processes at different stages of production, from the fiber, the yam, or the carpet, depending on the product use, economy of the process, and market demand for the color. Dyeing technology for carpets has evolved to advanced processes and is discussed in this paper. Fiber can be dyed as it is extruded, as in the case of solution dyeing; yam can be dyed as in skein, or space dyeing; or whole carpet pieces can be dyed as in beck or continuous dyeing. This paper is the first direct comparison of these five carpet dyeing processes with the goal to understand the technology changes to more advanced manufacturing. Using a life cycle approach, gate-to-gate (within the factory) inventories are created to assess resource and energy consumption associated with each of the processes. The life cycle inventories are created based on process flow models of product manufacturing to provide transparency. A single color agent (beta-copper phthalocyanine) and a single face fiber (nylon 6) are used for the comparison. The older batch processes, such as beck and skein, consume the most water and energy, while the most recent advanced process of solution dyeing uses the least amount of energy and water.

KEYWORDS
advanced catpet dyeing processes, life cycle inventory, manufacturing improvement

1 | INTRODUCTION

The earliest people used natural materials to stain and color items and to create art on the walls of ancient habitats. Although scientists have not precisely developed the timeline of coloring textiles, dye analysis on textile fragments date back to the first century. The ability of carpet manufacturing to impart color to floor coverings has evolved from a natural dye, with a manual process, to one of synthetic dyes and sophisticated machinery. With these changes, there have been several considerations that impacted the outputs of the dyeing process.

Normal dyeing processes have several goals. The most sought-after outcomes in the dyeing of carpet and rugs are aesthetics, color fastness, cost, process dependability, and natural resource consumption. With the advancements in the application of color to carpets, there has been an improvement in almost every outcome desired. However, it has not been a straight-line progression of advancing dyeing processes.

The earliest days of dyeing used the lowest amounts of water and energy. The energy was human energy, and the water was confined to small incremental batches. Dyes were obtained from natural substances, and little processing was necessary to achieve the coloring properties. Fibers were natural fibers from plants and animals. This basic process generates the lowest life cycle impacts. Outcomes pertaining to aesthetics and durability were limited.

Manufacturing technological advances led to processes with the ability to create materials from synthetic fibers, which required different dyestuffs to add color. Most of the fibers and dyestuffs developed during this evolution were designed for performance and flexibility. The outcomes were greater varieties of color and design married with better durability. During this age of dyeing process and chemical advancements, little thought was given to the rise of energy and water consumption or the raw material extraction processes necessary to implement these improvements.[1]

Carpet manufacturing processes became synthetic fiber-centric, and the dyestuffs were matched to the chemistries of the fibers being used. Carpet processes evolved from the hand-made, narrow selection of products to mass-produced, large-batch processes. The focus was on improving efficiency, lowering costs, and raising the durability of the products, leading to growth of the carpet industry. Only around lowered costs was any discussion forthcoming on the cradle-to-grave impacts of the carpet process.

The dyeing processes for both natural and synthetic fibers were undergoing changes in how the prer dyestuffs were matched to each fiber and how to best create col<X" and aesthetics in carpets. There was a progression from dyeing individual fibers to creating the carpets with greige fibers and then adding color. However, no direct comparative and quantitative energy comparisons of these dyeing technologies have been conducted. When qualitatively comparing the manufacturing energy impacts of skein vs beck dyeing, it was discovered that skein dyeing used much less energy.[2] However, productivity was lower foc skein dyeing vs beck dyeing. With process improvements, continuous dyeing/printing of carpets became the standard for most products in the 1980s. This change lead to lower manufacturing life cycle impacts due primarily to larger volumes of carpet being processed with a lower overall water and energy consumption.[3]

Today, there has been a carpet manufacturing movement toward the use of solution-dyed fibers as the method for imparting color and design to carpets (early 2000-2005). Solution-dyed fibers have taken a step forward in the diversity of colors offered while maintaining the durability of these colors. With a lower water profile and less energy needed to dry these products, the life cycle impacts are the lowest of any current process.

Balancing the needs of the market with concerns over life cycle impacts is a challenge. The carpet industry is an example of the progression of technology to support market needs while lowering life cycle impacts. However, the historical perspective detailing the path to lower life cycle impacts is not always direct but is closely tied to matket needs and technology availability.

In 2016, about L1 billion kg of fiber, mostly nylon, were dyed to make L1 billion square meters of carpet.[4] Commercial carpet is predominantly nylon face material. The dyed carpet must resist fading from light, wetness, and friction, requiring dyes to resist degradation.

The scope of this research paper is to track the advances in carpet manufacturing dyeing as technology has evolved. We seek to perform the first direct. quantitative energy comparison of five carpet dyeing processes. Transparent gate-to-gate (within the factory) inventories are used to compare dyeing processes at different stages of carpet manufacture: before yam production, after yarn production, or after tufted carpet production. In addition, the life cycle of an example dye is included to account for the mass efficiencies of various dyeing technologies.

2 I RESULTS

Each of the five dyeing processes was analyzed with a process flow diagram from field observations and process

TABLE 1 Relationship of MJ energy used in chemical manufacturing processes to MJ total NRE consumed to produce that energy

Scale-up factors	Electricity[a]	Dowthenn	Steam	Nontr<msport direct use of fuel	Transport fuel	Heat potential re<:overy
Precombustion factors, MJ fuel extracted and used per MJ delivered (this excess is consumed in delivery)	LI	1.15	1.15	1.15	1.20	1.15
Generation/combustion factors, MJ HHV fuel delivered per MJ energy to process	3.13	L25	L25	L00	L00	L25
Total scale-up factor (precombustion times generation/combustion), MJ total fuel extracted for this use per MJ into process	3.44	L44	L44	1.15	1.20	L44

Abbreviations: HHV, high heat value; MJ, megaJoule; NRE, natural resource energy.
[a]Based on US energy grid.

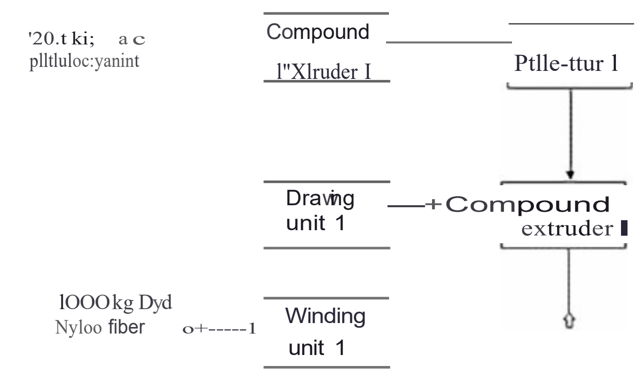


FIGURE 1 Solution dyeing process flow diagram

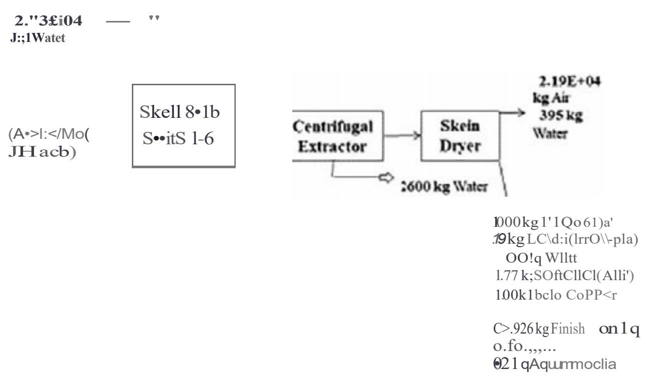


FIGURE 2 Skein yam dyeing process flow diagram. Abbreviation: ADP

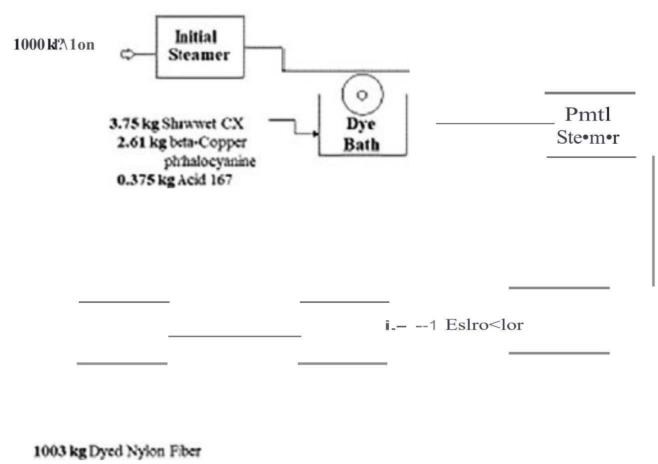


FIGURE 3 Space yarn dyeing process flow diagram

conditions provided by companies at the Carpet and Rug Institute.[5] Using the advanced life cycle inventory methodologies in the Environmental Genome,[6,7] the energy and dye use results were first produced (referred to as dyeing

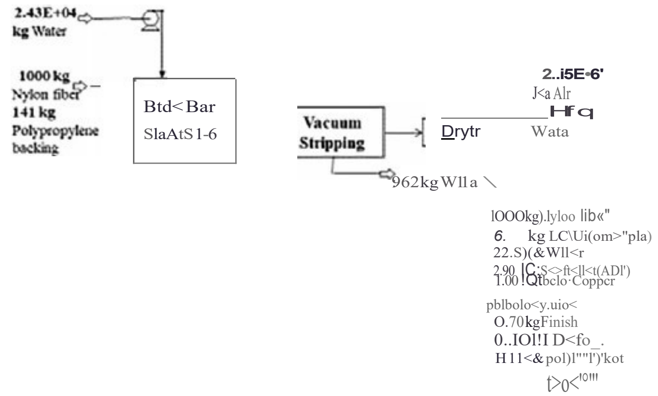


FIGURE 4 Beck carpet dyeing process flow diagram. Abbreviation: ADP

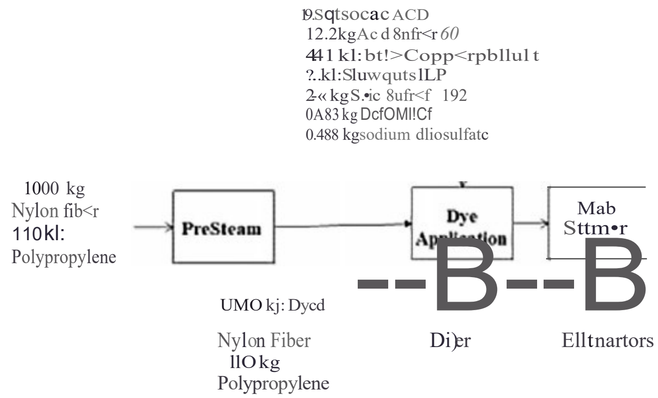


FIGURE 5 Continuous carpet dyeing process flow diagram. Abbreviation: ACD

gate-to-gates [gtg]). These detailed data are given in Ponder.[8] The basic flow diagrams to show the differences in dyeing technologies are provided in this paper.

Dyeing process energies are made available by consumption of fuels (Table 1). For each megaJoule (MJ) of energy put into the manufacturing process, there are direct fuels needed to create that MJ of energy, and fuel is also needed to deliver these fuels to the point of use, as described in Table 1. In this paper, the energy values in Table 1 are used and referred to as natural resource energy (NRE).

With solution dyeing, nylon fiber can be colored before it is drawn into fiber by adding pigment encased in nylon pellets to the undyed nylon pellets in the extruder. The nylon can then be drawn into the dyed nylon fiber (Figure 1). The solution dyeing process only requires the electricity from the extruder and pelletizec to mix in the colorant. As solution dyeing adds pigment during the extrusion of the fiber, no water is needed.

Undyed nylon can be drawn and wound into yam and then dyed by either immersion in a heated dye bath, as in skein dyeing, or printed with the dye, as in space dyeing. In skein dyeing, skeins of yarn are put on a rack and inserted into a square open tank. Watec, pigments, and chemicals are added, and a lid is placed on the tank. A recirculating pump provides agitation,

TABLE 2 Inputs and process energy required for dyeing processes, arranged in the general order of advancement in dyeing technologies

		Input<;, kg			Energy, MJ/1000 kg nylon			
Dyeing process		Nylon	Dye	Water	Electricity	Steam	Other	Total
Postcaipet	Beck	1000	1.05	52 100	682	19 941		20 624
Postfiber	Skein	1000	1.05	39 800	90.1	12 639		12 729
Postfiber	Space	1000	2.61	9.1	429	5 114		*5544*
Postcaipet	Continuous	1000	4.41	7003	12.3	649	1183	1844
Prefiber	Solution	1000	20.4	0	33.3			33.3

Abbreviation: MJ, megaJoule.

and steam coils provide heating. After about 30 minutes, the color is checked, and if acceptable (about 40% of the time), the skeins are removed. If further color adjustment is needed, a second addition and recirculating time is provided (about 60% of the time). The skeins removed are put into a centrifuge water extractor and maintained at about 40 wt% water. The skeins are then placed on a short conveyor system through a hot air dryer and are then are air-cooled (Figure 2).

In space dyeing, parallel strands of nylon yam are randomly printed with dye to create a yam with intermittent color patterns. Next, the yam is steamed to set the color, and then, excess liquid is extracted. Finally, the yam is dried and wound for further processing (Figure 3).

Tufted, unfinished nylon carpet, consisting of undyed nylon face fiber and a polyolefin backing (such as polypropylene), can be dyed by beck or continuous dyeing processes. Jn beck dyeing, tufted carpet pieces are dipped into heated dye baths and rinsed, excess water is extracted, and the pieces are dried (Figure 4).

In the continuous carpet dyeing process, tufted carpet is presteamed before going through a dye bath. After the dye bath, the carpet is steamed to fix the dye, and excess liquid is extracted. The carpet is dried and cooled to ambient temperature (Figure 5).

The results of the gtg dyeing process inputs and energy consumption for each dyeing process are shown in Table 2. All used the same amount of nylon. Solution dyeing uses the most dye as the pigment is mixed throughout the nylon fiber during the extrusion process. In the other methods, the dye is on the surface of the nylon fiber. A breakdown of the energy per process within each dyeing process is shown in Table 3. These results are for the d!irect dyeing process without the addition of the energy for the required dye (dye manufacturing from cradle-to-gate [ctgJ).

To illustrate the relationship of the dyed fiber to the whole carpet, a styrene-butadiene latex-backed broadloom was selected. This illustrates the inputs and emissions to manufacture a square meter of carpet (as shown in Table 4). Table 5 shows the energy for the dyeing process and the gtg and ctg carpet manufacture in units of megajoules per square meter of carpet. Not all of the dye and finish used in the dye

TABLE 3 Energy per process within dyeing processes (not including diesel transport ene©)

	Energy per process, MJ/HMIO kg nylon				
Dye process	Beck	Skein	Space	Continuous	Solution
Extrusion					32.9
Pelletizing					0.33
Presteam			17.3	135	
Dye application 1	12 701	8357	0.18	67.4	
Dye application 2	3932	1363			
Rinse	1.80	1.16			
Steam			2247	447	
Extraction	393	28.8	280	10.3	
Dcying	3596	2979	2850	1 185	
Winding			149		
Total	20 624	12 729	*5544*	1845	33.3

Abbreviation: MJ, megaJoule.

TABLE 4 Inputs and waste emissions for 1 square meter of styrene butadiene latex-backed broadloom commercial carpet (1 square meter = 2.3 kg on the floor of a building)

Inputs	kg/sq meter
(Dyed) nylon fiber	1.03
Polypropy Jene	0.23
Calcium carbonate	0.61
Aluminum hydroxide	0.30
Styrene butadiene latex	0.26
Total inputs	2.43
Material losses	**kg/sq meter**
(Dyed) nylon fiber	0.045
Polypropy Jene	0.020
Calcium carbonate	0.Q35
Aluminum hydroxide	0.017
Styrene butadiene latex	0.014
Total emissions	0.133

TABLE 5 Fnergy for carpet manufacture (styrene butadiene latex-backed broadloom)

	Energy, MJ per square meter				
	Beek	Skein	Space	O>ntinuous	Solution
Gate-to-gate dye process	21.6	13.5	6.1	2.4	0.5
Gate-to-gate xarpet manufacturing (no dye)	7.4	7.4	7.4	7.4	7.4
Cradle-to-gate carpet manufacture	74.4	60.8	51.3	54.0	48.8
Dyeing energy as % of cradle-to-gate carpet manufacture energy	29	22	12	4	

Abbreviation: MJ, megaJoule.

TABLE 6 Dyeing proces.ses and requisite dye energies, MJ/1000 kg nylon 6 dyed

Dyeing type	Dyeing processenergy only	Dyeing proce...-; only, NRE	Beta copper phthalocyanine dye CTG, proce...-;	Beta copper phthalocyanine dye CTG, NRE	Dyeing process plus dye, process energy	Dyeing proce.<;s plus dye, NRE
Beck	17 687	26 789	71	121	17 758	26 910
Skein	12 716	18 460	77	120	12 793	18 580
Space	5528	8802	178	300	5706	9102
Continuous	3559	4332	300	5(17	3859	4839
Solution	32	111	1330	2253	1362	2364

Abbreviations: MJ, megaJoule; NRE, natural resource energy; CTG, cradle-to-gate.

bath solution remain on the dyed fiber. Of the dye and additives used, 93% of the dye and 50% of the softener and finish remain on the carpet The balance is discharged in the wastewater to the publicly owned treatment works (POTW).[9,10]

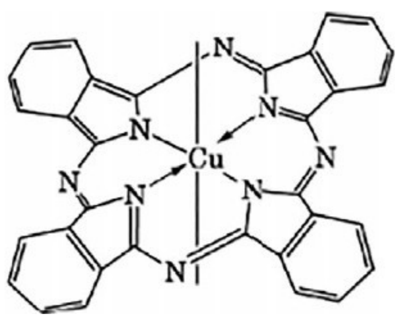
The full dyeing technology energy is the sum of the physical process (Tables 2-3, and 5) plus the ctg life cycle inventory to manufacture the dye. This has significance because there is a 20-fold difference in the amount of dye required across these five dyeing technologies (Table 2). Using one dye, beta-copper phthalocyanine, we next developed the ctg data for 1000 kg of dye. Table 6 provides the information on the energy of each dyeing process and also the effect of including the amount of dye required by each process. These are expressed as process energy, a direct link to the costs of energy in the carpet manufacturing plants, and the NRE, which caprures the full energy of these systems (fable 1). These data show a hidden environmental factor regarding the major modem dyeing process, solution dyeing. At the factory level, solution dyeing energy use (and probably operational cost) is over a 100-fold less than the next higher technology. If expressed as natural resources energy, the entire fuel use is the NRE and is only about 40-fold better than the next higher technology (Table 6). However, because this process requires about a 20-fold larger amount of dye as it is incorporated across the whole fiber diameter, the dye-manufacturing energy is significant. Adding the dye manufacturing and use, the NRE comparison to the next higher dyeing process is now 2-fold better, still a significant improvement. Because of the 5- to 20-fold greater amount of dye in solution technology, this also drives up other environmental impact metrics; however, because we only used one dye, these results are not presented as the range of dyes might give different answers.

3 | METHODS

A design-based methodology [11] using process flow diagrams and engineering design principles was used to collect inventory data for each gtg inventory used to complete the carpet dyeing inventory. Industry data are also used for the carpet dyeing inventories.

The gtg inventories are the first level inventories, and manufacture of the yarn or carpet is not included. The ctg life cycle inventory for a carpet product has been performed previously[5] and includes the supply chain chemicals.

All processes are compared on a basis of 1000 kg nylon 6 fiber, so the functional unit is 1000 kg dyed nylon 6 fiber. The same dye (beta-copper phthalocyanine) is used in all cases to allow comparable results.



4 CONCLUSIONS

In general, carpet manufacturing continues to evolve to use less energy and water. In the carpet plant, dye application and drying are the most energy-intensive steps in dyeing. The older technologies of beck and skein dyeing are quantitatively higher in energy use. The next generation, with continuous and space dyeing, succeeded in reducing the energy environmental footprint. The recent advances to solution dyeing have led to a significant further advance in dyeing energy reduction, although the higher use of dye must be investigated to determine the magnitude of this effect.

ACKNOWLEDGEMENTS

The authors thank Shaw Industries, Inc., J & J Industries, and the members of the Carpet and Rug Institute Sustainability Issues Manufacturing Team for their input to this work.

CONFLICT OF INTEREST

This carpet manufacturing study was undertaken as an engineering analysis with no conflict of interest.

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How to cite this article: Ponder C, Gregory B, Griffing E, Li Y, Overcash M. Life cycle comparison of carpet dyeing processes. *J Adv Manuf Process.* 2019;1:e10012. htq>s://doi.org/10.1002/amp2.10012