The Surfboard Cradle-to-Grave
Life Cycle Assessment of a Common Surfboard: Epoxy vs. UPR

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Some History

Surfboarding is a sport of the ancients; exact dates are hard to pin down, but the practice of standing on boards, and riding the "curl" of a breaking ocean wave, has existed on the shores of the Polynesian Islands for centuries, at least. The first written description of surfboard riding comes from the log of Lieutenant James King in 1779; King described in detail the act of surfboard riding off the Kona coast of the Big Island of Hawai'i. His description of the sport described an activity nearly identical to how it is practiced today (1).

Figure 1: Early Artistic Representation of Surfing in Hawai'I (1). Courtesy Hawai'i State Archive.

Though the activity itself is the same today, the boards used in its practice are completely different. The most detailed history of board-shaping is available from Hawai'i, where boards were hand-shaped from the wood of the *ulu, koa* or *wiliwili* trees (*Artocarpus altilis* , *Acacia koa* and *Erythrina sandwicensis,* respectively). The *koa* and *wiliwili* are both native to the Hawaiian island chain; the *ulu,* also known as the breadfruit tree, exists all around Polynesia (2).

There were four primary varieties of historic surfboards hand-shaped in Hawai'i (listed from longest to shortest): the *olo, kiko'o, alaia,* and *paipo.* The *olo* boards were typically around 18 feet in length or more, and could weigh over 200 pounds, whereas the *alaia* boards—the shortest board meant for stand-up surfing—would range between 9 and 12 feet in length. The four different categories of surfboard were reserved for different classes in ancient Hawaiian society.

Ancient Shapes

None of these boards had fins on the bottom, though their surfaces would range from concave to convex, depending on the performance desired in the water. While the 18-foot *olo* boards were nearly large enough to ride open-ocean swells, the *alaias* were meant for waves breaking in shallower water, closer to shore. The *alaia* boards are most similar to the longboards ridden today (3).

Some More History

The sport nearly vanished with the coming of the Christian missionaries to the Hawaiian islands; the activity was banned in the 19^{th} century by the European colonists. The knowledge of board-shaping fell away; the near extinction of the *koa* tree (also known as sandalwood), and a general disintegration of ancient Hawaiian culture, did not help to keep the sport alive.

Surfing was rediscovered in the late 19^{th} and early 20^{th} century, however; the first instance of surfing on the mainland of the United States was reported in 1885 in Santa Cruz, California, at the San Lorenzo Rivermouth. The Hawaiian princes who introduced the sport there surfed on boards made of redwood, milled locally. Duke Kahanamoku popularized the sport immensely in both Australia and America in the 1910s and 1920s.

Progress in Board Creation

For the next 40 years, boards continued to be made from wood; redwood, cedar, and especially balsa, were all common materials used in the production, especially in America. Surfboards skegs were introduced (fins), which drastically improved the maneuverability of the boards.

In the 1950s and 1960s, a revolution in board manufacture was introduced with the invention of foam core boards; in this type of construction, a polyurethane (P/U) foam core is encapsulated by fiberglass soaked with hardened unsaturated polyester resin (UPR). These boards are far lighter than wooden boards, and hence much more maneuverable in the surf.

Surfboards built with P/U cores and UPR “skins” represent roughly 70% of surfboards on the market today. A cutaway image of the typical construction is shown below.

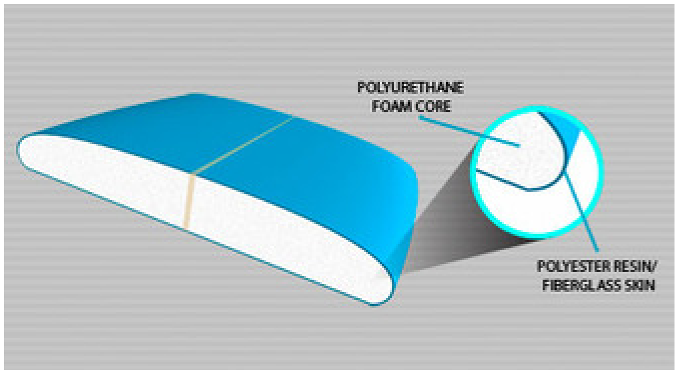

Figure 2: Cutaway of conventional surfboard construction. Image from Stewart surfboards website (4).

The construction of a conventional surfboard has not altered from this pattern. Most new designs of surfboards, including the expanded polystyrene (EPS) and epoxy resin forms studied in this paper, follow an identical construction, with different materials.

Motivation

Interest is growing in the surf community to design a surfboard from "green" materials; however, no life-cycle assessment (LCA) of a common surfboard has ever been conducted. Without an LCA for the baseline materials used in surfboard manufacture, it is impossible for members of the surf community to make informed decisions about reducing their footprint.

The surfing community is at a crucial juncture; decisions made, if ill-informed, will waste both money and time in the effort to make surfboarding an environmentally friendly pursuit. This LCA is meant to fill this information gap.

Scope

The results of this LCA are composed of three parts; carbon footprint, toxic by-products from manufacturing, and local toxic exposures in board construction (along with associated toxic components) of the surfboard. These results reflect what was observed to be three of the primary concerns of the surfing community.

These results will address inputs and outputs from two types of surfboard; P/U core construction with unsaturated polyester resin-soaked fiberglass (UPR construction), and EPS core construction with epoxy-resin soaked fiberglass (epoxy construction). As mentioned, UPR construction is preponderant on the market today; however, epoxy resin construction has shown widespread adoption in recent years. Together, these types of construction represent by far the majority of surfboards produced today, exceeding 95% of market share. From board surveys circulated for this research, it is estimated that roughly 70% of existing surfboards are made of UPR construction; the majority of the remaining 30% are made from epoxy.

The assessment methodology was kept generalized in scope; manufacture of all the components (foam core, UPR, and epoxy resin) all differ widely across the market. This report focuses on the products in a general sense, assessing the footprint of a "typical" surfboard. Differences in the market are reflected in a range of outputs for both carbon and toxic outputs.

The study of local toxic exposures was difficult to assess in quantitative detail. The market for these materials varies widely, as do their constituent chemicals; in addition, the toxic effects of many of the chemicals utilized are not well understood. Rather than focus on a quantitative analysis, the assessment of local exposure provided is an inventory of chemicals used in resin and catalyst/hardener combinations; weighted toxicity information is provided, as available.

Description of the components used in surfboard manufacture, as well as the methodologies for their constituent life cycle assessments, are addressed below.

Construction and Methodology

A summary of construction materials, and LCA methodology, is provided in the table below. Further text descriptions of each are also provided.

Component	Quantity UPR	Quantity Epoxy	Units	Assessment Methodology
Foam Core dimensions	6'2" x 20⅝" x 2.5"	6'2" x 20 ¼" x 2.8"	inches	EIO-LCA: *Sector #3261A0*
Fiberglass	4.35	4.39	yd^2	EIO-LCA: *Sector #32721A*
Resin	80	75	fl. oz.	EIO-LCA: *Sector #325211*
Catalyst or Hardener	1.6	15.0	fl. oz.	EIO-LCA: *Sector #325190*
Surfacing Agent	3.2	0.0	fl. oz.	EIO-LCA: *Sector #325211*
Board Shaping	14.0	14.0	kWh/board	Process assessment
Board Maintenance	5.5	5.5	repairs/life	Direct survey
Board Lifetime	380	650	hours	Direct survey

Table 1: Overview of construction materials and assessment methodology. All EIO-LCA methodologies refer to the 1997 model (5).

Foam Core or "Blank"

The foam core, typically called a "blank", is most commonly made from polyurethane (P/U). Since the closing of Clark Foam in 2005, there has been widespread experimentation in the industry, including the use expanded polystyrene (EPS). This report assesses the footprint of P/U and EPS blanks, when used in construction of surfboards.

The report is based on construction of a 6’0” shortboard. Boards in the 6-7’ range are very common.

Prices were obtained from several companies, selling both P/U and EPS blanks. Using prices from these companies, an EIO-LCA analysis was performed for both polyurethane and expanded polystyrene (5). Results include carbon footprint, and total toxic releases and transfers.

Fiberglass

Made from woven strands of glass, this is the primary structural part of a surfboard. Once the resin hardens, the fiberglass becomes strong and flexible. The primary weights of fiberglass used in surfboard construction are 4 ounce and 6 ounce (corresponding to weight per square foot). Higher-weight means a stronger fabric, and it is noted that in boards requiring extreme levels of strength, such as those used in tow-in surfing, higher weight fiberglass is used. In this analysis, 4-oz fabric was assessed.

An EIO-LCA methodology was used for the fiberglass. Results include carbon footprint, and total toxic releases and transfers. Pricing was based on company prices. The yardage of fiberglass per surfboard was estimated as follows:

$$yd^2 = 3 \cdot (h \cdot (w + 2t)) + 3 \cdot (0.5 \cdot h_f \cdot w_f)$$

Equation 1: Fiberglass required. h is the height of the surfboard, w its width, t its thickness; h_f and w_f are the height and width of the fins.

Three layers of fiberglass were included, two for the bottom, one for the top. The formula is for a simple rectangular shape, which is assumed to include waste fiberglass. The fins are assumed to required triangular pieces of fiberglass; there are assumed to be three fins.

Resin

Unsaturated polyester resin (UPR) has predominant market share today, though there has been increasing adoption of epoxy resin. While other types of resin are being used in the industry, these two are by far the dominant types, and are addressed in this paper.

UPR is a somewhat generic term, and refers to a broad family of polyester resins. In marine applications (including boats and surfboards), the primary chemical composition is propylene glycol/phtalic anhydride, mixed with styrene monomer.

Epoxy resin is an even more generic term, referring to a broad family of chemicals. Epoxy resin results in more durable surfboard construction than unsaturated polyester resin, though it is more expensive.

Typically, two coats of resin are used on a surfboard. The first coat is the “gel coat”, and is the primary structural base. The second coat is the “sanding coat”; mixed with surfacing agent (required only in UPR construction), this produces a harder material, which can be sanded. A third coat, the “gloss coat”, is used in some surfboards, for desired aesthetic purposes, and improved structural performance.

Discussions with surfboard shapers led to the conclusion that for a 6’0” surfboard, approximately 40 fluid ounces of UPR were needed for each coat, with slightly less resin used for construction with epoxy.

Along with prices, this lent itself to EIO-LCA methodology. Results include carbon footprint, and total toxic releases and transfers. Material Safety Data Sheets (MSDS) for several companies were analyzed to collect an inventory of toxic chemicals found in these materials.

Surfacing Agent

Hardened UPR is too soft for direct sanding, which is required to make the board surface uniform. The UPR is instead mixed with a “surfacing agent,” styrene monomer, to improve sanding capabilities. Most surfboard laminating resins are in fact made up of a mixture of UPR and styrene monomer, though most often for the “hot coat,” more styrene is added to the mixture.

Epoxy resin does not require surfacing agent for sanding.

Amounts of surfacing agent were based on the required ratios of each chemical, which were found on the chemical manufacturer website. This ratio is typically around 5% by volume of monomer to UPR; a 4% ratio was used.

EIO-LCA was used to assess a carbon footprint, and total toxic releases and transfers. Styrene monomer is a chemical whose toxicity is already established, and its weighted toxicity information is included, based on the MSDS sheets from various companies.

Catalyst and Hardener

UPR uses a catalyst to induce resin hardening; this catalyst is typically composed mainly of methyl ethyl ketone peroxide.

Epoxy resin requires a chemical hardener, which is incorporated into the chemical structure of the epoxy after hardening. The chemical hardener used varies from company to company; depending on the chemical composition of the resin and hardener, differing ratios of resin/harder are required.

Amounts of catalyst/hardener were based on the required ratios of each chemical, which were found on the chemical manufacturer website. A 2% by volume mixture of catalyst to UPR was assumed; for hardener, ratios of hardener to epoxy are much larger. A 20% (1:5) ratio of hardener to epoxy resin was used, based on manufacturer specifications.

EIO-LCA was used to assess a carbon footprint, and total toxic releases and transfers. Inventory of toxic chemicals, and available information on weighted toxicity, was provided, based on the MSDS sheets from various companies.

Construction Process

The first step in the process is the manufacture of the foam blank, either P/U or EPS. The blank industry has a strong domestic presence, and many surfboards made in California use blanks made domestically. (The results only take into account domestically produced materials.) Details of foam core manufacture are not analyzed in this report.

Once the foam core is produced, a surfboard company shapes the surfboard to have the desired properties. Desired attributes vary from surfer to surfer, but include such fine details as rail shape, and concavity of the bottom. There are companies which make boards using machines, but many boards are shaped by hand. Oftentimes the surfboard shaper will work closely with the surfer to produce personal, tailor-made surfboard.

This shaping process is taken as identical for EPS and P/U cores. There are molded EPS cores, which are "blown" into a pre-defined mold, much as injection molded plastics. This type of construction was not assessed in this paper.

Once the blank is made into the desired shape, sheets of fiberglass are laid on, and resin is applied. This process does not differ between UPR and epoxy resin, though the types of chemicals required do. At least two coats of resin are applied.

Once the resin hardens, a final sanding is performed to even out the surface of the board.

Fins come in multiple construction types; some boards are made with removable fins in mind, others are "glass-on," included in the fiberglassing process of the board shape. Neither type of fin was expected to result in significantly different emissions. Both were taken simply as triangular pieces of fiberglass; the board was assumed to have three fins.

Specific data regarding electricity consumption and board output were obtained from board shapers. Combined with information on California's electricity mix and emissions, this data was used to estimate the carbon emissions produced during the shaping process (6,7). Thus a simple relation of emissions per board shaped was created.

Other materials used in shaping—acetone, sandpaper, masks, brushes, etc.—were not included in the assessment. Shapers use a wide variety of different materials in different contexts, and developing a comprehensive model of these products was outside the scope of the project.

Board Lifetime & Maintenance

To include real figures on expected board lifetime, and the amount of maintenance required, a survey was used to collect information. The survey asked simple questions, such as “How often do you ding your board?”, as well as obtaining information on surfing patterns and past boards. Input from 30 respondents (out of total 70 replies) was used; these 30 reported surfing primarily on shortboards, which are typically close to 6’0” in length.

Estimates of board lifetime were made for UPR and P/U boards by dividing the total number of boards discarded by the hours spent surfing during a surfer’s lifetime. This insured that board lives were normalized to periods of actual activity in the water, when most of the damage is expected to be done to a surfboard.

Similarly, the number of incidents where damage occurred to a surfboard (a “ding”) was normalized by the number of hours spent surfing.

The following table summarizes some of the basic results.

	1st Quartile	**2nd Quartile (Median)**	**3rd Quartile**
UPR Board Lifetime in Hours	165	380	900
UPR Hours Between Dings	35.7	69.3	101.2
Epoxy Hours between Dings	30.8	118.9	Never

Table 2: Summary of responses from Board Lifetime survey. The “Never” for epoxy boards represents surfers who never reported damaging an epoxy board.

The large spread of the quartiles shows the wide variation in board lifetimes. Variations can occur based on surfing style, typical swell height of the region, and nearly an infinity of other factors. The median (2nd quartile) values were taken as representative. It is noted that as expected, epoxy construction does, in general, result in a more durable board, as they require less maintenance.

There was not a large enough sample size surveyed to create reliable statistics for epoxy lifetime, mostly because epoxy has not had significant market penetration for a sufficient period of time. Roughly 30% of the 30 respondents had owned epoxy boards at one time; less than 50% of these respondents had owned their boards for more than one year. Board lifetimes were not assessed directly for epoxy construction.

For epoxy construction, there was enough for estimates on board maintenance, but not for board lifetime. Board lifetime for epoxy construction was instead estimated by taking the ratio of time between damages; the ratio used was approximately 1.7.

The following table contains information on the materials used in a typical surfboard repair. These were estimated based on the author's firsthand knowledge of the process, and can be seen only as approximate.

Component	Quantity (UPR)	Quantity (Epoxy)	Unit
Fiberglass	0.1	0.1	sq yd
Resin	18.4	17.1	fl oz
Catalyst/Hardener	0.4	3.5	fl oz
Surfacing Agent	0.7	0	fl oz
Q-Cel/Epoxy Resin Filler	0.4	0.4	fl oz
Electrical Consumption	2.3	2.5	kWh

Table 3: Material required for one surfboard repair. All quantities estimated. Electrical consumption taken to produce 10% of the emissions in the end product, which was reflective of the ratio for board manufacture.

End of Life

Three possible scenarios are considered for the end-of-life of surfboard; transportation to a landfill, disposal on-site (in or outside of a residence), and re-use. These end uses were the most common responses to one of the survey questions ("When you can no longer ride a board any more, what do you typically do with it?").

For landfilling, emissions are negligible; the primary outputs are from transportation in a dump truck. Surfboards typically weigh less than 10 pounds. Assessing typical emissions per ton-mile of freight shows that transporting a 10 pound surfboard 100 miles would result in roughly 1 gram of carbon emissions (11). Examining the final results below, landfilling proves to have a totally negligible contribution, and was discounted in this analysis.

Disposal on-site can include two means; actual disposal outside, in the environment, or in a residence, including garages and living rooms. (Many respondents actually reported turning surfboards into furniture, for example). External disposal could include losing a surfboard, or discarding it in a backyard.

For external disposal, it is nearly impossible to quantify long-term effects. All the chemicals would eventually leach into the outer environment, but the composition of these leachants and their preponderance in the environment was outside the scope of this report.

For internal disposal, it was assumed that boards would either eventually be landfilled, or discarded outside.

Re-use was not quantitatively assessed in this report.

Data Quality

A summary of data quality is given in the table below.

Component	Acquisition Method	Independence of Data Supplier	Representa-tiveness	Precision	Data age	Geographical Correlation	Technological Correlation
Foam Core	4	4	5	5	2	5	5
Fiberglass	4	4	5	5	2	4	5
Resin	4	4	5	5	2	4	5
Catalyst or Hardener	4	4	5	5	2	4	5
Surfacing Agent	4	4	5	5	2	4	5
Board Shaping	4	2	5	2	5	5	4
Board Maintenance	5	5	5	5	5	5	5
Board Lifetime	5	5	4	3	5	5	5

Table 4: Data quality table.

The largest weakness in the data is the age of the EIO-LCA model used for most of the construction components, which is from a model created in 1997. This would not reflect any changes in the industries in the past decade, for any of the construction components.

A small sample size in the Board Lifetime survey was another weakness in data quality.

Results

Carbon Footprint

The following table gives the greenhouse gas emissions resulting from UPR and epoxy construction.

	UPR	Epoxy	UPR	Epoxy
Component	**kg CO_2e**	**kg CO_2e**	**%age**	**%age**
Blank	50	60	26%	26%
Fiberglass	10	10	5%	4%
Resin	30	70	20%	28%
Catalyst	3	20	2%	9%
Shaping Process	10	10	6%	4%
Lifetime Maintenance	65	70	37%	28%
Surfacing Agent	6	0	3%	26%
TOTAL	170	250		

Table 5: Carbon footprint of a surfboard. Numbers may not add, due to rounding errors.

The pie charts below illustrate graphically the different component's contribution to the carbon footprint.

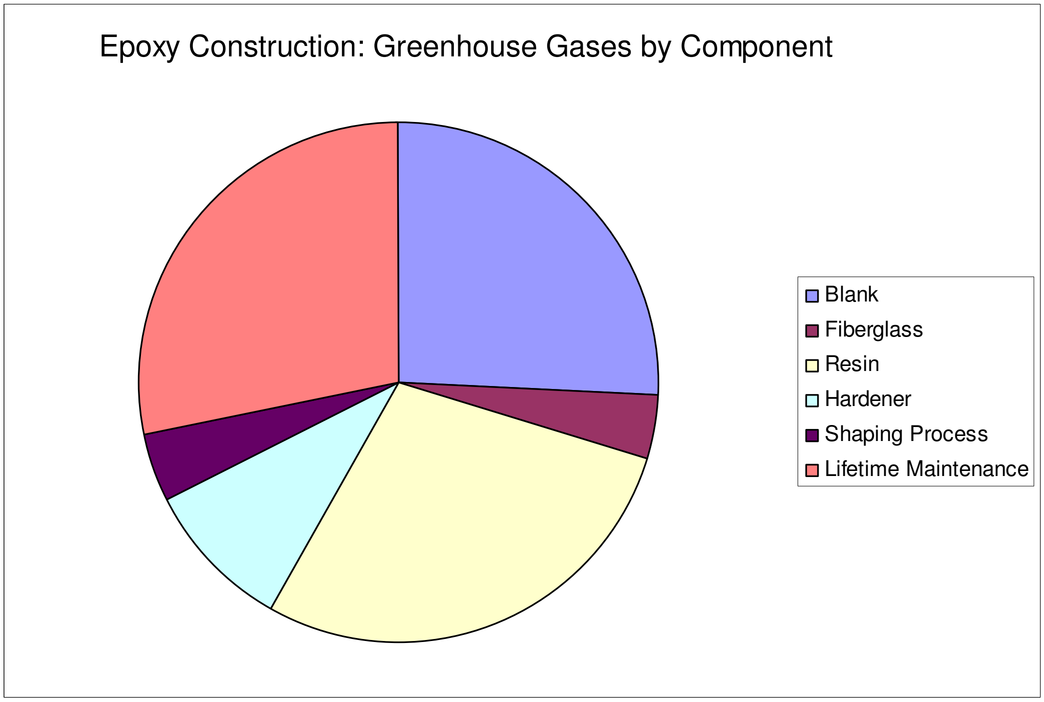

Figure 3: Carbon footprint for epoxy construction.

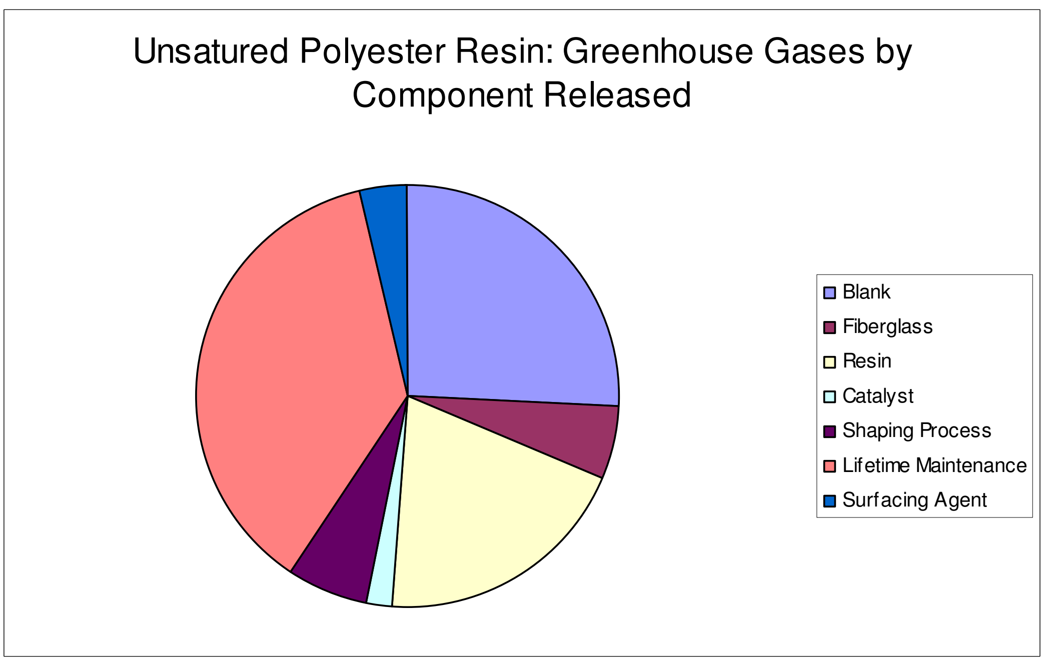

Figure 4: Footprint for UPR construction.

It is observed that in both types of construction, lifetime maintenance is the largest contributor to the lifetime footprint, followed by resin and blank manufacture. A breakdown of maintenance emissions are shown in the following figures.

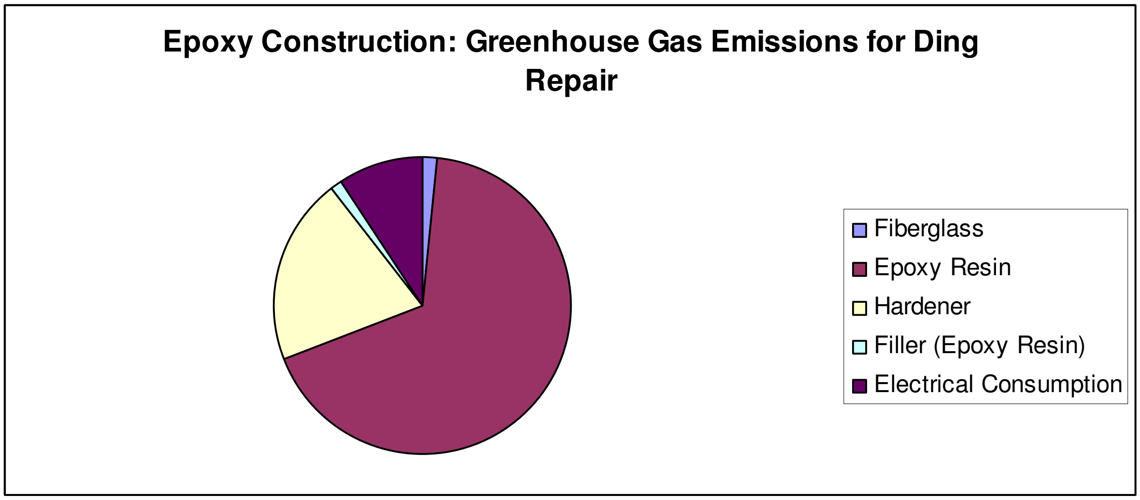

Figure 5: Emissions associated with surfboard repair.

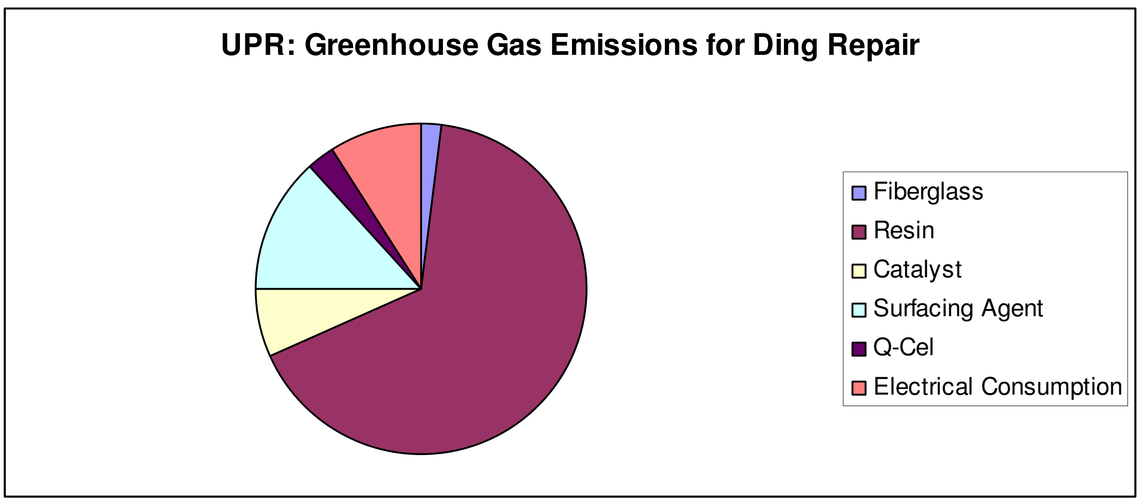

Figure 6: Emissions associated with surfboard repair.

Toxic Releases and Transfers

The total amount of toxic materials produced is included.

	UPR	Epoxy	UPR	Epoxy
Component	**grams**	**grams**	**%age**	**%age**
Blank	110	150	40%	42%
Fiberglass	10	10	4%	3%
Resin	60	100	21%	26%
Catalyst	5	30	2%	9%
Lifetime Maintenance	80	70	30%	20%

Surfacing Agent	8	0	3%	0%
TOTAL	260	360		

Table 6: Toxic by-products produced from surfboard manufacture. Quantities might not sum, due to rounding.

The following pie charts display the breakdown of toxic products, by component.

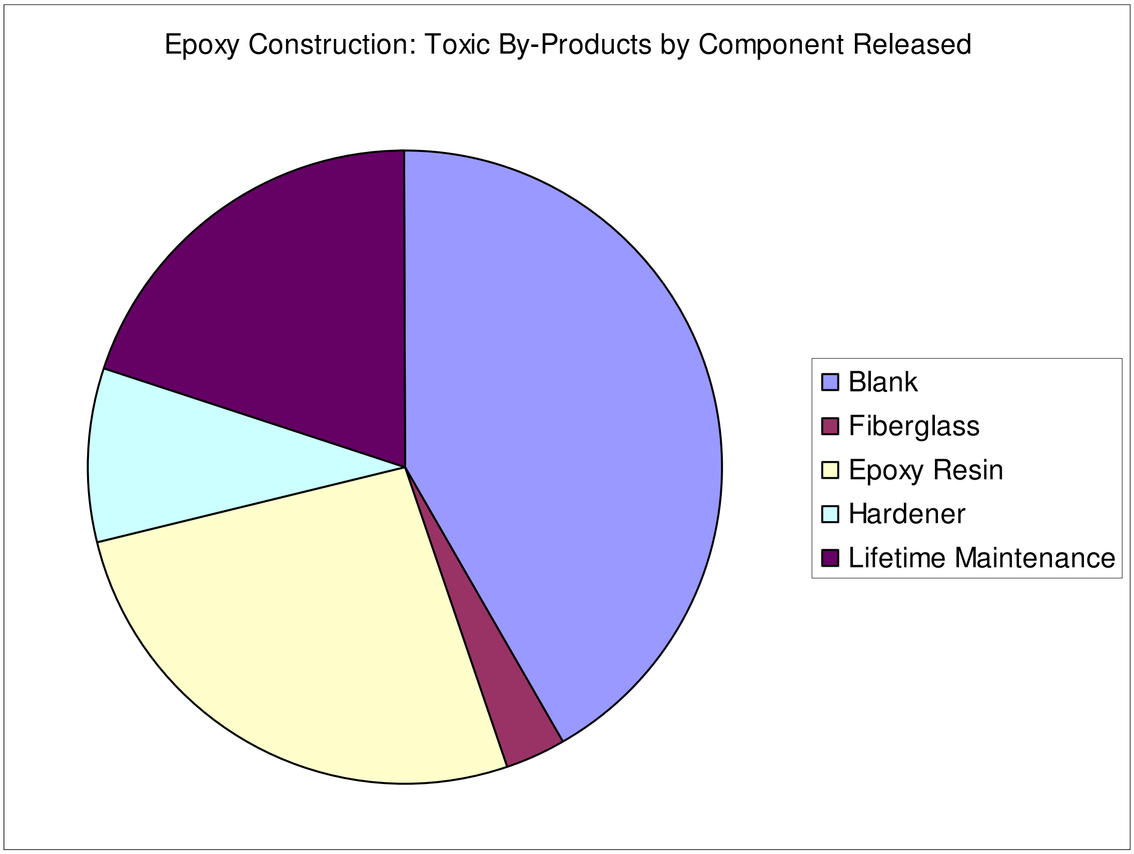

Figure 7: Toxic by-product footprint for epoxy construction.

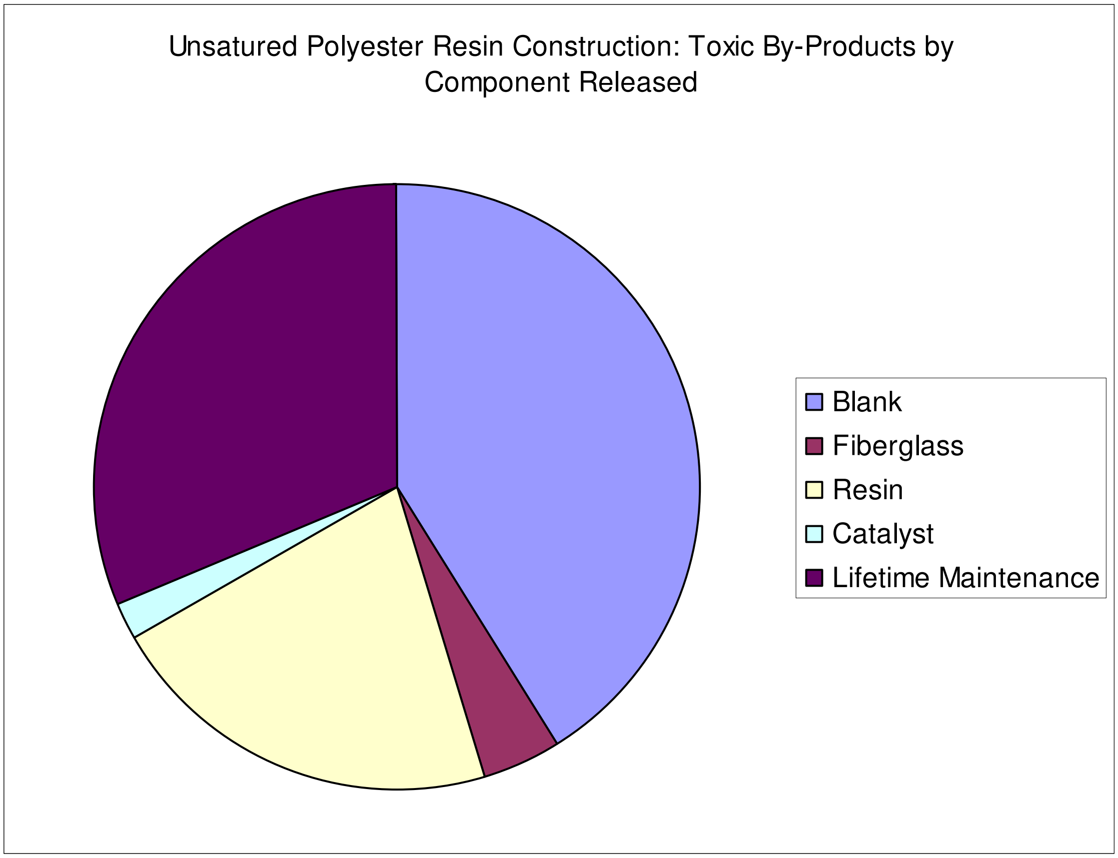

Figure 8: Toxic by-product footprint for UPR construction.

Local Toxics

As described in the Scope, toxicity information on most of the chemicals are mostly unavailable. Common amounts, and weighted toxicities, are given in the table below.

Component	Chemical Constituents	Volumetric Concentration	Volume per surfboard (fl oz)	Weighted Toxicity g H_2SO_4 equivalent
UPR	Unsaturated polyester base resin	63.5%	51	N/A
UPR	Styrene Monomer	36.5%	30.	3.7
UPR Catalyst	Methyl Ethyl Ketone Peroxide	38.0%	0.61	N/A
UPR Catalyst	Dimethylphthalate	47.0%	0.75	5.3
Surfacing Agent	Styrene Monomer	90.0%	2.9	0.40
Epoxy Resin	Bisphenol-A type epoxy resin	50.0%	38	NA
Epoxy Resin	Benzyl alcohol	20.0%	15	NA

Epoxy Resin	Bisphenol-F type epoxy resin	20.0%	15	NA
Epoxy Resin	Ethylene glycol monobutyl ether	0.3%	0.23	0.25
Epoxy Hardener	Polyethylenepolyamine	25.0%	3.4	NA
Epoxy Hardener	Reaction products of TETA with Phenol/Formaldehyde	25.0%	3.4	NA
Epoxy Hardener	Triethylenetetramine (TETA)	15.0%	2.0	NA
Epoxy Hardener	Hydroxybenzene 108-95-2	12.0%	1.6	2.7
Epoxy Hardener	Reaction Products of TETA and propylene oxide	12.0%	1.6	NA
Epoxy Hardener	Polyethylenepolyamine	12.0%	3.4	NA

Table 7: Inventory of toxic chemicals, from Material Safety Data Sheets. Manufacturer information can be found in the appendix. It is highlighted that this toxics data is insufficient to make a real comparison between epoxy and UPR construction. Description of weighted toxicity can be found in Appendix A.

It is noted that epoxy resins available on the market vary widely in their composition. There are resins available, for example, with no listed toxics. The epoxy resin here was chosen as representative.

Discussion

For both types of construction, and both for the carbon and toxic emissions footprint, the emissions are dominated by blank manufacture, resin manufacture, and lifetime maintenance of the surfboard. In UPR construction, fiberglass, catalyst, and surfacing agent combined account for less than 10% of the footprint, while the ratio is only slightly more for the epoxy construction.

Lifetime maintenance is found to be a major contributor to this footprint.

Local toxics are shown only as an inventory, due to lack of data, as well as large variability in the chemical stock. It is noted that some of the chemicals pose very little risk to the shaper, as they are bound up in the structure; others, notably styrene monomer and methyl ethyl ketone peroxide, are known to evaporate quickly, and are much more likely to be inhaled.

It is highlighted that the toxics data is insufficient to make an informed comparison between epoxy and UPR construction. This information is provided for reference only, and in the hope that more research will be pursued.

Uncertainty in Carbon Footprint

There were many sources of uncertainty in this model; all were combined into upper and lower bounds, and aggregated by importance. Sources of uncertainty include differences in material manufacture, inconsistencies in shaping processes (including material waste), and the large variability seen in both board lifetime and maintenance requirements. The upper and lower bounds of each component of the surfboard are shown in the table below.

	UPR Upper Bounds	UPR Amounts Used	UPR Lower Bounds	Upper Bound: Component Attribution to Final Uncertainty	Lower Bound: Component Attribution to Final Uncertainty
Component	**kg CO_2e**	**kg CO_2e**	**kg CO_2e**	**%**	**%**
Blank (P/U)	45	45	45	0%	0%
Fiberglass	19	10	9	6%	0%
Resin	43	34	31	5%	-2%
Catalyst	4	3	3	0%	0%
Shaping Process	12	11	9	1%	-1%
Lifetime Maintenance	119	65	19	31%	-26%
Surfacing Agent	7	6	2	0%	-2%
TOTAL	250	170	120	+43%	-32%

Table 8: Uncertainty in carbon footprint of UPR construction.

	Epoxy Upper Bounds	Epoxy Amounts Used	Epoxy Lower Bounds	Upper Bound: Component Attribution to Final Uncertainty	Lower Bound: Component Attribution to Final Uncertainty
Component	**kg CO_2e**	**kg CO_2e**	**kg CO_2e**	**%**	**%**
Blank (EPS)	64	64	64	0%	0%
Fiberglass	19	10	9	4%	0%
Epoxy Resin	77	70	52	3%	-7%
Hardener	74	23	23	20%	0%
Shaping Process	12	11	9	1%	-1%
Lifetime Maintenance	119	64	0	20%	-28%
TOTAL	370	240	160	47%	-36%

Table 9: Uncertainty in carbon footprint of epoxy construction.

In epoxy construction, hardener footprint showed a large variability. This was due to variability in manufacturing of these chemicals, and varying amounts of hardener/epoxy resin mixtures.

In both construction types, uncertainty in lifetime maintenance plays the largest factor in uncertainty. This is not surprising, as board repairs can occur at nearly random intervals. A summary of reported ding repair frequencies is given in Table 2, and illustrates the large variability in this portion of the analysis.

When uncertainty in the lifetime maintenance is removed, the footprint converges quickly. It is the inherent unpredictably in the sport of surfing that prevents a more precise estimate from being made.

Uncertainty in Toxic By-Products

The uncertainty in the amount of toxic by-products is presented in the same fashion as above.

	UPR Upper Bounds	UPR Amounts Used	UPR Lower Bounds	Upper Bound: Component Attribution to Final Uncertainty	Lower Bound: Component Attribution to Final Uncertainty
Component	g	g	g	%	%
Blank (P/U)	105	105	105	0%	0%
Fiberglass	22	11	11	4%	0%
Resin	59	46	42	5%	-2%
Catalyst	5	5	5	0%	0%
Lifetime Maintenance	147	80	24	26%	-22%
Surfacing Agent	9	8	3	0%	-2%
TOTAL	350	260	190	+35%	-26%

Table 10: Uncertainty in toxic by-products from UPR construction.

	Epoxy Upper Bounds	Epoxy Amounts Used	Epoxy Lower Bounds	Upper Bound: Component Attribution to Final Uncertainty	Lower Bound: Component Attribution to Final Uncertainty
Component	g	g	g	%	%
Blank (P/U)	150	150	150	0%	0%
Fiberglass	22	11	11	3%	0%
Resin	105	95	70	3%	-7%
Hardener	102	32	32	20%	0%
Lifetime Maintenance	131	72	0	16%	-20%
TOTAL	510	360	260	+42%	-27%

Table 11: Uncertainty in toxic by-products from epoxy construction.

The primary causes of uncertainty are identical to those for the carbon footprint.

Uncertainty Discussion

As described above, the largest uncertainty is really a variability factor; surfboard maintenance does not occur at scheduled intervals. In the large surf of Hawai'i, for example, it is possible for a board to be broken the first time it enters the water—conversely, in smaller waves, a board might not sustain a ding for months or even years of active surfing.

The summary spread of ding frequencies is given in Table 2, along with the spread of surfboard lifetimes.

Impact Assessment: External Cost Valuations

Though somewhat controversial and susceptible to ever-changing considerations, there are existing studies documenting external costs of carbon emissions and other primary air pollutants. Information from the source to assess external costs includes health effects and other adverse long-term effects in the environment (12).

The external costs used here are as follows: \$20/metric ton CO_2-equiv, \$790/MT of CO, \$1,611/MT of NO_X, \$2,736/MT of SO_2, \$4,256/MT of particulate matter (dust), \$2,128/MT of VOCs (all in 2009 \$); emissions per surfboard for each of these pollutants was assessed and presented in Appendix B. These emissions were not a primary part of the study, and did not include emissions from board shaping. Thus these external costs can be viewed as an underestimate.

Board	External Costs due to Air Pollution
UPR Construction	\$5.59
Epoxy Construction	\$8.19

Impact Assessment: Carbon Footprint per Session

To further put the footprint of a surfboard into context, the associated emissions were normalized by surf session, and compared to emissions associated with driving. Driving emissions shown here include all lifetime emissions, including those associated with vehicle manufacture and maintenance, as well as road construction and maintenance (10). Emissions associated with other surfing equipment, such as wetsuit, wax, and leash manufacture, are not included.

The comparison below takes into account the longer expected lifetimes of epoxy construction. A chart summarizing the findings are presented below, along with associated uncertainty.

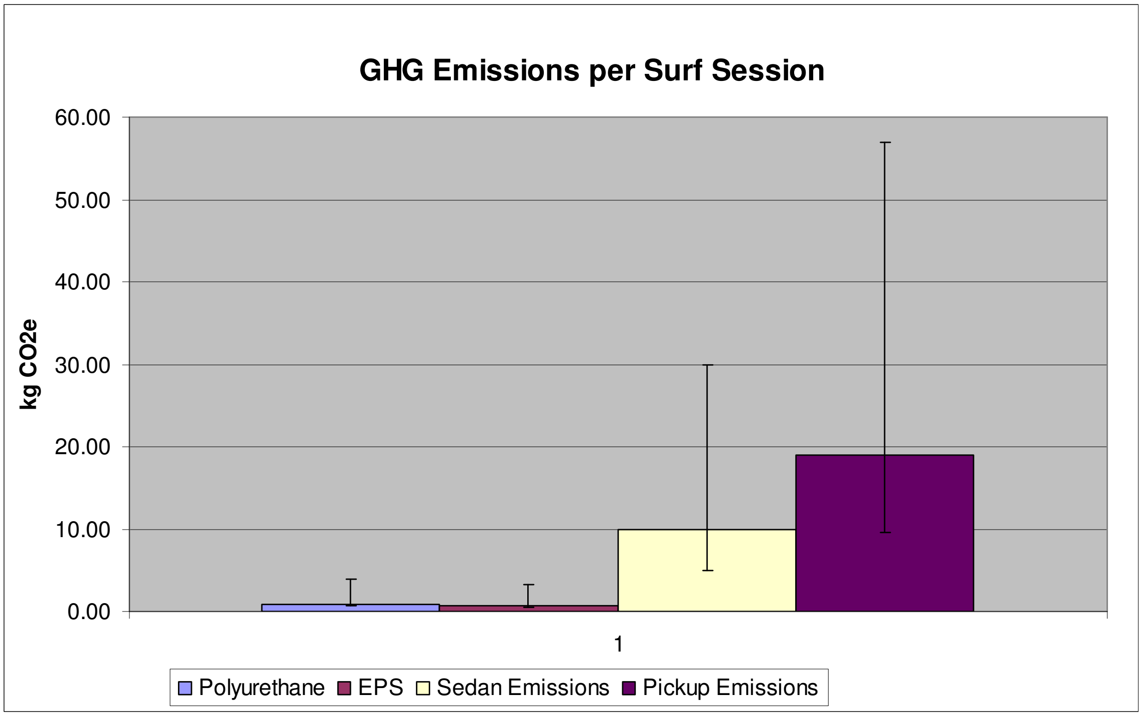

Figure 9: Greenhouse gas emissions per surfboard. Only emissions associated with surfboard and driving are included; other equipment, such as wetsuit, leash, and wax, not assessed. Variability in car emissions are due to variations in driving distance; error bars here represent round-trip for a break 2.5miles to 10 miles away. Average is taken as 5 mile distance. Emissions information taken from Chester report on passenger transportation (10).

What is immediately apparent from this chart is that emissions from driving dominate the footprint of surfing. The upper bound represented by this passenger transportation figure represents a round-trip distance of 10 miles; it is noted that in some locations, surfers drive much further than this (the author regularly drives 20 miles, for example).

For surfers, driving is by far the largest contributor to greenhouse gas emissions. A table showing the number of miles driven to equal the emissions from surfboard manufacture is shown below.

Driving equivalencies	UPR	Epoxy
Sedan miles driven	170	250
Pickup miles driven	90	130

Table 12: Table cataloguing miles driven in a sedan and pickup truck which equal carbon emissions from surfboard production. E.g. driving 90 miles in a pickup truck results in the same amount of carbon emissions as manufacturing a surfboard.

A comparison can also be made based on the external costs of driving, as developed in the section previous. This is outlined as a cost-per-session in the table below.

Category	External Costs
UPR For One Session	$0.02
Epoxy Construction P For One Session	$0.02
Sedan (10 miles driven)	$0.10
Sedan (40 miles driven)	$0.40
Pick-up Truck (10 miles driven)	$0.19
Pick-up Truck (40 miles driven)	$0.75

Table 13: External Costs of a Surf Session.

Again, the most important point is to note that there is an order of magnitude difference between surfboard production emissions and driving emissions.

Discussion

When surfboard manufacture is taken at face value, epoxy construction results in more emissions, for the footprint of both carbon and toxic by-products. However, when the longer lifetime of epoxy construction boards is considered (epoxy construction boards were estimated to survive for 1.7 times as long), epoxy boards are on par with UPR. This can be seen in Figure 9, and in Table 13.

It is noted, however, that with this lifetime factor accounted for, the footprint of UPR and epoxy construction are not significantly different, certainly not within the uncertainty bounds. A similar result is observed for toxic by-products.

For toxic constitutents, it is observed that in general, the chemistry in UPR construction is more uniform across the industry than with epoxy construction. There are epoxy resin/hardener combinations with more toxics than UPR; however, there are producers whose resin/hardener combinations have no toxic constituents.

Recommendations

Recommendations will now be made, based on the results presented here. More research must be performed for local toxic exposures, for example, to make recommendations on toxic exposures. But these recommendations can be viewed as the best available for decreasing the carbon footprint, and amount of toxic by-products, created in surfboard production.

Recommendations for Surfboard Shapers and Manufacturers

It was observed that for both epoxy and UPR construction, resin and blank manufacture take up the lion's share of the footprint of initial surfboard manufacture. Lifetime maintenance was responsible for an even greater proportion; within lifetime maintenance, resin was found to be the largest contributor. Carbon emissions, normalized by lifetime factors, are summarized in the figure below.

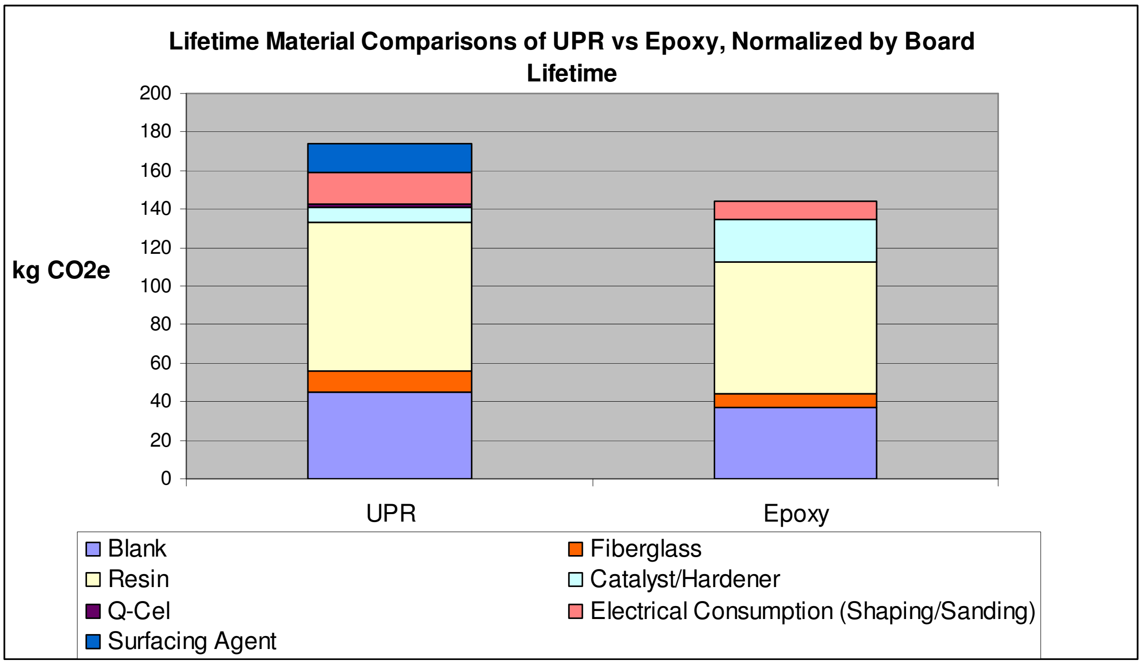

Figure 10: Emissions for normalized lifetime.

Epoxy construction, when lifetime normalization is included, does have a smaller footprint, though not by a significant margin. Uncertainties in data acquisition make a recommendation of epoxy over UPR unreliable; based on the carbon footprint, neither epoxy nor UPR is a clear "winner" environmentally.

For both types of construction, the majority of emissions come from two sources; resin and blank manufacture. Together, these account for over 70% of emissions coming from surfboard manufacture and maintenance. Toxic by-products follow a similar breakdown, though they are not shown here.

There are several salient points which can be drawn from these conclusions; recommendations for board shapers, based on these observations, are given below.

- *Find resin and blanks which are truly "green"—meaning an actual carbon footprint has been performed, and shown to be less than these standard materials.* Board shapers and manufacturers looking to decrease the environmental footprint of surfboards should look to improvements in the manufacture of these two materials. Finding "green" options for fiberglass, for example, can lead to at best 5% reductions in the carbon footprint of a surfboard, when life cycle considerations are taken into account. Board companies using wooden products as a substitute for fiberglass—balsa wood or bamboo, for example—do not produce boards with a significantly smaller footprint, even in a best case scenario. Even modest efficiency improvements in resin and blank manufacture can decrease the footprint of a surfboard notably.

- *Find clean epoxy resins.* For local toxic emissions, it is noted that there are epoxy resins on the market with no toxic constituents. It is recommended that a shaper pursue these alternative epoxy resins when finding the healthiest type of resin.

Recommendations for Surfers

Figure 9 shows very clearly that in the practice of surfing, driving dominates carbon emissions. There are four main recommendations this paper will include for the common surfer, based in order of priority.

1) *Live closer to the ocean.* There will be no carbon emissions associated with driving if a surfer can walk to their break. Driving less will result in drastically fewer emissions.
2) *Purchase a fuel-efficient vehicle.* The difference between pick-up truck and sedan emissions is large; surfers currently driving SUVs or pickups with fuel economies below 20mpg, for example, can nearly halve their carbon footprint by upgrading to a vehicle which gets 30-40mpg. This does not necessarily recommend top of the market models, such as hybrids; a shift from a low efficiency pickup truck to a medium economy sedan (25-30mpg, for example) will mean large carbon savings.
3) *Buy used surfboards from your local surf shop.* By purchasing a used board, a surfer can skip the manufacturing process entirely; this will result in an absence of toxic emissions, and reductions in carbon footprint. Local surf shops are preferred, to avoid the carbon emissions from driving long distances.
4) *Buy a board made from "green" resins or blanks, which have had a quantitative carbon footprint assessed.* As noted above, these are by far the largest contributors to the carbon footprint of a surfboard. Surfers wishing to purchase boards with a truly smaller environmental footprint should look to improvements in these materials. "Green" substitutes for fiberglass or catalysts will not result in significant environmental improvements.

Recommendations for Surfboard Disposal

As noted in the Scope, a detailed quantitative assessment was not conducted for end-of-life. Nonetheless, recommendations can be made based on the information arising from this report.

1) *Re-sell the surfboard.* A board in bad shape might still have useful life for a new surfer, who isn't as concerned about performance. This option can defer a surfboard from being manufactured, resulting in lower carbon emissions.

2) *Send it to a landfill.* Though it is difficult to quantify long-term leaching effects, it is noted that there are toxic components present in surfboards. A board left outside will degrade and chemicals will leach, leading to unknown contaminants going into the ecosphere. Putting a surfboard into a landfill means that these contaminants are safely contained.

Conclusions

The carbon footprint and amount of toxic by-products produced was assessed. An inventory of toxic chemicals was provided as well, for reference. It was found that in the sport of surfing, driving dominates greenhouse gas emissions; for surfboard manufacture, resin and blank production are the dominant contributors. Recommendations were made for both surfboard producers, and common surfers.

The results presented here can be used as a baseline to gauge other LCA options against, as well as create general guidelines for future improvements in surfboard production (as outlined in the Recommendations section).

Much interest in this pursuit was observed in my own interactions with board producers and surfers in general in the creation of this study. It is my hope that this work will guide the surf community towards real, measurable reductions in carbon and toxic emissions.

Appendix A: Weighted Toxicity

Weighted toxicity information was based on airborne threshold limit value (TLV) of a chemical in mg/m^3, supplied by the Occupational Safety & Health Administration (OSHA). Sulfuric acid (H_2SO_4) was taken as a baseline, as its TLV is 1 mg/m^3 (8). Weighted toxicity *T*, as an equivalent mass measurement to for chemical *i*, was then evaluated by the following equation.

$$T_i = \frac{1}{(TLV)_i}$$

This supplies a simple metric for comparing toxicities of different chemicals; a higher value of *T* means a chemical is more toxic. Where TLV was not available, no weighted toxicity was supplied.

Motivation for this methodology comes from Horvath (9), though specific values were supplied by an OSHA/EPA database (8).

Appendix B: Supplementary Tables

Component	Manufacturer MSDS URL	Product Name	Product No.
UPR	Interplastic Corporation St. Paul, MN http://www.foamez.com/pdfs/S249AMSDS.pdf	Unsaturated Polyester Resin	SIL65BQ-249A
UPR Catalyst	Polymer Additives Group Marshall, TX http://www.foamez.com/pdfs/MEKMSDS.pdf	HI-POINT 90	260 0104
Surfacing Agent	Lilly Industries, Inc. Elkhart, Indiana http://www.foamez.com/pdfs/SAMSDS.pdf	SURFACING AGENT	85-X3
Epoxy Resin	West System Bay City, MI 48706 http://www.kelloggmarine.com/msds/WSY-%20West%20Systems/WSY_105_MSDS.pdf	WEST SYSTEM® 105™ Epoxy Resin	105
Epoxy Hardener	West System Bay City, MI 48706 http://www.kelloggmarine.com/msds/WSY-%20West%20Systems/WSY_205A,B,E_MSDS.pdf	WEST SYSTEM® 205™ Fast Hardener	205

Table A 1: Manufacturers of chemicals included in the inventory.

Appendix B: Emissions of Criteria Pollutants due to Surfboard Construction

Though not the focus of this report, the following emissions of criteria pollutants were identified via the EIO-LCA method, to estimate the total external costs of surfboard manufacture. These emissions, for UPR and epoxy construction, are given below.

	CO g	SO2 g	NOX g	VOC g	PM10 g
UPR	630	180	180	200	32
Epoxy	950	280	270	350	49

Table A 2: Emissions of criteria pollutants.

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