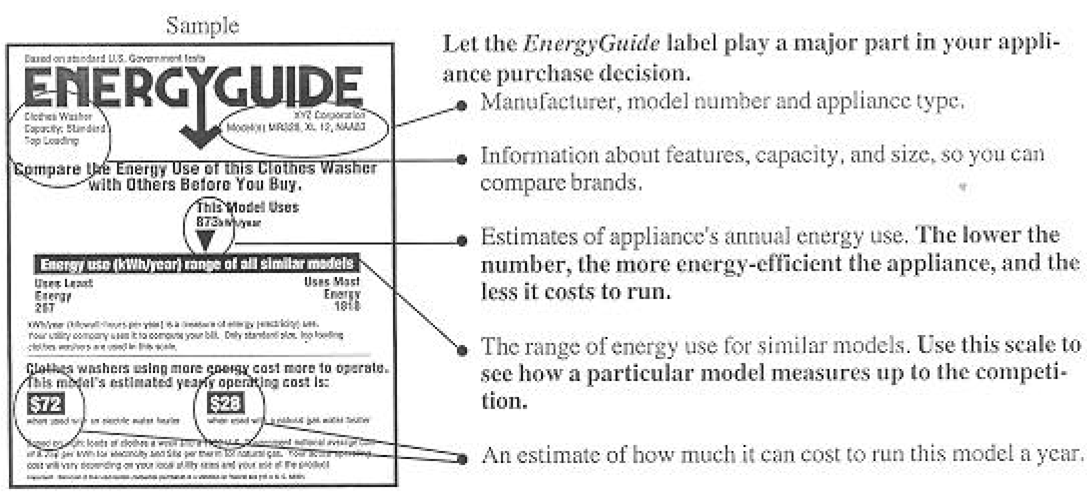
Sample Student Assignment
Streamlined Lifecycle Assessment

The Refrigerator; 1960 vs. 2000



I. INTRODUCTION

The domestic use of electric refrigeration appliances began in the early 20th century, but the unit itself didn't resemble the current refrigerator until the middle part of the century (The Fridge Doctor, 2000). The post WWII period saw enormous growth of domestic appliances, and in turn increased demand for fuels, electricity, and the raw materials necessary to create and distribute these appliances. Although this heightened use of power and raw materials may seem to be an environmental "bad", refrigeration allowes for increased longevity of food, thus reducing food waste. In turn, the reduced use of pesticides, water and land could have overall positive environmental effects. This benefit can be measured by the efficiency with which the refrigeration operates; for example, with the decreased long-term energy use. This paper will use the streamlined life-cycle assessment (LCA) to look at the environmental footprint of a 1960 refrigerator, and compare it to that of a refrigerator created in the year 2000.

II. METHODS

For simplicity, only the core function of food preservation will be measured. Modern refrigerators have vastly increased freezer space, water filtration technologies, ice makers, and other amenities. By comparison, their 1960 counterparts had very few of these functions; in order to level the comparison field, only the refrigeration capacity will be measured. Using the Allenby & Graedel LCA methodology (ESM 282 Reader, 2000), environmental performance will be graded for five waste categories, over five life-stages. Each life-stage - waste category matrix element will be given an environmental performance score, for both the 1960 and 2000 refrigerator. This environmental performance score will range from 0-4, with 4 representing "superior environmental performance". Ultimately, each life-stage category and each waste category will be given a weight to reflect the difference in the life-stage impact and the difference in environmental impact. It is a goal of this weighted matrix to accurately reflect the spatial scale, severity, degree of exposure and potential penalty for each of the environmental impacts.
The LCA information will be presented in the following manner:

Figure 1.1 LCA Life-Stage/Waste Matrix

	Material Use	Energy Use	Solid Residues	Liquid Residues	Gas Residues
Pre-manufacture	1,1	1,2	1,3	1,4	1,5
Product Manufacture	2,1	2,2	2,3	2,4	2,5
Product Delivery	3,1	3,2	3,3	3,4	3,5
Product Use	4,1	4,2	4,2	4,4	4,5
Refurbishment, Recycle, Disposal	5,1	5,2	5,3	5,4	5,5

III. MEASUREMENT

Pre-manufacture Stage

Material Use <1,1>

For the refrigeration appliance industry, much of the metal ore extraction, chemical creation (refrigerant gasses- CFCs, in particular Freon-12-12, or dichlorodifluoromethane) (Department of Energy), insulation materials, plastics, and glasses, are created and manufactured during the pre-manufacture stage. Appliance companies purchase these pre-fabricated base commodities, and modify them in the manufacture stage. For this reason, the environmental impact of the material use category in the pre-manufacture stage is high. In 1960, these materials included iron and steel, leaded paints/pigments, solder, ozone-precursor refrigerants, and carcinogenic insulators (ex: asbestos). The 2000 refrigerator by comparison, uses more aluminum and alloys than iron and steel, plastic and ceramic glazes in place of paint, glasses, more benign refrigerants, and less dangerous insulation.
In addition, the use of recycled materials in 1960 was much lower than it is today; for that reason, the 60s saw much greater use of virgin materials and resources. Regardless of resource source, all materials require fossil fuels to provide energy to the smelting-manufacturing process, and because of the limited store of these fossil fuels, the pre-manufacture of refrigerators, regardless of year, is an environmental liability.
(1960: 1 ; 2000: 3)

Energy Use <1,2>

As mentioned above, most of the raw resource extraction for the refrigerator is conducted in the pre-manufacture stage; for this reason, the energy necessary to extract those resources is also contained here. The smelting of metals, pressing and stamping of refined panels and shelves, and the application of paints and plastic coverings to the metals require enormous energy inputs. Because the 1960 refrigerator used virgin materials, the energy use level is particularly high. At the same time, the modification of pre-used materials for the 2000 refrigerator also requires large energy inputs, and the automation of much of the processing (as opposed to manual labor,) increases the energy input.
(1960: 2 ; 2000: 2)

Solid Residues <1,3>

The mining of metal ore for the 1960 refrigerator produced enormous tailing waste and byproducts. The application of paint to the refined panels also generated particulate matter. In many cases, this particulate matter contained lead, and other heavy metals. The 2000 refrigerator, by comparison, relies less on virgin resources, and thus has less of a footprint in the form of tailings from ore extraction. In addition, the paints used in the year 2000, adhere to modern codes regarding lead use, and in many cases have been replaced by plastic coatings.
(1960: 2 ; 2000: 3)

Liquid Residues <1,4>

Much like the wastes mentioned in the solid residues section, many industrial smelting and manufacturing facilities rely on water, in one form or another, to cool the machinery as well as the products. Paint and plastic applying machinery is cleaned using solvents and hazardous chemicals, which have been known to inadvertantly find their way into the environment. Overall, this is less of a worry, but a potential impact nonetheless.
(1960: 3 ; 2000: 3)

Gas Residues <1,5>

The use of Freon-12-12 in the 1960 refrigerator is one of the most concerning environmental impacts. Within the pre-manufacture stage, the Freon-12-based refrigerant is placed in containers that will eventually be used by the compressor, condenser, and evaporator within the refrigerator (Department of Energy). The inadvertant loss of some of these ozone-precursor gasses could have dire effects. The 2000 refrigerator uses less of this Freon-12-12 refrigerant, if at all, and the facilities within which it is installed are much better prepared to prevent, manage, and contain any releases.
In addition to Freon-12, the by-products of the energy necessary to smelt the base ores (CO, NOx, SOx, PAHs, etc.) have been indicated as agents in the ongoing global warming debate. Regardless of the fossil fuel burned to create the energy, there will be gas residues and byproducts. The 2000 refrigerator is more likely to be created using more benign energy sources, and therefore will be more likely to have less of a footprint in this area.
(1960: 1 ; 2000: 3)

Product Manufacture Stage
Material Use <2,1>

In the product manufacture stage, all of the materials that were extracted and refined in the pre-manufacture stage are modified to resemble the final product. The largest new material use is in the fossil fuels necessary to move the refrigerator parts from the pre-manufacture locations to those where the final product will be manufactured. Besides this input, the only additional resources necessary in the 1960 refrigerator include the soldering of steel to form the infrastructure, the folding, pressing and applying of metals to the outside, the installation of insulation, and the placement of the compressor, condenser, and evaporator. Other than the energy required to transfer the materials to the production floor, to solder the pieces together and to move the refrigerator along the production line, very little new materials are introduced at this stage. Likewise, the 2000 refrigerator has a relatively small environmental footprint in the product manufacture stage. Most of the costs of production have been accounted for in the pre-manufacture stage, and for this reason, the overall rating for both refrigerators is high.
(1960: 3 ; 2000: 3)

Energy Use <2,2>

The transfer of the fabricated materials to the production facility is the largest use of energy. This is true for both the 1960 and the 2000 refrigerator. Because these components are shipped in mass quantities, trucks, cargo liners and trains are used- all of which consume large amounts of fossil fuels. The production line for the 1960s refrigerator may be a larger consumer of labor than energy, but the transfer of these materials to the production facility was done in a less efficient manner. For this reason, the 1960 and 2000 refrigerators receive an identical score in this category.
(1960: 2 ; 2000: 2)

<u>Solid Residues <2,3></u>

Once the processed materials reach the production facility, they are modified for use in the refrigerator. This process may include trimming or cutting the metals, plastics and insulation, which produces solid residues in the form of large scraps, solder waste, and dust particulates. The 1960 refrigerator, which used some hazardous materials (lead, asbestos, etc.,) may have more dangerous solid residues. The 2000 refrigerator, which uses more plastics and alloys than the 1960 refrigerator, may have more difficulty recycling and reusing the scraps.
(1960: 2 ; 2000: 3)

<u>Liquid Residues <2,4></u>

If the processed materials that were delivered to the production facility require additional painting or fabrication, many of the impacts that took place in the pre-manufacture stage apply here as well. It is unlikely that a large concentration of liquid residue is present. If anything, the leaded paint residue from the 1960 refrigerator could pose a potential environmental problem in this stage.
(1960: 3 ; 2000: 4)

<u>Gas Residues <2,5></u>

If the Freon-12-12 is installed at this point in the production process (the compressor could be delivered empty, if required by law,) then the potential for CFC emissions from the refrigerant installation in the 1960 refrigerator are high. In addition to the Freon-12-12 potential, the refrigerators from both eras required the transport of materials, as mentioned in the material use stage. This transport process produces pollutants and greenhouse gasses as byproducts, and therefore has a large, negative impact on the environment. Parts for the 1960 refrigerator were more likely to be transported using leaded-gas, and therefore have a larger footprint on the environment. For this reason, the 1960 refrigerator receives a lower score than that of the 2000 refrigerator.
(1960: 1 ; 2000: 2)

Product Delivery Stage

Material Use <3,1>

Once the refrigerator has been manufactured and is ready to be delivered to warehouse, store, or home, it is packaged from head-to-toe in cardboard and plastics, and placed upon a wood pallet. This process is true for both the 1960 and the 2000 refrigerator, and hasn't been modified much through the years. Very few of these packaging materials, other than the pallet, are recycled materials. In addition to this damaging packaging process, the refrigerator must once again find its way onto a fossil-fuel consuming transportation source, before it gets to the end-user. Because of the damage done here, both refrigerators receive an equal, low score.
(1960: 1 ; 2000: 1)

Energy Use <3,2>

The delivery of the goods to the showrooms, storage facilities and kitchens is energy intensive; the refrigerators are heavy, and have a large volume (low units/load ratio). Fortunately, the fuel efficiency of modern transportation modes has increased, the emissions have decreased, and the potential volume has increased, making the 2000 refrigerator less environmentally damaging. For this reason both refrigerators receive a low energy use score, with the 1960 refrigerator one notch below the 2000 refrigerator.
(1960: 1 ; 2000: 2)

Solid Residues <3,3>

When the refrigerator makes it to its eventual home, what is left behind is the packaging: plastics, cardboard and wood pallets. In 1960, there were little options for these residues, other than the trash or fireplace. Likewise in 2000, little recycling is done with the cardboard and wood products, and even less with the plastic bagging. For this reason, both refrigerators receive an equal, but low score.
(1960: 2 ; 2000: 2)

Liquid Residues <3,4>

The liquid residue in the delivery stage is created primarily in the process of making the cardboard, plastic and wood packaging. Depending on the volume of material used, this impact could be very large, or very small, but nonetheless is one that could be avoided or mitigated. For this reason both refrigerators have been given the same score.
(1960: 3 ; 2000: 3)

Gas Residues <3,5>

The transport process produces pollutants and greenhouse gasses as byproducts, and therefore has a large, negative impact on the environment. The transfer of both refrigerators generates greenhouse gasses, but the 1960 refrigerator is more likely to be transported using leaded-gas, and therefore has a larger impact on the environment.

(1960: 1 ; 2000: 2)

Product Use Stage

Material Use <4,1>

The only major material use in the product use stage, besides replacement parts when the refrigerators break, is the fuel necessary to produce the electricity input. In 1960, more of this electricity input came from more environmentally damaging fuel sources; in particular from un-scrubbed coal. In addition, the 1960 refrigerator was less energy efficient, had poorer insulation, weaker seals around the various compartments, and was constantly "on". By comparison, the 2000 refrigerator is much more energy efficient, has greater insulation, stronger seals, and has the ability to minimize its use of electricity for the same marginal output. Simultaneously, the energy provided for the 2000 refrigerator comes from disparate, more environmentally-friendly power sources. For this reason, the 1960 refrigerator receives the lowest score available, and the 2000 refrigerator receives a more modest score.
(1960: 0 ; 2000: 3)

Energy Use <4,2>

Again, as mentioned above, the energy required to provide the same functionality is much greater for the 1960 refrigerator. More energy use and poorer insulation lead to higher energy bills, and more importantly- greater environmental damage. For this reason, the 1960 refrigerator receives the lowest score available, and the 2000 refrigerator receives a more modest score.
(1960: 0 ; 2000: 3)

Solid Residues <4,3>

Both refrigerators require electricity, and the only solid wastes associated with the product use stage are the byproducts of electricity production. As mentioned earlier in this paper, the 2000 refrigerator has access to electricity that is generated in more environmentally benign ways, and therefore receives a lower solid residue score.
(1960: 3 ; 2000: 4)

Liquid Residues <4,4>

Much like solid residues, the only liquid residues associated with the product use stage are from the production of electricity. Again, the 2000 refrigerator has access to electricity that is generated in more environmentally benign ways, and therefore receives a lower liquid residue score.
(1960: 3 ; 2000: 4)

Gas Residues <4,5>

If for some reason the refrigerator was fabricated in such a way that produced a faulty Freon-12 containment system, there is the potential for the loss of this ozone precursor into the environment. In addition to Freon-12, the by-products of the electricity production process (CO, NOx, SOx, PAHs, etc.,) are potential global warming agents. The fossil fuels that are burned to create the electricity generate gas residues and byproducts. The 2000 refrigerator is more likely to use benign energy sources, and therefore will be more likely to have less of a footprint in this area.
(1960: 2 ; 2000: 3)

Refurbishment, Recycle Disposal Stage

Material Use <5,1>

The refrigerator of 1960 was less likely to be recycled because its virgin inputs were of lower cost, landfill space was cheap, and the technologies for recycling as we know them today weren't present at that time. The 2000 refrigerator is much more likely to be recycled- both because of prohibitive laws, and because of the availability of recycling centers (The Fridge Doctor). Unfortunately, the 2000 refrigerator uses less metals, more plastics, and thus is more difficult to recycle. The landfill process for the 1960 refrigerator requires intensive land use as its main material use component, and because of this direct impact, receives a lower score.
(1960: 1 ; 2000: 3)

Energy Use <5,2>

Energy is required in the transfer of both the 1960 and 2000 refrigerator; the former to the landfill, and the latter to the recycling center. Ultimately, the transfer and decomissioning of the 2000 refrigerator is a more energy-intensive process, and thus it receives a lower energy use score.
(1960: 3 ; 2000: 2)

Solid Residues <5,3>

When the 1960 refrigerator is placed in a landfill, its entirety is a solid residue. As a product of metals, carcinogenic insulation, and leaded paint, it receives the lowest score possible. Alternatively, the recycling process for the 2000 refrigerator yields many unusable parts, and thus has its own share of solid residues. The processing of fossil fuels (to produce the petrol necessary to transfer the 1960 refrigerator to the landfill and the 2000 refrigerator to the recycling center) also generates solid residues. Both refrigerators receive a low score in this category, with the 1960 refrigerator much lower.
(1960: 0 ; 2000: 2)

Liquid Residues <5,4>

The recycling processes for the 2000 refrigerator undoubtedly produce liquid residues. The runoff from the landfill (which houses the interned 1960 refrigerator,) also may be considered a liquid residue which must be managed. The recycling of the 2000 refrigerator will reduce the materials needed to generate a new one, but the disposal of the 1960 refrigerator benefits no one.
(1960: 2 ; 2000: 3)

Gas Residues <5,5>

As the 1960 refrigerator breaks down under the weight and pressures of nature, any unused Freon-12 in the refrigerant canisters will be exposed to the environment. Because of the danger involved with this ozone precursor, the 1960 refrigerator receives a low score. Clean Air legislation has prohibited the disposal of known Freon-12 containing devices, so this isn't a concern with the 2000 refrigerator.
(1960: 1 ; 2000: 4)

IV. RESULTS

Figure 4.1 The 1960 Refrigerator

	Material Use	Energy Use	Solid Residues	Liquid Residues	Gas Residues	Total
Pre-manufacture	1	2	2	3	1	9/20
Product Manufacture	3	2	2	3	1	11/20
Product Delivery	1	1	2	3	1	8/20
Product Use	0	0	3	3	2	8/20
Refurbishment, Recycle, Disposal	1	3	0	2	1	7/20
Total	6/20	8/20	9/20	14/20	6/20	43/100

Figure 4.2 The 2000 Refrigerator

	Material Use	Energy Use	Solid Residues	Liquid Residues	Gas Residues	Total
Pre-manufacture	3	2	3	3	3	14/20
Product Manufacture	3	2	3	4	2	14/20
Product Delivery	1	2	2	3	2	10/20
Product Use	3	3	4	4	3	17/20
Refurbishment, Recycle, Disposal	3	2	2	3	4	14/20
Total	13/20	11/20	14/20	17/20	14/20	69/100

Figure 4.3 Combined 1960 - 2000 Results

	Material Use	Energy Use	Solid Residues	Liquid Residues	Gas Residues	Total
Pre-manufacture	1 3	2 2	2 3	3 3	1 3	9/20 14/20
Product Manufacture	3 3	2 2	2 3	3 4	1 2	11/20 14/20
Product Delivery	1 1	1 2	2 2	3 3	1 2	8/20 10/20
Product Use	0 3	0 3	3 4	3 4	2 3	8/20 17/20
Refurbishment, Recycle, Disposal	1 3	3 2	0 2	2 3	1 4	7/20 14/20
Total	6/20 13/20	8/20 11/20	9/20 14/20	14/20 17/20	6/20 14/20	43/100 69/100

Figure 4.4 Doubly Weighted Matrix (Multipliers)

	Material Use	Energy Use	Solid Residues	Liquid Residues	Gas Residues
Pre-manufacture	1.40625	1.40625	.46875	.46875	.9375
Product Manufacture	.46875	.46875	.15625	.15625	.3125
Product Delivery	.9375	.9375	.3125	.3125	.625
Product Use	3.75	3.75	1.25	1.25	2.5
Refurbishment,	.9375	.9375	.3125	.3125	.625

Recycle, Disposal					

Figure 4.5 Doubly Weighted Matrix (Actuals)

Weights		30%	30%	10%	10%	20%	100%
		Material Use	Energy Use	Solid Residues	Liquid Residues	Gas Residues	Total
18.75%	Pre-manufacture	1.40625 4.21875	2.8125 2.8125	.9375 1.40625	1.40625 1.40625	.9375 2.8125	7.5/18.75 12.66/18.75
6.25%	Product Manufacture	1.40625 1.40625	.9375 .9375	.3125 .46875	.46875 .625	.3125 .625	3.44/6.25 4.06/6.25
12.5%	Product Delivery	.9375 .9375	.9375 1.875	.625 .625	.9375 .9375	.625 1.25	4.06/12.5 5.63/12.5
50%	Product Use	0 11.25	0 11.25	3.75 5	3.75 5	5 7.5	12.5/50 40/50
12.5%	Refurbishment, Recycle, Disposal	.9375 2.8125	2.8125 1.875	0 .625	.625 .9375	.625 1.25	5/12.5 7.5/12.5
100%	Total	4.69/30 20.63/30	7.5/30 18.75/30	5.63/10 8.13/10	7.19/10 8.91/10	7.5/20 13.44/20	32.5/100 69.84/100

Following the Allenby and Graedel double-weighting methodology, each of the life-stage and waste categories have been given a weight to reflect their individual magnitudes. For the waste categories, equal weight (30%) was given to the material use and energy use sections. The extraction and processing of the raw ores necessary to fabricate the refrigerators, as well as the fuels and energy used in transferring and operating the refrigerator, are several times more damaging than the solid, liquid and gas residues. The impact of NOx, CO, SOx, and PAHs on the environment, as well as the volume of Freon-12 used, increase the potential of the environmental damage from the gas residues. Nitrogen and sulfur oxides (NOx and SOx) contribute to lake-acidification; carbon monoxide contributes to the greenhouse effect; poly aromatic hydrocarbons contribute to respiratory problems; Freon-12 has been proven to deplete ozone. Although these impacts are significant, there is still debate as to the magnitude of their impacts, so they are given a weight (20%) slightly less than the known environmental damages of material and energy use. Equal weights of 10% are given to both the solid and liquid waste categories.

Refrigerators are designed to operate over a 15-20 year life (The Fridge Doctor, 2000). For this reason, the life-stage weights are heavily slanted towards the product-use stage (50%). The product manufacture stage uses the least resources, relying mainly on the processed materials from the pre-manufacture stage, and on energy input. Consequently, the pre-manufacture stage is given a weight of 18.75% and the manufacture stage is given a 6.25% weight. The product delivery and recycling/refurbishment/disposal stages are given equal weights of 12.5%. The energy required to deliver and pick up the refrigerator is high, as are the uses of packaging materials and landfill space. The results of this doubly-weighted matrix are presented in Figure 4.5

V. CONCLUSIONS

The LCA methodology provides adequate insight on the environmental performance of the 1960 and the 2000 refrigerators. However, it isn't until stage weights are added to the individual matrix elements that we receive greater insight on the true environmental footprint. The pre-weighted values are 43/100 for the 1960 refrigerator, and 69/100 for the 2000 refrigerator, which would indicate that both are damaging to the environment, but that the 1960 refrigerator is particularly more damaging. When we apply the category weights to the matrix elements, we receive a decidedly different picture; the values change to 32.5/100 69.84/100 for each of the respective ages. Although there is little change for the 2000 refrigerator, the 1960 refrigerator loses over 10 points, which more accurately reflects the damage that the lifecycle of the older refrigerator imposes on the environment.

VI. REFERENCES

1. "Department of Energy" Newton BBS, Ask A Scientist© Engineering Archive, *How does a refrigerator work?*, 2000
http://www.newton.dep.anl.gov/newton/askasci/1993/eng/ENG30.html

2. Yuzik, Clarence W., "The Fridge Doctor", 2000
http://www3.sk.sympatico.ca/fridgedr/

3. Economic Input-Output Life Cycle Assessment, Carnegie Mellon University, 2000
http://www.eiolca.net/contact.html

4. ESM 282 Reader, Industrial Ecology, Winter 2000, Professor David Allen, pg 231-246