

**Promoting Tools that integrate LCA into the Product Design Process: a Case Study in
Ontario**

José Vera

Date: 16 September 2010

Abstract

Design decisions can greatly affect the environmental impact of a product. The European Commission estimated that eighty percent of the environmental impacts of a product are determined during its design phase.

Life Cycle Assessment (LCA) is a method for determining the environmental impact of a product or service. LCA can be utilized during the product design phase in order to evaluate the environmental impact of different design decisions. Engineers can use the information provided by the LCA to make decisions that lead to a reduction of the overall environmental impact. This study examines different tools that integrate LCA with the product design process including SolidWorks Sustainability. An LCA was performed on a simulation of a regular non eco-friendly 3D printer and on eco-friendly simulations of similar 3D printers as a case study of the challenges involved in integrating LCA with the design process. Public policy recommendations for promoting these LCA tools in Ontario and Canada were made based on the case study.

Introduction

Decisions made during the design phase of a product can have a significant effect on the product's environmental impact. It is estimated that eighty percent of the environmental impacts of a product are determined at the design stage (European Commission Enterprise and Industry, 2010, p. 3). Currently, there is a growing need worldwide for products and services that are "qualified in terms of Environmental Sustainability" (Capelli *et al.*, 2006, p. 185). This need can be met if environmental impact considerations become an integral part of the product design process. Life Cycle Assessment (LCA) is a method for determining the environmental impact of a product or service from "Cradle", the point where the raw materials are extracted from the earth, to "Grave", the point where the materials are returned to the earth (Curran, 2006, p. 1). Furthermore, there are new software tools that integrate LCA with product design by linking Computer Aided Design (CAD) software with LCA software (SolidWorks, 2010) (Sustainable Minds, 2010). These tools allow engineers to examine the environmental impacts of different design alternatives (e.g. material substitution and weight optimization) during the design phase. In fact, these new tools can be used as a vehicle to promote the adoption of "life cycle thinking" within organizations. This paper examines ways of promoting the adoption of these tools, which integrate LCA with the product design process, throughout different industries in Ontario and Canada.

Two of the leading CAD software companies in the world have recently announced new tools that link their CAD software with LCA software. SolidWorks Corporation has recently released SolidWorks Sustainability, which allows users to perform LCA studies directly on their CAD models (SolidWorks, 2010). Furthermore, Sustainable Minds LLC has created software that can perform an LCA on Bills of Materials created from AutoDesk's Inventor or from other

CAD software (Sustainable Minds, 2010). In this inquiry SolidWorks Sustainability will be used due to its strong integration of LCA and CAD software (i.e. the LCA software runs directly within the CAD software).

Although tools that integrate LCA and product design, such as SolidWork Sustainability, have the potential to facilitate the development of environmentally friendly products; their integration may involve several challenges. In order to gain a better understanding of the challenges involved in integrating LCA with the product design process the following case study was performed:

An eco-friendly version of a product was simulated by selecting materials that are believed to have a lower environmental impact. Likewise, a regular non eco-friendly version of the same product was simulated by selecting materials that are believed to have a higher environmental impact. An LCA was done on the regular non eco-friendly simulation of the product and on the eco-friendly simulation in order to quantify how the material selections affect the environmental impact of the product. Next, another LCA was done on an eco-friendly simulation of a more compact design of the product in order to quantify how using less materials affects the environmental impact of the product. The results of this case study formed the basis for public policy recommendations for promoting tools that integrate LCA with product design within Ontario and Canada.

Case Study – LCA of RepRap 3D Printers

The following simulations of 3D Printers from RepRap, an online open design community, were selected for this case study:

- a) A regular (non eco-friendly) simulation of the Darwin printer model
- b) An Eco-friendly simulation of the Darwin printer model
- c) An Eco-friendly simulation of the Mendel printer model

The printers from RepRap were chosen because their open design provided complete access to their CAD data and LCA data.

Goal Definition

The purpose of this LCA is to make the following comparative assessments:

- 1) A regular simulation of the Darwin vs. an Eco-friendly simulation of the Darwin: The components of the frame were analyzed.
- 2) An Eco-friendly simulation of the Darwin vs. an Eco-friendly simulation of the Mendel: The components of the frame and the printing operation were analyzed.

The frame components were analyzed in this study since they can be easily changed during the design process. Both the Eco-friendly Darwin simulation and the Eco-friendly Mendel simulation use frame materials believed to have a lower environmental impact than the materials used in the regular Darwin simulation. The Eco-friendly Mendel simulation is a more compact design (i.e. uses fewer materials) than the Eco-friendly Darwin simulation.

Scope Definition

Product Definition

The investigated functions are:

- 1) To obtain the mechanical components required for building the frame of one 3D printer.
- 2) To operate one 3D printer for one hour.
- 3) To cut out one bed board for one 3D printer from Medium Density Fiberboard (MDF).

Product Alternatives

The specifications of the printers call for steel to be used for the rods and fasteners; however, the specifications do not state if the steel is to be local or imported (RepRap, 2010). Furthermore, the specifications of the printers state that several different plastics could be used, such as ABS or Polylactide (PLA); however, the specifications do not favour one particular plastic over the other and do not state if the plastics are to be local or imported (RepRap, 2010). Finally, the specifications call for Medium Density Fiberboard (MDF) to be used for the bed board, but do not specify the type of MDF, for example regular MDF or MDF with a formaldehyde free binder (RepRap, 2010). Consequently, the flexibility of the specifications allowed for the simulation of a regular (non eco-friendly) printer as well as for the simulation of eco-friendly printers. All simulations were based on the specifications from RepRap.

The printer simulations were modeled as assembled in Toronto, Ontario. The Eco-friendly Darwin and Eco-friendly Mendel were simulated using steel rods and fasteners from relatively nearby Pittsburg in order to reduce the environmental impact caused by the Transport phase, in contrast to the regular Darwin that was simulated using steel rods and fasteners from Shanghai. These Eco-friendly printers were simulated using local PLA a compostable polymer

for their plastic parts, while the regular Darwin was simulated using local ABS for its plastic parts. In this study “local” means the closest available manufacturing location to Toronto. All printer simulations use MDF for their bed board; however, both Eco-friendly printers were simulated using MDF with a formaldehyde-free binder as per LEED Credit EQ-4.4 (Integrated Publishing, 2010). Both the regular Darwin simulation and the Eco-friendly Darwin simulation require NEMA 23 stepper motors. In contrast, the Eco-friendly Mendel simulation requires smaller NEMA 14 stepper motors. The product alternatives are summarized in Table 1.

	Regular Darwin Simulation	Eco-friendly Darwin Simulation	Eco-friendly Mendel Simulation
Steel Rod	Shanghai	Pittsburg	Pittsburg
Fasteners	Shanghai	Pittsburg	Pittsburg
Plastic Parts	ABS (Local)	PLA (Local)	PLA (Local)
Bed Board	MDF	MDF (LEED)	MDF (LEED)
Stepper Motors	NEMA 23	NEMA 23	NEMA 14

Table 1: Product Alternatives

Processes Considered

Steel Components

The following phases were considered for the steel rods and fasteners of the printers:

- Production
- Manufacture
- Transport of the finished goods to the assembly location
- Disposal

The Use phase was assumed to be negligible for the steel components, since the steel components do not directly consume energy during storage and product operation. Consequently the Use phase was not considered for the steel components. The transportation of the raw materials was not considered, since it was assumed that all the raw materials are obtained locally and consequently only the transportation of the finished goods (rods and fasteners) has a significant impact.

Plastic Components

Currently there is only Production phase data available for PLA (Vink *et al.*, 2003, p. 414). However, since both ABS and PLA parts are built using the same 3D printing process, more specifically the Mendel and the Darwin can build their own plastic parts using either ABS or PLA among other plastics (RepRap, 2010), it was assumed that the impacts of ABS and PLA in the Manufacture phase are similar. Likewise, since both the ABS and PLA come from local sources (in North America) it was assumed that their impacts in the Transport phase are similar as well. Furthermore, it was assumed that the Disposal phases of ABS and PLA have a significantly lower impact than their Production phase. This assumption was supported by a

review of the LCI database in SolidWorks Sustainability that shows that the Production phase has the strongest impact for plastics. Consequently, the Production phase for the plastics is considered the most critical phase and is the only phase that was considered for the LCI of the plastic components. Finally, it was assumed that the users will compost the PLA parts during the Disposal phase. This assumption is justified by the fact that the users are members of the RepRap printer community which shares best practices including sustainable practices (RepRap, 2010). However, testing is required to determine the type of composting that will be required.

Bed Board

MDF is not in the SolidWorks database; consequently an LCA was not done on the bed board. Instead peer-reviewed sources were used to compare the environmental impacts between MDF and MDF with formaldehyde-free binder.

Stepper Motors

Only the Use phase was considered for the stepper motors of the printers due to unavailable data for the Production, Manufacture and Transport phases of the stepper motors. This limitation does not present a problem, since it was assumed that the different stepper motors use the same materials and are manufactured in the same plant, and as a result the Production, Manufacture and Transport impacts of the motors should be similar. Consequently the Production, Manufacture and Transport impacts of the motors off set each other causing the Use phase of the motors (electricity consumption) to become the most critical phase.

The processes considered are summarized in Table 2.

	Production	Manufacture	Transport	Use	Disposal
Steel Rod	✓	✓	✓	✗	✓
Fasteners	✓	✓	✓	✗	✓
Plastic Parts	✓	qualitative	qualitative	✗	qualitative
Bed Board	No LCA done, used independent peer-reviewed study				
Stepper Motors	✗	✗	✗	✓	✗

Table 2: Processes Considered

Geographical Scope

The 3D printer simulations shall be modeled as assembled and used in Toronto, Ontario. The steel components (steel rods and fasteners) are modeled as produced in Pittsburg, Pennsylvania or Shanghai, China. The plastic components of the printer simulations are locally produced.

Technological Scope

This study assumes that the technology being used in all processes of this LCI is representative of the technology currently used in China and in North America.

Emissions and Energy Data

The emissions and energy data from SolidWorks Sustainability 2010 Software were used for all materials except for MDF and PLA, where peer reviewed sources were used instead, since MDF and PLA are not available in the SolidWorks materials database. Furthermore, the impacts in the Transport phase were calculated manually using information from peer-reviewed sources,

since the aforementioned software does not currently allow for specific distances to be considered in its calculations (e.g. one can specify in SolidWorks Sustainability transportation from Asia to North America but not from Shanghai to Toronto).

Environmental Parameters

The following environmental parameters were considered:

- Global Warming Potential (GWP)
- Energy Consumed (from nonrenewable sources)
- Material Intensity
- Formaldehyde in Medium Density Fiberboard (MDF)

Life Cycle Inventory (LCI)

Open Design Data for LCI

RepRap provides in their website (<http://reprap.org/>) a complete Bill of Materials (BOM) of all the components of their printers, as well as complete CAD files of their printers. Both the BOM and the CAD files from the RepRap website were used to obtain the materials and mass of the components included in the LCI.

CAD Data for LCI

As previously mentioned, the mechanical components of the frame were analyzed in this study. Figure 1 shows a complete CAD model of the Darwin. Figure 2 shows the CAD model of the Darwin showing only the components of the frame, which were used for the LCI.

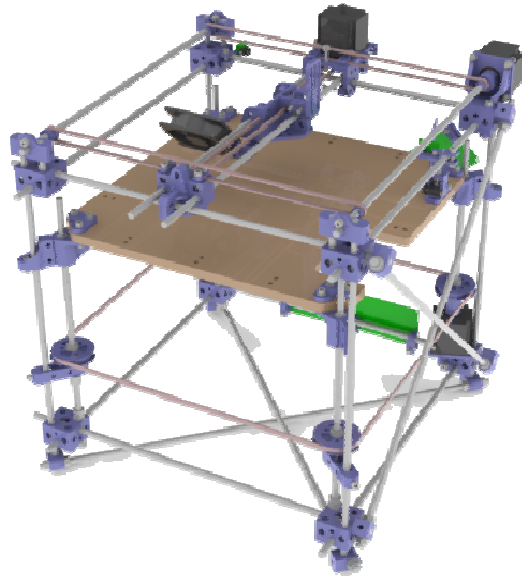


Figure 1: Darwin 3D Printer (CAD data from RepRap, Rendering by Author)

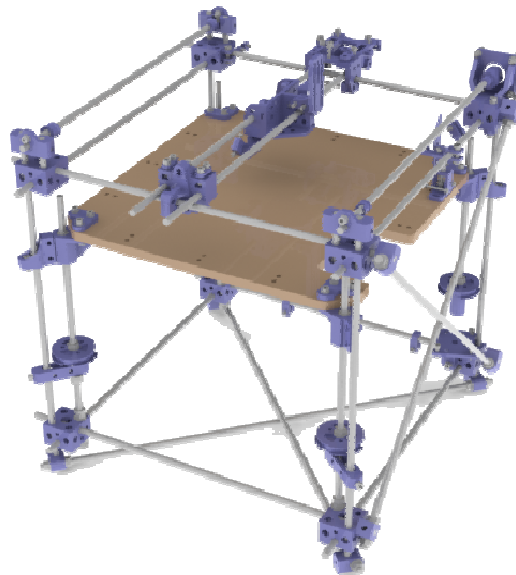


Figure 2: Darwin 3D Printer Frame Only (CAD data from RepRap, Rendering by Author)

Processes and Materials for LCI

The different materials and processes included in this study are listed in Table 3.

	Production	Manufacture	Transport	Use	Disposal
Steel Rod	Plain CS (Billet)	Extruded (cold rolled)	Truck/Ship rods	* - negligible	Landfill, recycling & incineration
Fasteners	Plain CS (Bar Stock)	Milled (machined)	Truck/Ship fasteners	* - negligible	Landfill, recycling & incineration
Plastic Parts	ABS (resin) PLA (resin)	3D Printing similar	Local similar	* - negligible	Landfill vs. Compost
Bed Board	Raw material acquisition	Board manufacture	Raw material transport	Board cutting	Waste treatment
Stepper Motors	* - similar cancel out	* - similar cancel out	* - similar cancel out	Electricity	* - similar cancel out

Table 3: Processes and Materials for LCI

In the steel rod making process steel billets are cold rolled into rods (Lee, 2004). In this study it was assumed that all the fasteners (i.e. nuts, bolts, and washers) during the Manufacture phase are machined from bar stock, as per their respective ASTM standards (Industrial Fasteners Institute, 1988). In reality, fasteners could also be manufactured by pressing, punching or forging (Industrial Fasteners Institute, 1988). Machining was chosen since its impacts are similar to the other manufacturing processes available in SolidWorks Sustainability. Furthermore, the Production phase has the highest impact of all the phases for steel (as per SolidWorks Sustainability); consequently, the differences in the manufacturing processes will not have significant impact.

SolidWorks Sustainability does not include “cold rolled” or “machined” in its manufacturing options; however, it was assumed that concerning environmental impacts the

“extruded” option in SolidWorks is similar to “cold rolled” and the “milled” option in SolidWorks is similar to “machined”. This is a fair assumption, since rolling is a form of extrusion and milling is a form of machining.

Regular Darwin Simulation vs. Eco-friendly Darwin Simulation

The Global Warming Potential (GWP) of the Eco-friendly Darwin was lower than the GWP of the Darwin (from this point on “the Darwin” refers to “the regular Darwin”). In fact, the rods of the Eco-friendly Darwin had a lower GWP than the rods of the Darwin. The same applied for the fasteners and the plastic parts, as per Figure 3.

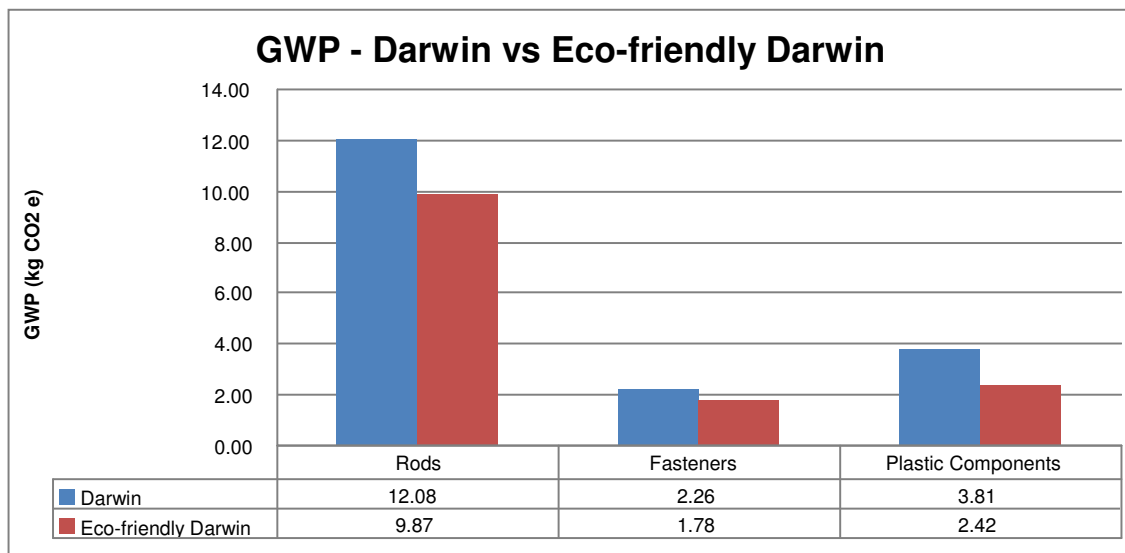


Figure 3: (Source Data: SolidWorks Sustainability and Chalmers University, 2008)

The energy consumption of the Eco-friendly Darwin was lower than the energy consumption of the Darwin. In fact, the energy consumption of the steel rods of the Eco-friendly Darwin was lower than the energy consumption of the steel rods of the Darwin. The same applied for the fasteners and the plastic parts, as per Figure 4.

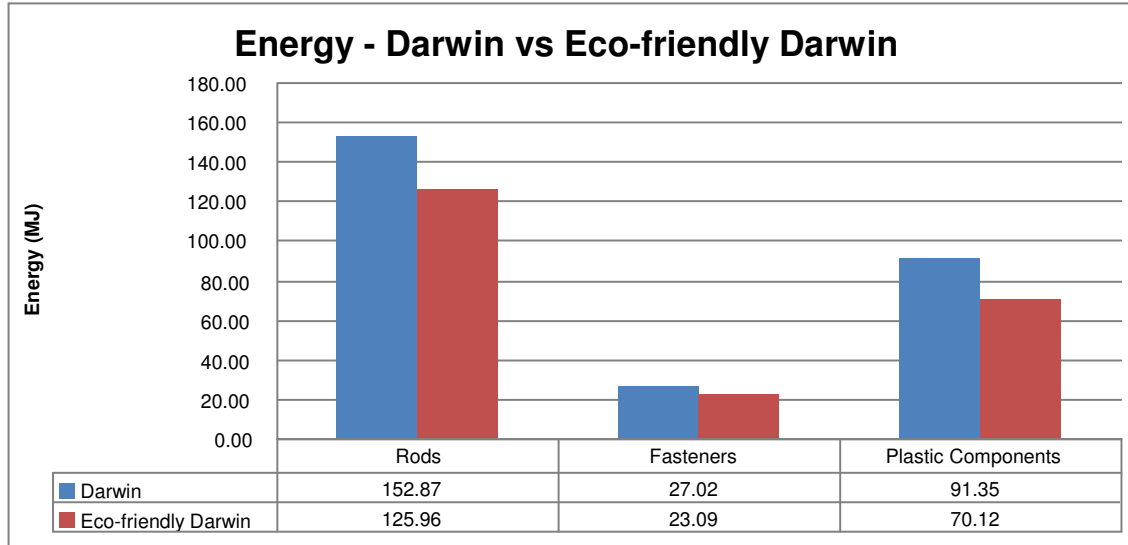


Figure 4: (Source Data: SolidWorks Sustainability and Chalmers University, 2008)

Figure 5 shows that the Transportation phase of the steel rods accounted for the difference between the GWP of the Darwin’s steel rods and the GWP of the Eco-friendly Darwin’s steel rods, since the GWP of the other phases were similar. Transporting the steel rods from Pittsburgh to Toronto for assembling the Eco-friendly Darwin would naturally have a lower GWP than transporting them from Shanghai to Toronto for assembling the Darwin.

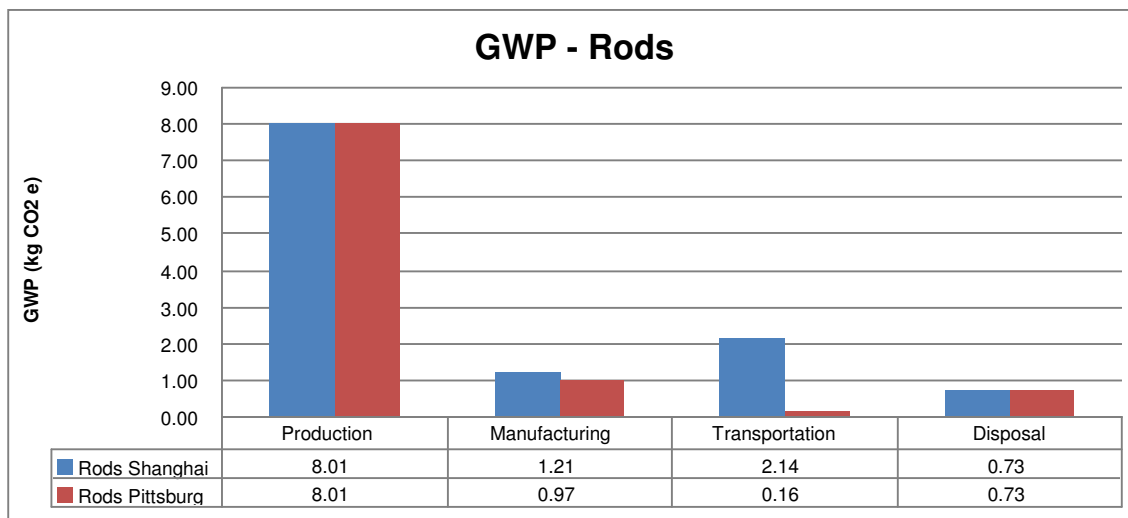


Figure 5: (Source Data: SolidWorks Sustainability and Chalmers University, 2008)

A verification calculation was performed to ensure that the results from SolidWorks Sustainability were reasonably accurate and free of errors. The production phase of the steel rods of the Darwin was examined due to its relatively large impact. LCI data from the Chalmers University of Technology was used to calculate the GWP of the Production phase of steel rods. According to the LCI data from Chalmers University the manufacturing of steel tube results in 7% scrap (there is no data for rods). If one assumes 10% manufacturing scrap for the steel rods the calculated GWP for the production of steel rods was 8.44 kg of CO₂ equivalent. SolidWorks Sustainability calculated 8.01 kg of CO₂ equivalent for the GWP of the production of steel rods. Table 4 shows the calculation data assuming 10% manufacturing scrap.

Production Phase	Manual Calculation	SolidWorks Sustainability
Virgin Steel (kg)	6.36	Not Available
Steel Billet(kg)	5.29	Not Available
Steel Rod (kg)	4.76	4.76
CO ₂ (kg)	7.92	Not Available
CH ₄ (kg)	0.02	Not Available
CH ₄ in CO ₂ equivalent (kg)	0.52	Not Available
Total CO ₂ equivalent (kg)	8.44	8.01

Table 4: Verification Calculation of GWP of Steel Rods 10% Scrap

A sensitivity analysis was done by changing the assumed manufacturing scrap to 5% from 10% for the steel rods. With 5% manufacturing scrap the calculated GWP for the production of steel rods was 8.00 kg of CO₂ equivalent, which is actually quite close to the 8.01 kg of CO₂ equivalent from SolidWorks Sustainability. Table 5 shows the calculation data assuming 5% manufacturing scrap.

Production Phase	Manual Calculation	SolidWorks Sustainability
Virgin Steel (kg)	6.02	Not Available
Steel Billet(kg)	5.01	Not Available
Steel Rod (kg)	4.76	4.76
CO2 (kg)	7.50	Not Available
CH4 (kg)	0.02	Not Available
CH4 in CO2 equivalent (kg)	0.50	Not Available
Total CO2 equivalent (kg)	8.00	8.01

Table 5: Verification Calculation of GWP of Steel Rods 5% Scrap

As previously mentioned the environmental impact of the Transport phase was calculated manually, since SolidWorks Sustainability currently does not allow exact transportation distances to be entered. LCI data from the Chalmers University of Technology was used to calculate the transportation impacts. In these calculations it was assumed that long distance transportation trucks and high sea shipping are used. The impacts included the emissions from the combustion of fuel, and the energy of the fuel consumed. The impacts did not include the production and distribution of fuel, the maintenance and fabrication of the trucks and ships, and the establishment and maintenance of infrastructure, since these impacts were cut off from the LCI data from the Chalmers University of Technology. Table 6 summarizes the Transport phase environmental impact calculations for the steel rods of the Darwin and the Eco-friendly Darwin. The calculations used for the transportation of the fasteners and plastics followed a similar process.

Transport Phase	Pittsburg - GTA	Shanghai - GTA
Steel Rod (kg)	4.76	4.76
Distance traveled by ship (km)	0	13,321
Distance traveled by truck (km)	516	4,190
CO2 Š ship (kg)	0	0.82
CO2 Š truck (kg)	0.16	1.32
CO2 Š Transport (kg)	0.16	2.14
Energy consumed Š ship (MJ)	0	11.4
Energy consumed Š truck (MJ)	2.21	18.0
Energy consumed Š Transport (MJ)	2.21	29.4

Table 6: Transport Phase Impact Calculations

The Transport phase calculations in Table 6 relied on ton-km impacts. For example, to transport 1 ton of cargo 1 km consumes 0.9 MJ of fuel energy via long distance trucks (Chalmers University of Technology, 2010). Therefore, to transport 4.76 kg of steel rod 516 km from Pittsburgh to Toronto via long distance trucks consumes:

$$0.9 \text{ MJ} * 4.76 \text{ kg}/1,000 \text{ kg} * 516 \text{ km}/1 \text{ km} = 2.21 \text{ MJ of fuel energy}$$

Figure 6 shows that the Transport phase of the rods of the Eco-friendly Darwin had significantly lower energy consumption than the Transportation phase of the rods of the Darwin, while the Production phases, Manufacturing phases and Disposal phases were similar in energy consumption. Consequently, the Transport phase was the most critical phase for energy consumption.

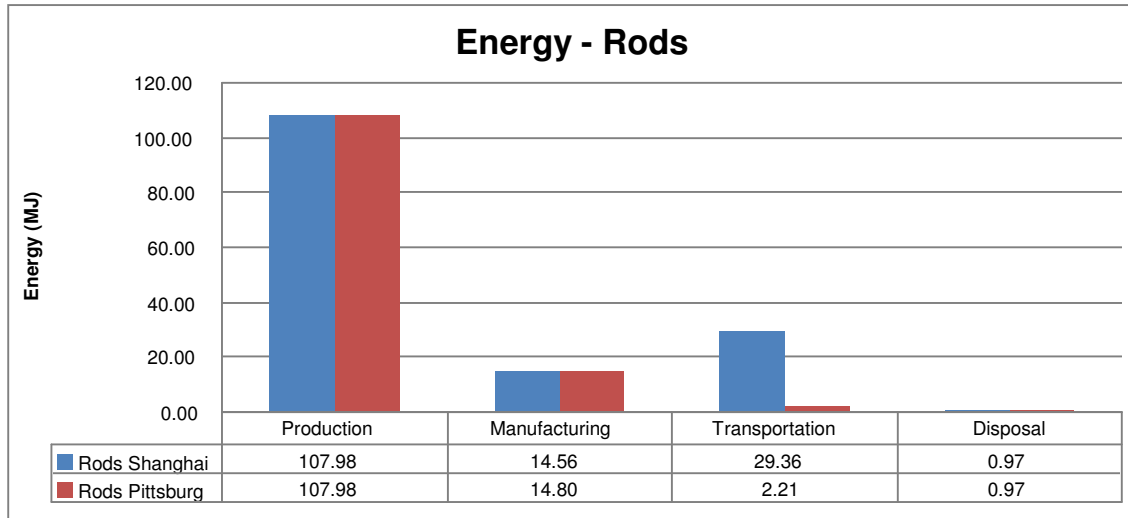


Figure 6: (Source Data: SolidWorks Sustainability and Chalmers University, 2008)

Figures 7 and 8 show that both the GWP and the energy consumption of the fasteners were lower for the Eco-friendly Darwin, due to their lower transportation impacts. Like the rods, the Transport phase was the most critical phase for fasteners.

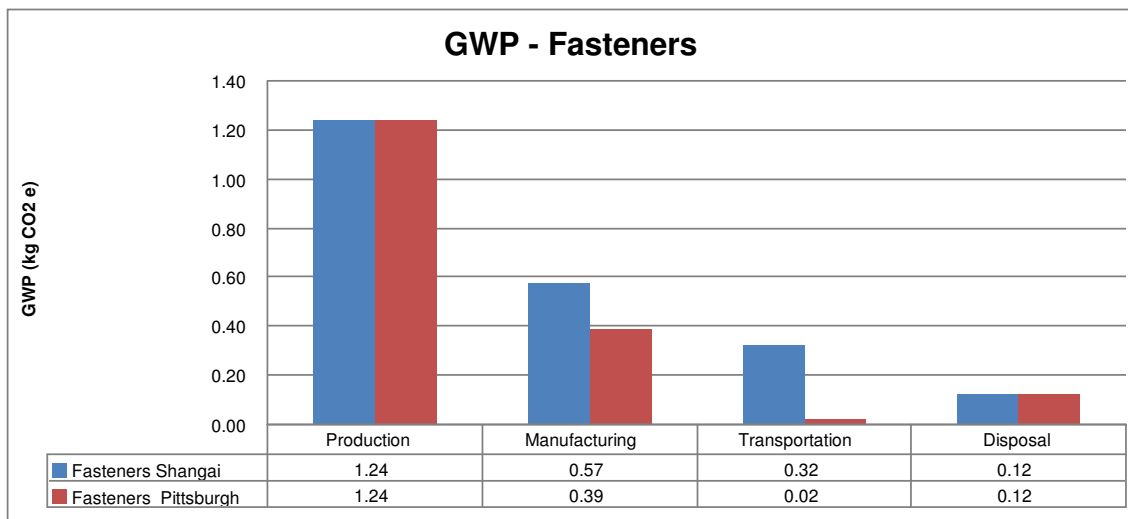


Figure 7: (Source Data: SolidWorks Sustainability and Chalmers University, 2008)

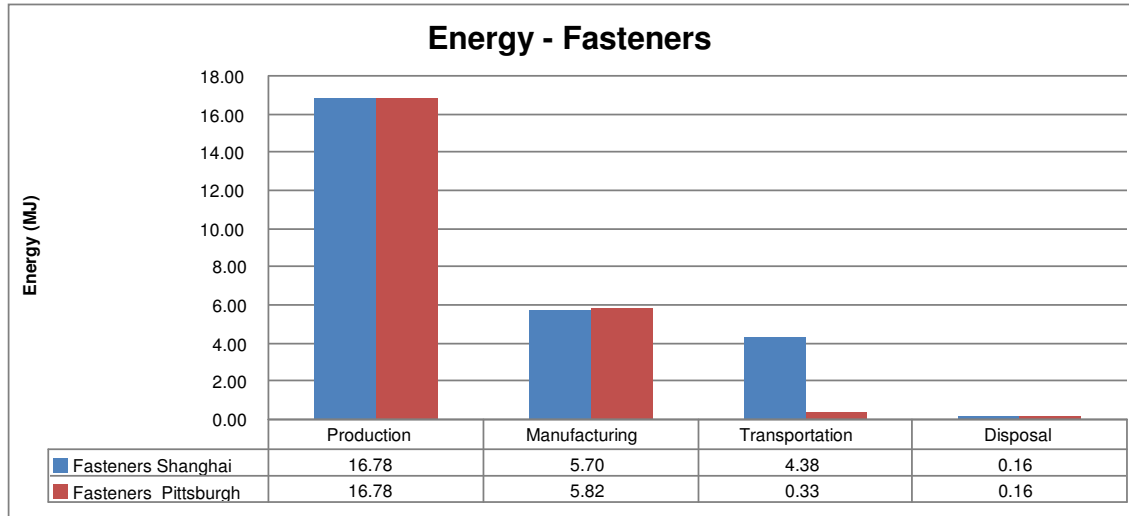


Figure 8: (Source Data: SolidWorks Sustainability and Chalmers University, 2008)

As previously mentioned, PLA was chosen for the plastic components of the Eco-friendly Darwin due to its compostable properties. PLA is not in the database of SolidWorks Sustainability. As a result, LCI data from peer-reviewed journals was used for PLA. Furthermore, currently there is only LCI information for the Production phase of PLA (Vink et al., 2003). Consequently, only the Production phase of the plastic components was considered in this study. It is important to note that PLA recycled through composting can obtain emissions and energy credits compared to land filling (Patel *et al.*, 2005). However, it must be noted that PLA production requires the following: fertilizers, vehicle fuels, herbicides, insecticides, natural gas, and electricity (Vink *et al.*, 2003). ABS is commonly used for the fabrication of the plastic components of the RepRap printers (RepRap Wiki, 2010). Consequently, ABS was chosen for the plastic components of the Darwin. Figures 9 and 10 show that the GWP and energy consumption during the production of PLA were lower than the GWP and energy consumption during the production of ABS. As previously mentioned, since it is believed that PLA and ABS have similar environmental impacts during manufacture and transportation, it follows that the

overall environmental impacts of PLA would be lower than the environmental impacts of ABS. One can make this deduction, since PLA has been shown to have a lower environmental impact during production than ABS while having similar impacts in manufacture and transport, and furthermore PLA gains emissions and energy credits when composted during disposal for use as compost fertilization (Patel *et al.*, 2010). In contrast, it is very likely that the ABS plastic parts would not be recycled in Toronto, since they would not be accepted by Toronto's blue box program (City of Toronto, 2010) and therefore, ABS parts could end up in a landfill and not gain any emissions and energy credits. The amount of credits gained by PLA depends on the type of fertilizer the compost fertilization replaces and the type of crop that uses the compost fertilization (Patel *et al.*, 2010). It is unknown what type of fertilizer would be replaced as well as the type of crop that will use the compost. Consequently, the amount of credits gained cannot be estimated. However, these credits give PLA an advantage, since ABS has no emissions and energy credits at all.

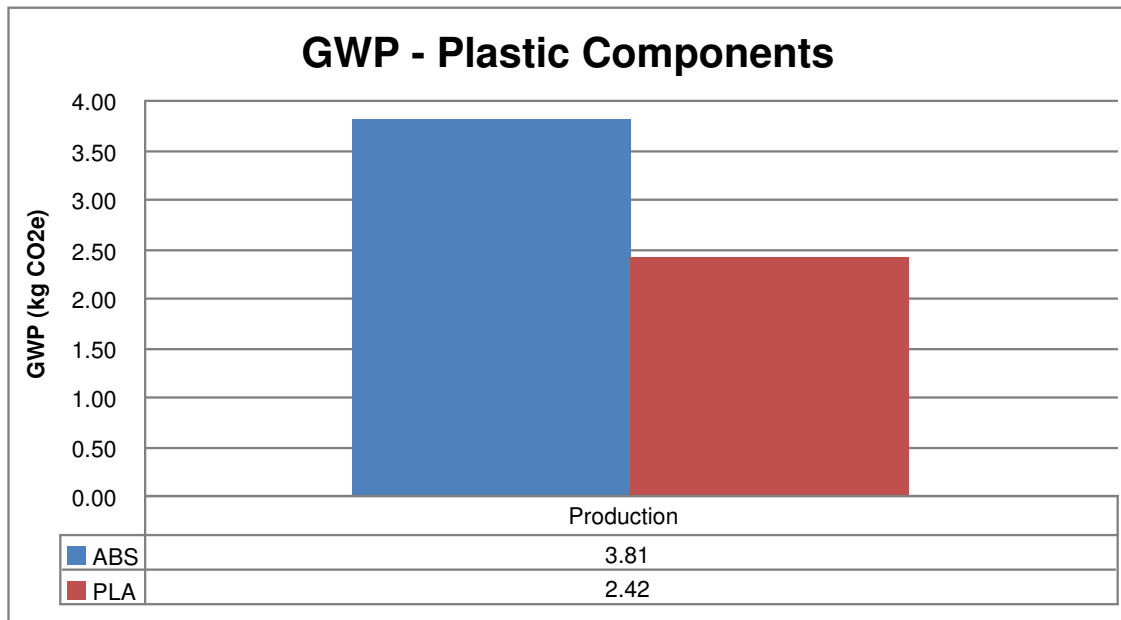


Figure 9: (Source Data: Solid Works Sustainability and Vink *et al.*, 2003)

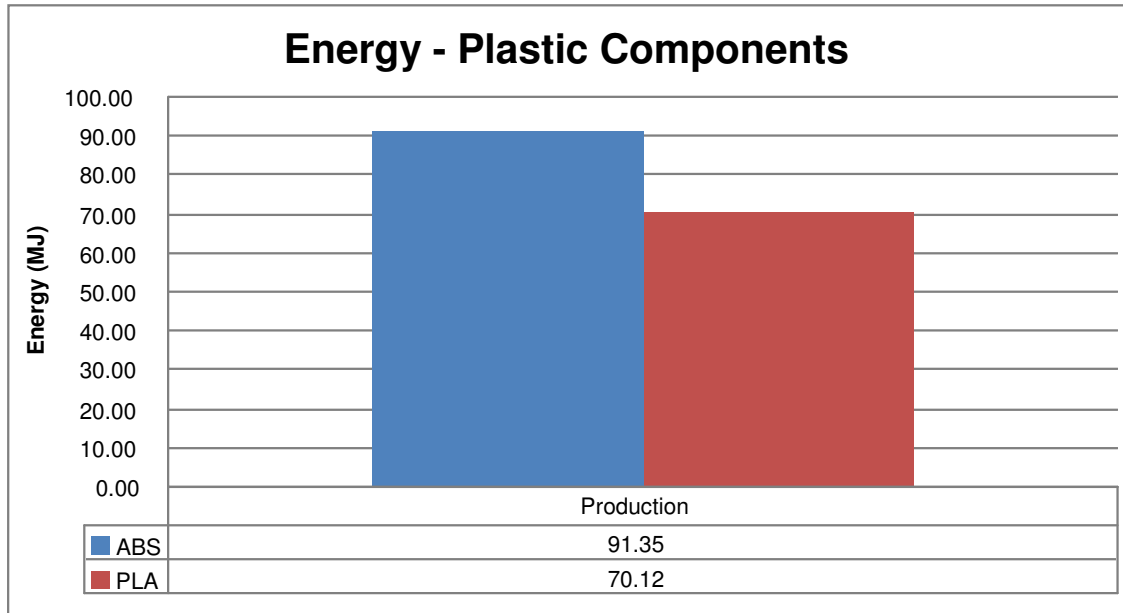


Figure 10: (Source Data: Solid Works Sustainability and Vink *et al.*, 2003)

As previously stated, the Darwin uses MDF for its bed board. The binder of standard MDF contains urea-formaldehyde (Healthy Building Network, 2008). Formaldehyde is of particular concern, since the World Health Organization has classified it as a known carcinogenic (Healthy Building Network, 2008). In contrast, the Eco-friendly Darwin uses MDF with formaldehyde-free binder, as per LEED credit EQ-4.4 (Integrated Publishing, 2010). Physical tests on the Darwin bed board would need to be done to find out the amount of formaldehyde emissions produced during cutting. It is beyond the scope of this study to perform these physical tests; however, the MDF with formaldehyde-free binder is recommended due to health and safety reasons. Furthermore, a study comparing the environmental impacts of different engineered woods stated that low formaldehyde particleboard had a lower overall impact than standard particleboard (Bovea *et al.*, 2004, pg. 115). One could assume from this study that MDF, which shares similar characteristics to particleboard, also has a lower environmental impact if it is made with low formaldehyde content.

Eco-friendly Darwin Simulation vs. Eco-friendly Mendel Simulation

The Eco-friendly Darwin uses more rod material than the Eco-friendly Mendel. On the other hand, the Eco-friendly Mendel uses more plastic material and fastener material than the Eco-friendly Darwin. However, the overall material intensity (in kg) of the Eco-friendly Mendel was lower than the overall material intensity of the Eco-friendly Darwin, as per Figure 11. In this case the material intensity is critical when comparing environmental impacts, since the Eco-friendly Darwin and the Eco-friendly Mendel use the same type of materials, made using the same manufacturing processes, transported from the same locations, and disposed in the same manner.

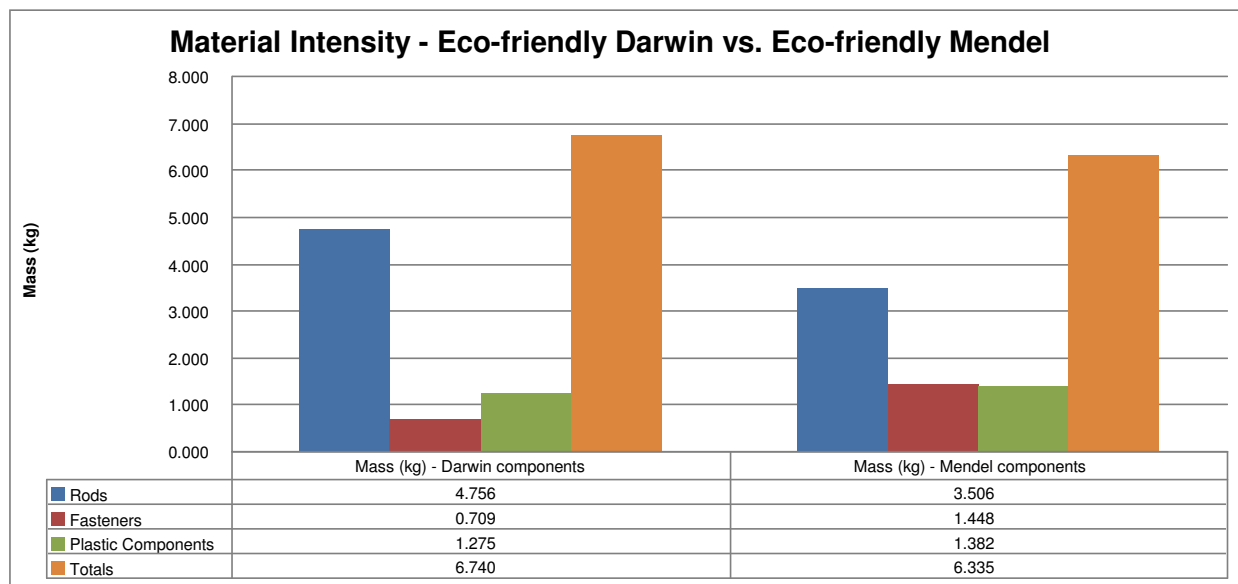


Figure 11: (Source Data: SolidWorks Sustainability and Chalmers University, 2008)

GWP is directly related to the material intensity of a product (G. Irons, personal communication, February, 2010). Consequently, the Eco-friendly Mendel, which was less material intensive than the Eco-friendly Darwin, also had a lower overall GWP as per Figure 12. Furthermore, the material intensive rods of the Eco-friendly Darwin essentially account for its

higher GWP. In contrast, the Eco-friendly Darwin used less plastic material and fastener material than the Eco-friendly Mendel. As a result the GWP for the plastic components and the fasteners of the Eco-friendly Darwin was lower.

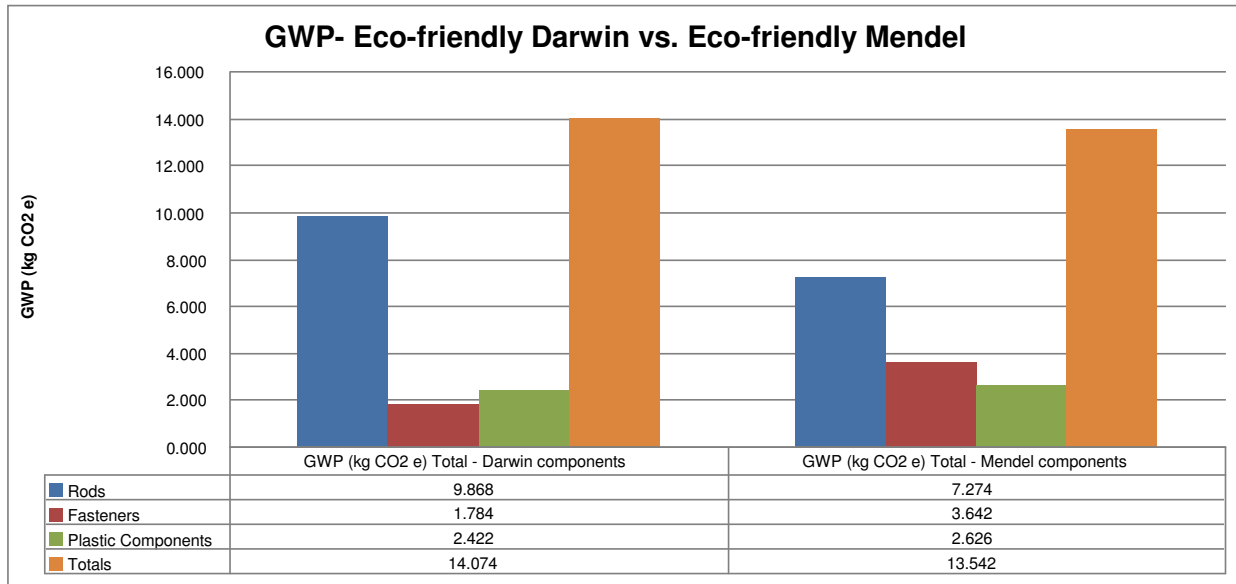


Figure 12: (Source Data: SolidWorks Sustainability and Chalmers University, 2008)

Energy consumption is also related to the material intensity of a product (G. Irons, personal communication, February, 2010). Consequently, the energy consumption of the Eco-friendly Darwin and the Eco-friendly Mendel follow the same pattern as their material intensity. The Eco-friendly Mendel had a lower material intensity and as a result a lower energy consumption, as per Figure 13. The Eco-friendly Mendel used more fastener material and plastic material; therefore, the energy consumption of the fasteners and plastics was higher for the Eco-friendly Mendel. However, the Eco-friendly Darwin used significantly more steel rod material and as a result it consumed approximately 1.5% more energy overall, as per Figure 13.

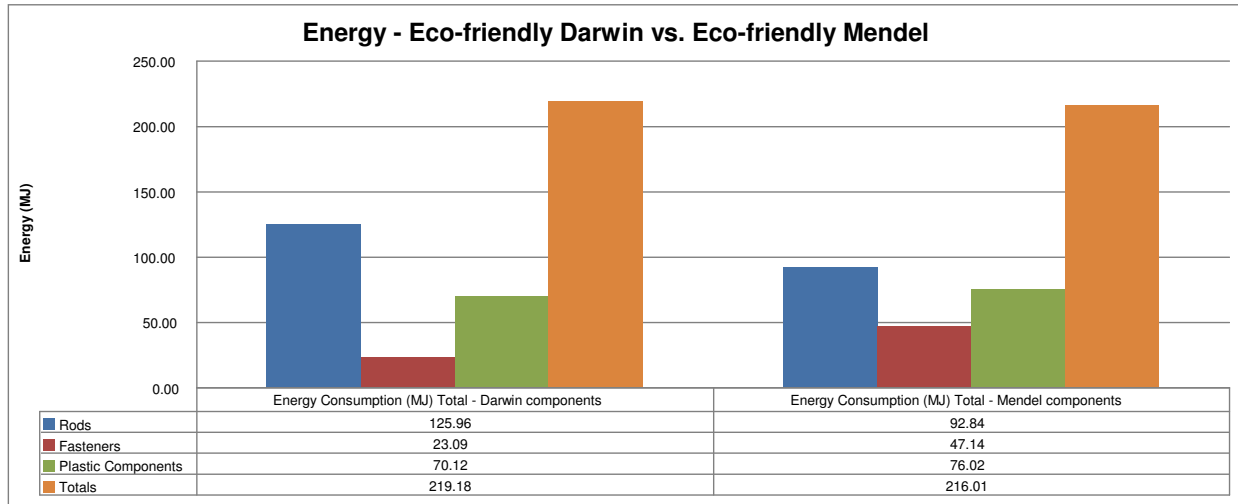


Figure 13: (Source Data: SolidWorks Sustainability and Chalmers University, 2008)

As previously stated the energy consumption of the frame components of the Eco-friendly Mendel is lower than the energy consumption of the frame components of the Eco-friendly Darwin. Next we consider the energy consumption during the operation of these two 3D printers. Physical tests would be required to measure the kilowatt-hours consumed during one hour of operation by both 3D printers. It is beyond the scope of this study to perform these physical tests; however, there is still enough information to make some deductions. For example, the Eco-friendly Mendel uses roller bearings and consequently requires approximately 8 times less torque than the Eco-friendly Darwin (RepRap, 2009). As a result, the Eco-friendly Mendel uses smaller NEMA 14 stepper motors, whereas the Eco-friendly Darwin requires larger NEMA 23 stepper motors (RepRap, 2009). With less torque and smaller stepper motors it is quite probably that the Eco-friendly Mendel consumes less Energy during normal operation than the Eco-friendly Darwin. Finally, it seems logical that the more compact Eco-friendly Mendel (Figure 15) has a lower environmental impact than the larger Eco-friendly Darwin (Figure 14).

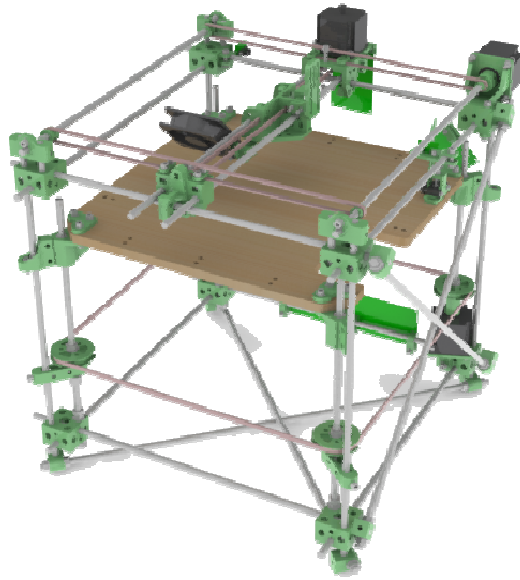


Figure 14: Eco-friendly Darwin (CAD data from RepRap, Rendering by Author)

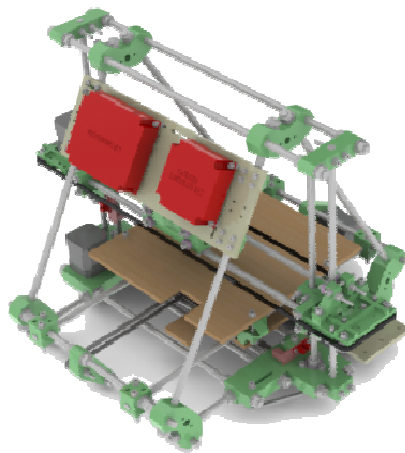


Figure 15: Eco-friendly Mendel (CAD data from RepRap, Rendering by Author)

Impact Assessment

Regular Darwin Simulation vs. Eco-friendly Darwin Simulation

An assessment of the environmental impacts of the Darwin versus to the Eco-friendly Darwin shows that:

- The rods had the strongest impact on the energy consumption and the GWP for all the frame components.
- The Transport phase had a significant impact on the energy consumption and the GWP for all the frame components. Consequently, local components have lower energy consumption and a lower GWP.
- PLA had a lower energy consumption and GWP than ABS in the Production phase, and probably in the other phases if it were to be composted.
- The Eco-friendly Darwin had lower energy consumption and a lower GWP than the Darwin.

Eco-friendly Darwin Simulation vs. Eco-friendly Mendel Simulation

An assessment of the environmental impacts of the Eco-friendly Darwin versus to the Eco-friendly Mendel shows that:

- The Eco-friendly Mendel required less rod material than the Eco-friendly Darwin.
- The Eco-friendly Mendel required more fasteners and plastic material than the Eco-friendly Darwin.
- The Eco-friendly Mendel had a lower overall material intensity, a lower GWP and lower energy consumption than the Eco-friendly Darwin.
- Furthermore, the Eco-friendly Mendel probably consumes less energy (electricity) than the Eco-friendly Darwin during operation.

Interpretation of Results

The results of this study were interpreted as follows:

- Using local components in the Eco-friendly Darwin and the Eco-friendly Mendel resulted in a lower environmental impact due to significantly reduced transportation impacts.
- The Eco-friendly Mendel, which is a more compact design, had a lower environmental impact than the Eco-friendly Darwin.
- MDF with formaldehyde-free binder should be used for the bed board of the 3D printers for health and safety reasons.

Main Assumptions

The following assumptions were made in this study:

- The LCI data is reasonably accurate and free of errors.
- The BOM and CAD data from RepRap is reasonably accurate and free of errors.
- The impacts of the Use phase of the steel components and plastic components are negligible.
- The Manufacture and Transport phases for ABS and PLA have similar impacts.
- For ABS and PLA the Production phase impacts are significantly greater than the other phases.
- The PLA parts will be composted during disposal and used as fertilizer.
- The motors are manufactured in the same plant using the same materials and processes.
- Long-distance trucks and high seas shipping are used in the Transport phase.

Limitations

The following limitations were identified in this study:

- The transportation of the raw materials of the steel components is not considered, since as previously mentioned it was assumed in this study that all the raw materials were obtained locally and consequently only the transportation of the finished goods had a significant impact. However, if there is a supplier whose raw materials are not obtained locally then the transportation of these raw materials could have a significant impact and must be considered in the LCI. For example if the steel rods are obtained from Pittsburg, but the limestone used to make the steel is from Brazil then the transport of the limestone from Brazil must be considered.
- Likewise, it was assumed that the raw materials for the ABS and PLA plastic parts were obtained locally. Once again, if there is a supplier that uses raw materials that are not local then the transport of these raw materials needs to be considered in the LCI.
- As previously mentioned there was some LCI information that was not available that could be obtained by physical testing. While this testing is beyond the scope of this study, the following tests could be done in the future by users of the RepRap printers:
 - Measure the energy required by a 3D printer to manufacture the plastic parts in ABS and PLA with a kilowatt-hour meter. This measurement would allow one to estimate the impact of the Manufacture phase of the plastics.
 - Measure the time for the PLA parts to degrade and the degradation achieved during composting. Determine if there are any special requirements for composting, such as temperature or if the PLA parts need to be cut to smaller pieces. This test would allow one to estimate the impact of the Disposal phase of PLA.

- Measure the energy consumed during one hour of operation by the Mendel and the Darwin with a kilowatt-hour meter. This measurement would allow one to estimate the impact of the Use phase of the stepper motors.

Conclusions

Two conclusions were drawn from the LCA portion of this study:

- Using local steel not only reduces the impacts in the Transportation phase of a the printers, but it reduces the overall impacts, since the Production, Manufacture and Disposal phases for steel in Pittsburgh and Shanghai are similar as reported by SolidWorks Sustainability.
- The Eco-friendly Mendel has a lower environmental impact than the Eco-friendly Darwin, since it used fewer high environmental impact materials (i.e. steel rod).

Three conclusions were drawn from the research portion of this study:

- Using biodegradable plastics results in emissions and energy credits gained during the Disposal phase.
- Design changes, such as installing ball bearings, can reduce the energy consumption during a product's operation.
- Inherently non-hazardous materials, such as MDF with formaldehyde-free binder, should be used as per the 12 principles of Green Engineering (Anastas *et al.* 2003).

Policy Recommendations

In this study it was shown how performing an LCA at the design stage of a product provided information on how to minimize the environmental impact of said product. Certainly, governments, companies and consumers can benefit from this practice. However, it remains to be seen if companies in Ontario and Canada will start incorporating LCA into their design processes in a meaningful scale. Nonetheless, public policy can be used to promote the adoption of tools that integrate LCA with the design process.

The first step in promoting these tools would be to inform both corporations and the public about the benefits of LCA at the design stage. This information can be disseminated via an educational campaign run by the federal and provincial governments in Canada.

Engineers and designers in Canada receive training on the physical properties of design materials as well as their costs; however, not enough attention is given to the environmental impacts of design materials. Colleges and universities in Canada should deliver training on the environmental impacts and the environmental benefits of design materials to help to fill this gap.

Corporations do not pay the real cost of pollution in Canada. This disparity is one of the reasons why Canada's energy use per capita is considerably high compared to other developed countries (Google Public Data, 2010). Implementing the polluter pays principle would encourage companies to reduce pollution and seek tools like LCA to help minimize the environmental impact of their products and services.

A carbon tax would help account for the real cost of pollution and encourage corporations to develop more eco-friendly products. In the last federal election Liberal leader Stéphane Dion proposed the concept of a tax shift or a "green shift". In essence a tax shift would tax "bads", such as pollution, and remove the taxes from "goods", such as labour taxes (Brady *et al.* 1999).

This shift would help reduce “bad behaviour” like pollution and encourage “good behaviour” like hiring new employees (Brady *et al.* 1999).

Furthermore, Canadians need to closely examine how our governments subsidize environmentally harmful activities. For example, the oil sands projects in Alberta receive tax incentives from the Canadian government (The Canadian Press. 2010). Removing environmentally harmful subsidies, such as these tax incentives, would help encourage the development of greener services and products.

As a corollary it follows that subsidizing environmentally helpful activities would have strong benefits. There are some signs that this is taking place in Ontario. A good example is the Green Energy Act with its feed-in-tariff that helps promote the use of renewable energy (Ontario Government, 2009).

While all these recommendations may be laudable on their own, what is needed in Canada is the coordination of these different ideas via a national green energy strategy, which lays out our goals as a country on how we will reduce emissions and energy consumption while promoting a green economy (Heintzman. 2010. p. 235). This national vision would help Canadians from all walks of life work towards a future that balances our social, environmental and economic needs from coast to coast to coast.

References

- Anastas, P.T., and J.B. Zimmerman. (2003) Design through the Twelve Principles of Green Engineering. *Environmental Science and Technology*. (2003): 94A-101A.
- Brady, Kevin, Patrice Henson, and James A. Fava. (1999). Sustainability, Eco-Efficiency, Life-Cycle Management and Business Strategy. *Environmental Quality Management*.. Spring (1999).
- Bovea, María D., and Rosario Vidal. (2004). Materials selection for sustainable product design: a case study of wood based furniture eco-design. *Materials and Design*. 25(1999):111-116.
- The Canadian Press. (2010). Harper rejects advice to budge on oil patch tax breaks. Retrieved from <http://www.ctv.ca/CTVNews/Canada/20100627/G8-oil-ptach-tax-100627/>
- Cappelli, Federico, Massimo Delogu, and Marco Pierini. (2006). Integration of LCA and EcoDesign guideline in a virtual cad framework. *13th CIRP International Conference On Life Cycle Engineering* (2006): 185-188.
- Chalmers University of Technology. (2010). CPM LCA Database. Retrieved from <http://www.cpm.chalmers.se/CPMDatabase/>
- City of Toronto. (2010). What goes in the blue bin? Retrieved from <http://www.toronto.ca/garbage/single/calendars/pdf/info.pdf>
- Curran, Mary Ann. (2006). Life Cycle Assessment: Principles and Practice. Scientific Applications International Corporation (SAIC).
- European Commission Enterprise and Industry. (2010). Ecodesign Your Future: How Ecodesign can help the environment by making products smarter. Retrieved from http://ec.europa.eu/enterprise/policies/sustainable-business/sustainable-product-policy/ecodesign/files/brochure_ecodesign_en.pdf

Google Public Data (2010). Energy use per capita. Retrieved from

http://www.google.com/publicdata?ds=wb-wdi&met=eg_use_pcap_kg_oe&idim=country:CAN&dl=en&hl=en&q=canada+energy+use+per+capita#met=eg_use_pcap_kg_oe&idim=country:CAN:USA:CHN:GBR:AUS

Healthy Building Network. (2008). Formaldehyde and Wood. Retrieved from

<http://www.healthybuilding.net/formaldehyde/>

Heintzman, Andrew. 2004. *The New Entrepreneurs: Building a Green Economy for the Future*.

Toronto: Anansi.

Industrial Fasteners Institute. (1988). *Fastener Standards: 6th Edition*. Ohio: IFI.

Integrated Publishing. (2010). LEED® Credit EQ-4.4: Low-Emitting Materials - Composite

Wood. Retrieved from [http://www.tpub.com/content/gsa/gsa/gsa/leed/gsa/leed0146.htm](http://www.tpub.com/content/gsa/gsa/gsa/gsa/leed/gsa/leed0146.htm)

Lee, Youngseong. 2004. *Rod and Bar Rolling: Theory and Applications*. New York: Marcel

Dekker.

Ontario Government: Ministry of Energy and Infrastructure. (2009). Ontario's Green Energy Act:

Our Path to a Green Economy and a Cleaner Environment. Retrieved from

<http://www.mei.gov.on.ca/en/energy/gea/>

Patel, Martin and Ramani Narayan. (2010). Review and Analysis of Bio-based Product LCA's.

Retrieved from <http://www3.abe.iastate.edu/biobased/LCAreview.pdf>

RepRap. (2009). Mendel's Improvements over Darwin. Retrieved from

<http://vimeo.com/6983001>

RepRap. (2010). Welcome to RepRap. Retrieved from http://reprap.org/wiki/Main_Page

RepRap Wiki. (2010). ABS. Retrieved from <http://reprap.org/wiki/ABS>

SolidWorks Corporation. (2010). SolidWorks Sustainability: The easy way to more environmentally friendly designs. Retrieved from www.solidworks.com/2010sustainability

Sustainable Minds LLC. (2010). Connecting ecodesign with LCA for a new generation of greener products. Retrieved from www.sustainableminds.com/ecodesign-and-lca

Vink, Erwin T.H., Karl R. Rábango, David A. Glassner and Patrick R. Gruber. (2003). Applications of life cycle assessment to NatureWorks™ polylactide (PLA) production. *Polymer Degradation and Stability* (2003): 403-419.