The Environmental and Economic Impacts for Producing the Port Jackson from Novatein®

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Abstract

Preserving meat quality is paramount during meat processing. Contamination is reduced by preventing contact between faecal matter and the carcass. Rectal plugs are used for this purpose during slaughtering, and the animal's intestines can be removed and entered directly into the rendering process. Polypropylene plugs contaminate rendered products, while Novatein® plugs (the Port Jackson) will break down during the rendering process.

A life cycle assessment (LCA) was used to determine and compare the environmental impacts of plugs made from either polypropylene or Novatein®. Two scenarios were considered, in which the production of the plugs could be contracted out, or manufactured in-house. On an environmental basis, the difference was negligible. Resin production accounted for 73% of the total non-renewable primary energy (NRPE) use and global warming potential (GWP), with the balance shared between plug production, use, and disposal.

Injection moulding and packaging each contributed 31% to GWP, as well as 25.8% and 40% of the NRPE use respectively during plug production and disposal, dominating impacts during plug production. In contrast, operations with the lowest impacts were conditioning and transport, collectively contributing to less than 4% of the entire LCA impacts.

The life cycle impacts were particularly sensitive to packaging, the allocation method used for farming impacts on bloodmeal production, and the ratio of the electricity grid mix. By eliminating cardboard boxes reduced GWP and NRPE use by 6.1% and 6.9%. Allocating impacts from farming to bloodmeal production could increase the GWP by up to 193%, and NRPE by 14%. Allocation is not under the control of the manufacturer, and is a limitation of the assumptions made in this study. By using coal-based electricity, the GWP can increase by 66%, and NRPE by 20%. Impacts from electricity use could change noticeably if the plugs were manufactured overseas.

The net present value (NPV) of capturing 10% of the market, and selling the plugs at $0.15 NZD, at a 35% discount rate was $143,629 when contracting out plug production. Under all costing assumptions, contracting out provided a higher NPV

than manufacturing in-house. This is primarily due to the large capital costs when producing in-house.

The critical factor that will cause manufacturing in-house to be more financially viable is the capital cost. The difference between the NPV of the two scenarios is $240,442, and the estimated total cost of buying, shipping, and installing the injection moulder is $355,153. If this can be reduced to $114,711, the two scenarios become equal. Because manufacturing in-house has a higher ongoing cash inflow per year, this scenario will also benefit more from scaling up volume above the 10% market share threshold.

When comparing the Port Jackson with the polypropylene plug, the Novatein® plug has a higher GWP (0.0166 kg CO_2eq per plug) than the PP plug (0.0126 kg CO_2eq per plug), however, it requires less NRPE (0.302 MJ per plug and 0.430 MJ per plug respectively), and if contracted out, can be sold competitively at a matching market value of $0.15 or $0.16 per plug. The price may be lowered even further to $0.12, and still have a positive NPV. These factors are slightly in favour of producing Novatein plugs, but the Port Jackson's advantage over PP is the fact that it not only breaks down during rendering, but it is also non-toxic, so simply becomes part of part of meat and bone meal.

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1 Introduction

Polymers comprise a major segment of the materials and products industry. However, with rising concern over fossil fuel depletion, international focus is shifting towards bio-based polymers that are derived from renewable biological feed stocks. Plants are grown and waste from animals is collected to be transformed into bio-polymers [1].

Although bio-polymers are often associated with renewability and eco-friendliness, their production can be surprisingly energy intensive and can even emit more harmful volatiles during production and disposal than standard fossil-based polymers [2]. As such, to gain an accurate picture of the true environmental impact of bio-polymers, it is important to evaluate the entire life cycle of production methods.

A life cycle assessment (LCA) is an evaluation system that can be used to determine energy use, emissions to the atmosphere, eutrophication, acidification, eco-toxicity, and other environmental impacts. The results on an LCA can be used to identify areas of improvement in the process, and if performed objectively, compare multiple materials that could perform a similar function [3].

In this study, the life cycle assessment will compare an abattoir rectal plug made from polypropylene to a new plug formed from Novatein thermoplastic protein (Novatein®). The current plugs' material composition (polypropylene) can contaminate rendered products. However, a plug that is created from a material that is hydrophilic and breaks down in water will break down during the rendering process. In brief, rectal plugs are inserted into the anus of a slaughtered animal to stop faecal matter contaminating the carcass; the animal's intestines are then removed and entered directly into the rendering process. It is at this point the material composition of the plug can contaminate the products.

Bio-based polymers are often considered as alternatives for commonly used polymers like polyethylene (PE), polyethylene terephthalate (PET), and polypropylene (PP) because of their sustainability and degradability. The best known bio-based polymers include polylactic acid (PLA), starch based plastics, poly(itaconic acid) (PIA), sugar-based PE, and various bio-composites (using plant fibre instead of glass or carbon fibre) [4].

Novatein® is a bovine bloodmeal based thermoplastic that has been developed jointly between Aduro Biopolymers and the University of Waikato. The proteins in bloodmeal are used to create a thermoplastic by breaking disulphide bonds, disrupting hydrophobic bonds, and thereby creating linear chains [5]. This is done with the addition of sodium sulphide (SS) and sodium dodecyl sulphate (SDS), TEG, urea, and water. The bloodmeal powder consolidates when extruded, enabling it to be granulated and injection moulded [5].

Products made from Novatein® resin are sensitive to moisture, as proteins are hydrophilic. This means that Novatein® breaks down in a matter of weeks in high humidity conditions, or days when immersed in cold water. Due to its hydrophilic nature, Novatein® plugs can be broken down during rendering, whilst the non-toxic nature of the plugs ensure the quality of the rendered waste products are not compromised. These properties make Novatein® plugs a perfect candidate for a one-use only product, and an ideal substitute for polypropylene plugs.

Life cycle assessments (LCAs) quantitatively study a product's inputs and outputs over its lifetime; specifically, LCAs analyse the emissions and environmental impacts the product poses, from creation to disposal (cradle-to-grave). In general, an LCA is comprised of the life cycle inventory (LCI), and the life cycle impact analysis (LCIA).

LCIs consist of the raw inputs and outputs of a system, including raw material, energy, waste, and emissions. Life cycle impact analyses (LCIAs) are concerned with environmental impacts of the LCI data, including: land use, emissions, and the effect that energy use has on the environment. As an extension to the environmental impact analysis (which comprises the LCA) the economic viability of the product can also be studied.

Performing an LCA provides the opportunity to draw fair and accurate comparisons between similar polymers, based on the environmental impacts associated with each polymer. However, this can be difficult as the procurement of feed stock, polymerisation, production, and end-of-life can vary greatly between polymers, especially when comparing a fossil fuel-based plastic to a bio-based one. There are several methods that can be applied to draw fair comparisons, and these are explained in detail later.

In this study, a full cradle-to-grave LCA is carried out on “The Port Jackson” plug produced from Novatein®. A sensitivity analysis is used to compare and contrast the new product with the current polypropylene version. A commercial feasibility study is conducted for a more complete analysis. Throughout the study, two scenarios are considered: (1) the production of the plug could be contracted out; and (2) the plug could be manufactured in-house, by adding a small production facility next to the Novatein® production plant.

2 Recent Developments in Polymer Life Cycle Assessment

2.1 Life cycle assessment

Life cycle assessment is a tool used to determine the environmental impacts of using a material or product to fulfil a specific function. It can be performed from cradle-to-gate or from cradle-to-grave. A cradle-to-gate study starts with the raw materials being extracted from the environment, and ends when the processed material is formed, but prior to an actual product being manufactured. A full cradle-to-grave LCA considers impacts from the moment raw materials are produced or extracted from the earth, the impacts from its production and use, right through to the end of the product's life. In 1997, the International Standards Organisation released ISO 14040 to standardise studies that looked at the effects of manufacture, use, and disposal of products in a holistic manner [2]. ISO 14040 specifies the framework, procedures, and limitations of an LCA. Later, ISO 14041, 14042, and 14043 were released to expand the activities within an LCA, however, ISO 14044 has combined the three standards, along with corrections. It has also been revised and updated in 2012. Now, only ISO 14040 and 14044 are required to complete a thorough LCA [2, 3, 6].

A summarised version of ISO 14040 shows that a life cycle assessment requires these four activities:

1) goal and scope definition;
2) life cycle inventory analysis (LCI);
3) life cycle impact assessment (LCIA); and
4) life cycle interpretation.

A full cradle-to-grave assessment is used to create an environmental profile for a particular product. This profile can then be used for comparison against similar materials, but is more often used to aid decision making, or production refinement [3]. The entire process is performed in an iterative manner, and as data is gathered, changes can be made to the goal, scope, and the LCI.

2.1.1 Goal and scope definition

The goal is the reason for conducting the study, and needs to be defined unambiguously. A goal should include what the study is trying to find out, its intended application, and the targeted audience [7]. The goal influences the system boundaries, how complex the study will be, and the depth of the final report. After the goal is set, the scope needs to be defined.

The scope determines whether or not the study will be comparative, and also determines the system boundaries, the level of depth and detail of the study, and also states what the functional unit will be. A subjective study only looks at a material or product itself, and what its impacts are. A comparative study takes the information, and compares it to similar materials or products. The system boundary defines where the study begins and ends. A true cradle-to-grave study will have no product crossing the system boundary, and wastes will be the only output. This is not always possible to achieve, but depending on the depth of the study, should be strived for.

The functional unit plays a large role in determining the outcomes of the study. A functional unit is based on the function of a product, and not the amount produced. The flows between all of the unit processes in a system are related to a reference flow, which allows for all system input and output data being referenced to the functional unit [6]. E.g. the amount of flour, sugar, or water required to produce 1 kg of bread dough, where 1 kg of bread dough is the reference flow.

A good example of a functional unit is the supermarket bag, which needs to carry a certain volume of groceries. A plastic bag won't necessarily carry the same volume as a paper bag. Therefore the functional unit cannot be "number of bags produced", but should rather be based on the volume of the bags. There are products that perform the same tasks for the same duration of time, that may or may not use the same amount of material, which can be measured by units produced. An example of this is disposable cutlery, where the function is to help people eat a single meal, and the size of the knives, fork and spoons, and even the meal is largely irrelevant, provided that they function properly. Disposable cutlery is often produced using polyethylene or polypropylene, but starch based thermoplastics are also being used more frequently. Once the functional unit is selected, a reference flow will specify the amount of material required to fulfil the function dictated by the functional unit.

2.1.2 Life cycle inventory analysis (LCI)

An LCI consists of establishing the inputs and outputs of each step of the life cycle. Unit processes are the processing steps required to deliver the functional unit. Each unit process must undergo a thorough mass and energy balance, and results expressed in terms of the functional unit. An ideal cradle-to-grave assessment starts with the unit processes that use raw materials before human intervention, all the way through to when wastes and emissions are returned to the environment (with no further human involvement).

These inputs and outputs are called elementary flows. This isn't always practical or even possible, but whenever assumptions are made, they should be logical and stated unambiguously. Assumptions must be justified and checked via sensitivity analysis. The ideal LCI should include acquiring raw material, the production of the primary ingredients, making the product, use during product life, and the end of life (EOL). It should also include any energy use and transport requirements. Figure 1 shows the simplified flow diagram of carrying out a life cycle inventory analysis [8].

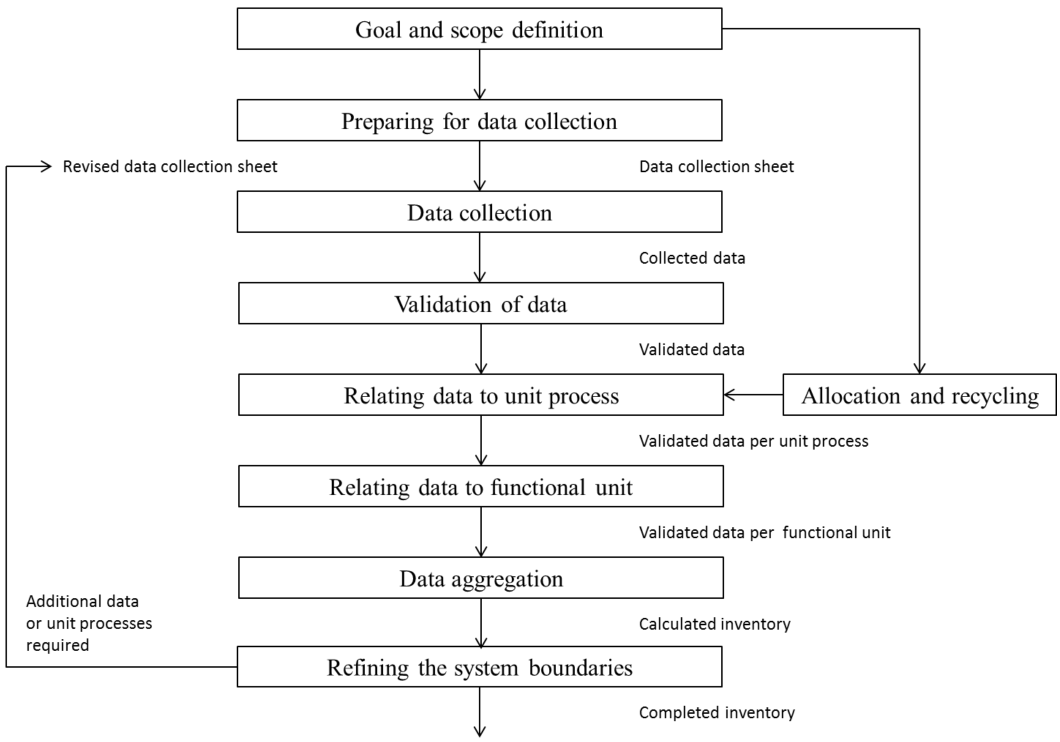

Figure 1 – Simplified procedures for inventory analysis [8]

The allocation of inputs and outputs is used when a unit process has more than one function. For example, when a unit process has more than just one product output, a portion of the total in and outputs needs to be allocated to each of the products (or functions). This method is used to determine how much of the impacts associated with a process should be allotted to a specific product or waste stream that is created by a system, especially if there are multiple product or waste streams that stem from the process.

I.e. consider a system with one product and one by-product. Without allocation, the all of the outputs generated are considered to be a result of manufacturing the product. However, this may be inaccurate as the by-product may have contributed to some of the output generation. Therefore by using allocation, a large amount of the total output is considered to be directly caused by the manufacture of the main product, while the remainder is considered to be the result of creating the by-product (Figure 2).

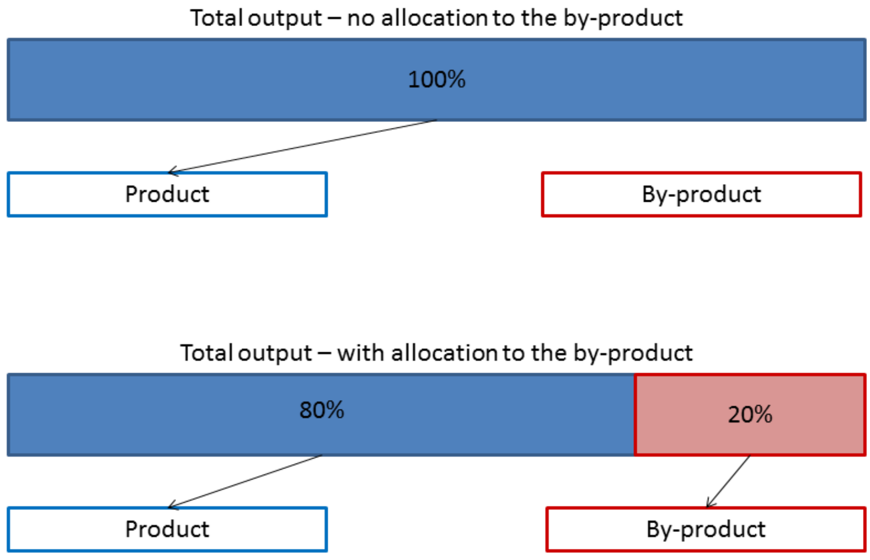

Figure 2 – Allocation to by-products

Figure 3 shows the step wise procedure for allocation. Whether allocation is used or not, the sum of the inputs and outputs should always be the same. Additionally, if wastes are present, inputs and outputs are allocated to co-products only. Examples of what an LCI consists of includes energy input and output (chemical, electrical, heat), raw material input, CO_2eq gas outputs, nitrogen compound outputs, and any other waste material output. In general, the LCI includes the mass and energy flows between unit operations, and the raw data for system wide in and outputs, which require further assessment to produce the life cycle impact analyses (LCIA). As such, the raw data from the LCI could stay constant for a specific scenario, and the LCIA may vary depending on the methods used to interpret the LCI results.

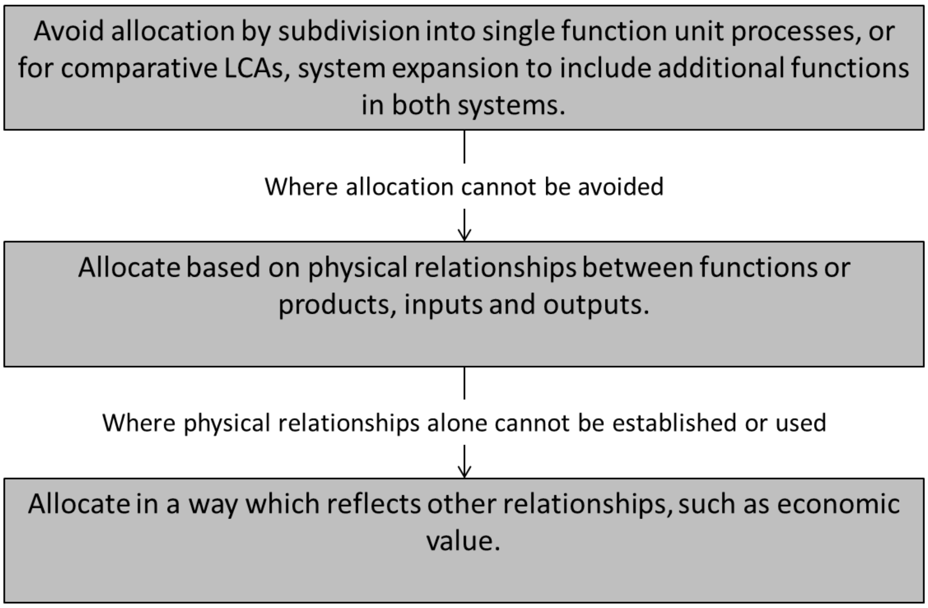

Figure 3 – Stepwise allocation procedure [8]

2.1.3 Life cycle impact assessment (LCIA)

The LCIA phase uses and evaluates the data from the LCI to reach a quantifiable conclusion for the impact caused by the system. The LCIA is a relative approach based on the functional unit, consisting of three mandatory elements, and including several optional elements (Figure 4).

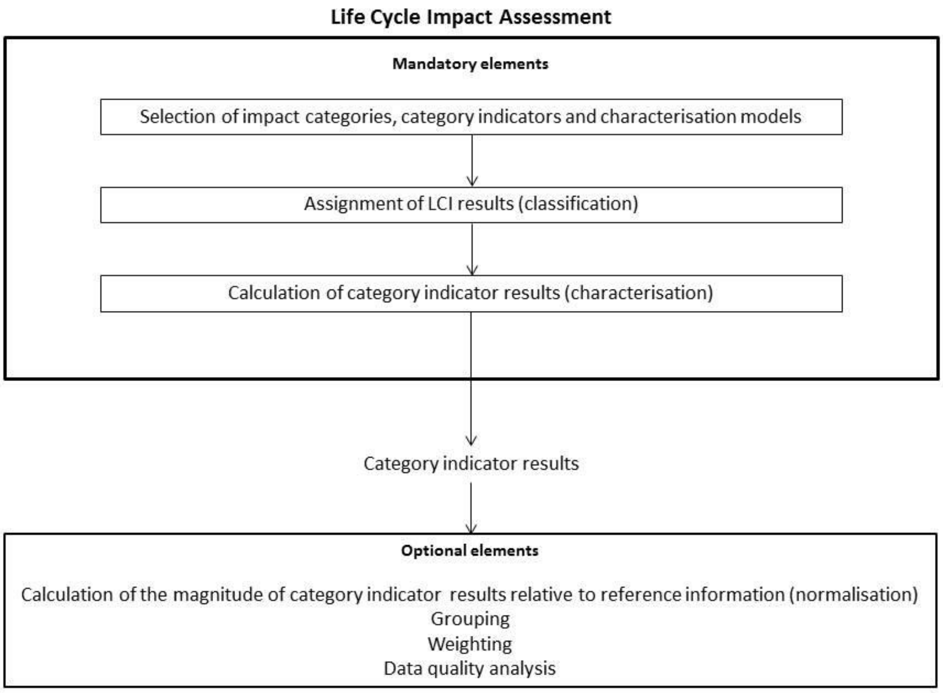

Figure 4 – Elements of LCIA phase [9]

The separation into different elements in Figure 4 is necessary for several reasons:

- each element is distinct and can be clearly defined;
- the goal and scope can consider each element separately;
- each element can undergo a quality assessment of methods, assumptions and decisions made; and
- each element can undergo critical review and reporting if made transparent.

The selection of impact categories includes impacts on human health, natural environment quality, natural resource usage, and impacts on man-made environments. These groupings are generalisations, and are not part of the ISO standard. ISO 14044 simply gives criteria for what an appropriate impact category must have. Impact categories can vary greatly from study to study, and includes acidification (ground and water), ozone depletion, land use impacts, and many others. The most significant of these are explained in detail later.

Impact categories define what effect the LCI results have on the environment, and are made up by several technical terms:

- characterisation factors - selected to show how the inputs and outputs from the LCI affect the environment;
- characterisation model – used to select characterisation factors;
- category endpoints – the effect of the LCI results on the environment;
- category indicator - calculated by multiplying the characterisation factor with the relevant LCI results for each category; and
- indicator result - The common units used for any category, derived by multiplying the LCI results with the characterisation factors (see calculation). Every impact category will have its own indicator result, however LCI results may well affect more than one impact category.

Indicator result = $\sum\left[[Characterisation\ factors] \times [Relevant\ LCI\ results]\right]$

An example of each of the terms can be seen in Table 1.

Table 1 – Example of terms [6]

Term	Example
Impact category	Climate change
LCI results	Amount of green house has per functional unit
Characterisation model	Baseline model of 100 years of the intergovernmental panel on climate change
Category indicator	Infrared radiative forcing (W/m^2)
Characterisation factor	Global warming potential (GWP_{100}) for each greenhouse gas (kg CO_2-equivalents/kg gas)
Indicator result	Kilograms of CO_2-equivalents per functional unit
Category endpoints	Coral reefs, forests, crops
Environmental relevance	Infrared radiative forcing is a proxy for potential effects on climate, depending on the integrated atmospheric heat adsorption caused by emissions and the distribution over time of the heat absorption

Once the impact categories have been selected, the inputs and outputs need to be assigned to relevant categories. Where more than one category is affected by a set of data, it needs to be decided whether the effects are from parallel or serial mechanisms. In a parallel mechanism, all the categories involved will have the total effect contributed to each of them. In the series mechanism, the total effects will be portioned for each category.

LCI results can then be converted into standard units through the use of characterisation factors. It must be noted that these units are not always SI units. Converted results are then classed together to give the indicator results for the whole life time.

This concludes the compulsory part of the LCIA.

The optional elements all take judgement or comparison into account, and are not scientifically viable. "Normalisation" divides the results by a reference to obtain ratios. These ratios are used for comparison, and to work out percentage of impact for each category. "Grouping" simply groups related categories together, and then value judgements are made using the goal and scope, but are not scientifically derived. "Weighting" groups the results of different impact categories based on importance to give the total score. This involves value judgements, with any justifications and assumptions recorded.

2.1.4 **Common impacts**

There are several common impacts used in an LCIA. These are non-renewable primary energy (NRPE), total energy use, global warming potential (GWP), depletion of abiotic sources, photo-oxidant formation, acidification, eutrophication, eco toxicity, and water & land use.

Non-renewable primary energy is the term used to describe energy generated by fossil fuels, either electricity or heat, to create a product. The energy required to operate a machine, or generate heat is called delivered energy. Primary energy is the term used to describe the net amount of energy required to generate delivered energy, and accounts for all the upstream inputs as well as the delivered energy. Primary energy can be in the form of renewable energy, like wind farms, hydroelectricity dams, or solar energy [10], and non-renewable energy is usually in the form of coal, crude oil, or natural gas [11].

Climate change is most commonly used impact category, and is usually expressed as global warming potential (GWP). The first step in calculating GWP is to work out what gasses are released to atmosphere. The next step is to calculate the CO_2 equivalent. For GWP, CO_2 is the base unit, with a value of one. Every gas released to atmosphere has a certain amount of GWP. But to simplify the process, their mass values are multiplied by a ratio to produce the equivalent amount of CO_2 that will give the same amount of GWP. Thus the CO_2eq can be used for easy understanding and comparison. The most commonly used ratio is the Intergovernmental Panel on Climate Change (IPCC) GWP values and lifetimes tables. For example, 1 kg of methane over a 20 year period has the GWP of 72 kg of CO_2, therefore the CO_2eq number for methane is 72 over 20 years [12].

It is important to note that the period of time for which GWP is considered will influence the values. GWP values change over time depending on the substances' decay in the atmosphere. These numbers aren't always exact and reference needs to be given to the calculation used. For instance, 1kg of methane have a GWP of 72 kg CO_2eq over 20 years, but this number decreases to 25 kg CO_2eq over 100 years, and 7.6 kg CO_2eq over a 500 year period (Table 2) [12]. A similar climate change measure to GWP is greenhouse gas emissions (GHG), however this simply uses the raw inputs and outputs to atmosphere to generate an emissions value, and is not as specific to the potential for environmental impact.

Table 2 – GWP of three common emissions over 20, 100, and 500 years

Industrial designation or common name	Chemical formula	Lifetime (years)	Radiative efficiency ($W\ m^{-2}\ ppb^{-1}$)	Global warming potential for given time horizon (CO_2eq)		
				20-yr	100-yr	500-yr
Carbon dioxide	CO2	-	$1.4x10^{-5}$	1	1	1
Methane	CH4	12	$3.7x10^{-4}$	72	25	7.6
Nitrous oxide	N2O	114	$3.03x10^{-3}$	289	298	153

The depletion of abiotic sources refers to lowering the future availability of non-renewable resources like iron ore, zinc ore, crude oil, etc. [13].

Photo-oxidant formation is the formation of reactive substances (mainly ozone) which can be harmful to people, ecosystems and even farm crops. It is expressed as kg ethylene equivalents/kg emission.

Acidification is the emission of acidifying substances which can have great impacts on soil, groundwater, surface water, organisms, ecosystems and materials (buildings). It is expressed as kg SO_2 equivalents/ kg emission.

Eutrophication includes excessive levels of macro-nutrients in the environment caused by emissions of nutrients to air, water and soil. It is expressed as kg PO_4 equivalents/ kg emission.

Eco-toxicity covers land, air and water and refers to substances which are harmful to organic life in general. It can be measured in a variety of ways, but usually as 1,4-dichlorobenzene equivalents/kg emission [14].

Land use impacts currently has a wide variety of meanings ranging from species density change, biodiversity change, conversion of cultural land, and many more. For specific cases, the most prominent change will have the highest impact, but this will vary from case to case as standardisation is still not in place [15].

2.1.5 Interpretation

The final phase of life cycle assessment is interpretation. Here the data from the LCI and LCIA are considered, any significant issues are identified, and data is evaluated for completeness, sensitivity, limitations, and consistency. Here the conclusions and recommendations are drawn. Again this part of the LCA is iterative and as issues are identified, the problem areas will need to be revisited and improved. At this stage it will also become clearer if the goal and scope need to be refined.

Interpreting the life cycle assessment is the final phase, and involves drawing conclusions based on the data generated through the life cycle assessment, and making recommendations based on the results. This process involves checking the data for completeness (ensuring that all relevant data is in the dataset), consistency (ensure the quality of the data is as uniform as possible), and sensitivity (how much the results may vary when changes are made to the major assumptions). If any data required for the goal and scope is missing or incomplete, a check is required to decide whether or not the data is necessary. If missing data is important, it needs to be revised in the LCI and LCIA. If the missing information is considered unnecessary, the reason for this should be recorded [6].

The sensitivity aspect checks to see if data is reliable, and to check the effects of uncertainty. This part of the study includes the sensitivity analyses of the inventory and impact assessment, and again the process is iterative. The level of depth is also dependant on the goal and scope; if the LCA is to be disclosed to the public, a detailed analysis is required.

A consistency check determines if the assumptions, methods and data are consistent with the goal and scope. ISO14044 states that the following questions are to be addressed [6]:

a) are differences in data quality, along a product system life cycle and between different product systems, consistent with the goal and scope of the study;
b) have regional and/or temporal differences, if any, been consistently applied;
c) have allocation rules and the system boundary been consistently applied to all product systems; and
d) have the elements of impact assessment been constantly applied?

Once these evaluations are complete, preliminary conclusions may be drawn. Once the conclusions have also been checked, and are found to be consistent with the rest of the study, they may be reported as full conclusions. Recommendations will be based on the final conclusions, and fully explained [6].

An example of such an interpretation would be to look at the production phase of an item. If the item has had data gathered in a similar fashion to the rest of the LCA, and there is enough data, then it must pass the checklist above. Once satisfied that the data falls within the goal and scope, inside all boundaries, and there is consistency with the rest of the assessment, a conclusion may be drawn. This conclusion may hypothetically be that the production phase is using too much power, or that the emissions are much higher than any other part of the life cycle. Once again, this conclusion must be checked and verified. If the conclusion is found to be accurate, recommendations could include that a more energy efficient production method must be considered, or that a treatment system must be installed to reduce emissions to atmosphere.

2.2 Comparison of polymers using LCA

The comparisons between fossil fuel-based polymers and bio-based polymers has always been difficult. Although there is an international standard to conduct and report findings from an LCA [3, 6], in practice, key assumptions including impacts investigated and allocation methods vary from study to study. Even the same material, like polyethylene, can be produced in different ways. As there is also no blanket statement to confirm that bio-based polymers are in fact better or worse for the environment, assessments and comparisons need to be done on a case by case bases, taking a specified functional unit into account.

LCA has been used in several studies to compare bio-based polymers with fossil fuel based polymers. These studies range from comparing different polymers (including bio-fibre reinforced materials) to comparing the use of ethanol as a monomer.

2.2.1 Fossil fuel vs bio-based polymers

One of the most prominent questions that arise is whether or not bio-based and bio-degradable polymers are in fact better for the environment and reduces non-renewable resource use. In reality the results vary, with bio-polymers often having a higher impact than fossil fuel based counterparts. This does depend largely on the study conducted and the methods used for obtaining and disposing of any polymers.

One study into the life cycle impacts of modern polymers included a review of bio-based polyethylene terephthalate (PET), recycled PET, polylactic acid (PLA), and man-made cellulosics. The study considered NRPE use and GHG emissions as the most important impacts; however, the use phase was not included, as it can vary greatly between functions. The results showed that bio-based polymers and recycled fossil fuel-based polymers both offer benefits over conventional virgin fossil fuel-based polymers. When PET is considered on its own, the results showed that recycling bio-based PET had the lowest GHG emissions and NRPE use, with recycled fossil fuel-based PET having the second lowest impact, and virgin bio-based PET generated the largest emissions and energy use of the three. Virgin fossil fuel-based PET used the most energy of all, with the highest emissions. Both of the bio-based polymers (PLA and cellulose) had lower impacts than fossil fuel-based PET and bio-based PET. However it was noted that impacts were strongly affected by allocation method for recycling; the "cut off" method considered the collection of waste as the cradle; and the "waste valuation" method shared the impact of virgin polymers between virgin and recycled materials. Finally system expansion takes the entire life cycle into account and does not allocate any environmental burden between first and second lives. The cut off method showed recycled PET to have lower impacts than bio-PET, whereas the system expansion method showed that all the polymers had similar impacts. This is also a reminder that any allocation method used must be thoroughly justified, as results can vary quite significantly. In this case, system expansion proved that PET had similar emissions and energy use to the bio-based polymer, but the other two allocation methods stated that PET (bio and fossil-based) had higher emissions and used more energy [16].

PLA, bio-based PE, bio-based polyester, polypropylene (PP), paper, and standard PE were all investigated for the use of bio-based wrappings. NRPE, total energy use, GWP, depletion of abiotic sources, photo-oxidant formation, acidification, eutrophication, and water & land use were considered. The study took into account the different purposes of inner and outer packing, with inner packing needing to be of a higher quality due to contact with food. For the inner packs, bio-based polymers were comparable with petrochemical polymers. However, paper/PP laminates performed similarly to PP when landfilled, and had lower impacts than standard PP if incinerated with energy recovery. For the outer packs, bio-based PE and paper/bio polyester laminates both resulted in lower impacts than standard PP. PLA showed advantages for inner and outer packs when wind credits were accounted for, or future level of production [17]. However, comparisons should be made based on initial data, without the purchase of emission credits, and efforts should be made to reduce impacts in the actual life cycle of a product, instead of trying to offset impacts using emission credits [18] (i.e. wind credits cannot be used to lower an absolute impact). Finally, advantages differ based on use (inner/outer), with outer packs having lower overall impact as specifications are less demanding [17]. This is a great example of how the functionality can influence the conclusions drawn.

When starch-based biopolymers were compared to PE, human health, ecosystem, and resource use were considered. Starch-based plastics consume fewer resources in terms of fossil fuels, but have a higher impact on the ecosystem and human health. In terms of disposal, starch proved to have higher impacts than PE when both were land filled, and recycling PE proved to have the lowest impact of all. It must be noted that impact results can vary based on weighting placed on impact categories, and which ones are included in the LCA. Also noted is that this study does not include biodegradability, which could change the outcome significantly [19].

One of the most common current bio-polymers is poly(itaconic acid) (PIA) [20]. PIA can be incorporated into other polymers as a comonomer, and be used as in coatings, adhesives, binders, fillers, synthetic glass, etc. [21]. Research into an attributional life cycle assessment (ALCA) of poly(itaconic acid) production from northeast US biomass focused on the production of PIA derived from itaconic acid (soft wood biomass). The study was compared to corn derived PIA, and fossil fuel poly(acrylic acid) (PAA). From the cradle to the gate, the focus was on GWP, fossil energy demand (NRPE), acidification, eutrophication, water use, and land occupation. The soft wood based PIA proved to have a lower GWP, CED, and acidification value than the other two polymers. It also showed lower eutrophication and water use than corn based PIA, but higher than PAA. It had the highest impact for land use, as soft wood trees have slow growth rates and produce low yields. PAA had the least land use impact. The conclusions were that soft wood based PIA could be a viable replacement for PAA with some optimisation [22].

A sustainability assessment of bio-based polymers was performed, and included a summary of various LCAs performed on PLA, polyhydroxyalkanoates (PHA), thermoplastic starch (TPS), and five common petroleum polymers. The primary impacts compared were GWP and fossil fuel depletion. The results showed that because bio-polymers are still new, they mainly have similar impacts to petroleum based polymers. The EOL study gave more comprehensive results but added more uncertainty. This proved that there is still little data for EOL variation of bio-polymers, and therefore each study requires thorough research into the disposal [23].

Another case study on biodegradable polymers proved that biodegradable plastics (BDPs) aren't always more economical or environmentally friendly. TPS, PLA, and PP were added together to form three different material mixes of TPS-PLA, TPS-PP, and PLA-PP. The material mixes were then tested in different concentration levels. Results showed that varying the percentage of BDPs used in any application can make a significant difference. Both BDPs work better for injection moulded products, making the most of large surface areas, allowing for low material impact, and high cycle times. But it was also noted that increasing the concentration of PLA or TPS, when mixed with PP, increased environmental impacts. Another conclusion drawn was that if the production phase has a lower impact during an LCA, then disposal and EOL need to be specified and chosen carefully, for example, performing an in depth comparison of land fill, composting, and recycling. It was also found that there is not a lot of information on recycling bio-polymers at this point in time, and due to this, recycled PP is still a competitive choice when aiming to reduce environmental impacts. In the end, using PP still had a lower impact, but it was noted that BDP has a lot of room for improvement [24].

The use of Kraft lignin as a polymer additive is commonly used in cement mixing, water treatment, textile dyes, and various agricultural chemicals. The lignin that was investigated originated from black liquor obtained through the paper pulp process. Black liquor can also be used as a bio-fuel, or energy source for paper mills. When looking at only the cradle-to-gate of lignin, the process of obtaining the lignin has a high energy use, mainly from natural gas. Also used during the process to improve material potential is CO_2 for precipitation, sulphuric acid for washing, and NaOH for sodium replenishing. The results showed that early life from black liquor derived lignin is relatively energy efficient, and is environmentally less impact than other similar polymers. The conclusion drawn is that black liquor lignin can be used as a biologically derived substitute for petroleum alternatives, or use as a bio-fuel, and have a lower environmental impact than both [25].

From these examples, it is clear that if a definitive conclusion needs to be drawn regarding a particular product system, that the system itself needs to be investigated and compared with alternative materials or methods. Not only do different polymers have different impacts, but the same product or polymer can be produced and disposed of in varying ways. Any alteration to the production, use, or disposal can lead to an increase or decrease in impacts. Additionally, the functionality of any product can have a large influence on how the product needs to be assessed.

To make sure that these comparisons can relate to each other is sometimes more difficult than merely comparing the raw data. Some research has been conducted to eliminate any ambiguities in face value comparisons, and focus has also been on reducing impacts through smarter design. The idea is that any significant impacts can be avoided or reduced before the manufacturing of a polymer or product.

To this end, a study was conducted to look at how green design affects the life cycle assessments of polymers. Green design is about reducing resource wastage during the manufacture of man made goods, and that sustainability should be focused on during design. A total of 12 polymers were investigated, seven petrochemical, four bio-based, and one mixed polymer. The study looked at economy, mass used from renewable sources, biodegradability, percent recycled, distance of furthest feedstock, price, life cycle health hazards and life cycle energy use. It was found that green design does reduce impacts all round, but the polymer groups showed interesting results. Although bio-polymers have high green design incorporation, their production has high environmental impacts at the moment. Because of this, bio-polymers score the highest in green design, but their impacts are still comparable to most fossil fuel-based polymers. Polyolefins had the lowest impact, with PET, polyvinyl chloride (PVC) and polycarbonate (PC) achieving the lowest rankings in both categories, with high impact and little green design incorporation. This proves that both bio and fossil based-polymers have room for improvement [26].

It must be emphasised that the impacts and comparisons of polymers vary from study to study, but there is definitive proof that smart and sometimes qualitative design can reduce impacts from the earliest levels of process development. Also, both fossil and bio-based polymers showed strengths and weaknesses in terms of environmental impacts, and with improvement to the design both polymers can achieve a more environmentally friendly status.

2.2.2 Fibre and composites

An interesting use of bio-based polymers is integrating bio-fibres into polymers. Currently there are well established polymer matrices, both thermoplastics and thermosets that are fossil based, with a glass or carbon fibre integration to form the composite. However, research has been primarily focussed on creating composites of fossil fuel-based polymers with bio-based fibres, and maintaining the physical properties, while reducing impacts through altering only the fibre input.

A comparative LCA of a transparent composite facade system (TCFS, bio-fibre) and a glass curtain wall system (GCWS) looked at the thermal performance of glass window coatings. The coatings were tested for use on a 10 story building, with panels being 4 m high and 4.9 m wide. The life span of the TCFS was estimated at 10 years, while the GCWS had a span of 20 years. As the entire life cycle was to span over 40 years, this meant the TCFS would need to be replaced 4 times, as opposed to twice for the GCWS. However, as the purpose of these coatings is thermal insulation, the use phase is dominant, with production and EOL being insignificant. When energy consumption and CO_2 emissions were measured, rooms equipped with TCFS used 93% of the energy that GCWS equipped rooms used. Similarly the total CO_2 emitted by TCFS was 89% of the total amount GCWS emitted. In short, the bio-fibre facades were more thermally efficient than the glass walls, and since the use phase was the most dominant, it clearly marked the bio-fibre walls as the best option [27].

Natural fibre composites can often show advantages over current market fibres such as glass and carbon fibre. One life cycle assessment of a novel hybrid glass-hemp/thermoset composite looked at the possibility of replacing glass fibre with hemp matts. The composite would be used in pipes for transporting cooling sea water to petro-chemical plants. The glass/hemp composite provided lower costs and had less impact during production phase. Also, due to the added fibre, less glass fibre and resin was required. To further reduce impacts, organically grown hemp was used, reducing the effects from fertiliser and pesticide, leading to less eco-toxicity and eutrophication [28].

In another study, recycled PP & HDPE were combined with rice husks and recycled cotton. This study was compared to virgin PP and HDPE. The functional unit was 1 kg of material produced. The combinations tested were PP & cotton, PP & rice husks, and HDPE & cotton. The EOL only covered incineration and landfill. The impacts investigated covered 100 years GWP, NRPE, acidification, and eutrophication. Fertiliser use increased rice husk impacts (due to eutrophication), but still had a lower impact than conventional counterparts. Generally, the use of recycled plastics and bio-fibre had a lower impact than using virgin polymers. However, composites use more electricity, and thus there is a chance that more research can lead to even lower emissions/impacts. The impact allocation was based on economic value (as husks are a co-product), and future studies could include land use [29].

When natural fibre and glass fibre composites were compared to traditional metal structures, it was found that due to lower weight of the composites, the functional unit would need to be readjusted. As plant fibres have lower strength, but also a lower density than glass fibre, it would be preferred if weight reduction in a manufactured part is critical. Again for higher temperatures, one would mainly use thermosets as matrices rather than thermoplastics. Because of these points, the LCIA looked at energy demand, GHG emissions, and eco-points. The functional unit could not be "per 1 kg" as it would penalise lighter polymers, so strength, stiffness, and equal weight/geometry was used. The production of fibre reinforced polymers (FRP) has a high environmental impact due to energy intensity of producing carbon fibre. Compared to production, EOL has insignificant impacts. In aerospace, energy savings due to weight reduction dominates the industry. However, in the automotive industry the use phase energy savings are less obvious. Because of this, further studies would be required on a case by case basis. If the data can be obtained, bio-FRP can be a viable energy saving substitute (if physical requirements are met on a case by case basis), but further research is needed [30].

The studies on bio-fibre composites have reaffirmed that LCAs need to be conducted on a case by case basis to confirm whether or not integrating bio-based polymers has a lower impact than pure fossil fuel based polymers. However, it also shows that more research is required to lower the impacts of bio-based polymers. Another conclusion drawn is that it is not necessary to completely replace petroleum based polymers in order to reduce environmental impacts. By simply creating a hybridised composite there can be benefits, but it is not guaranteed.

2.2.3 **Sugar cane**

An area of production that often contributes to large environmental impacts is the cradle-to-gate stage. The problem arises when there are several techniques to obtain the polymer, or that the solutions used to obtain the monomer can be used for alternative applications. A great example of this is the use of sugarcane to produce ethanol, which can then be used in a variety of applications.

A life cycle assessment on polyethylene compared sugarcane against fossil fuel for the production of LDPE. The highest impacts were found to come from ethanol production, polymerisation, and long distance sea transport. This showed that sugarcane production consumes more energy; however the major share of it comes from renewable energy sources. The effects of eutrophication, acidification, and photo ozone formation were even for both sugarcane and fossil fuel-based LDPE. However, the GWP can double for sugarcane due to land use change (LUC), making it comparable with fossil fuel. This means that LUC had the biggest impact, but there needs to be a better assessment for LUC in future cases, as it has not yet been investigated extensively, and needs to be more consistent. Therefore, it showed that sugarcane based LDPE did not have less environmental impact, but can be improved significantly [31].

Another LCA performed on Brazilian sugar cane ethanol compared using ethanol as fuel to using it to produce PE and PVC. The functional units were 1 kg fuel vs 1 kg ethylene monomer. Both uses of sugar cane ethanol (fuel and polymerisation) had less environmental impact and GHG emissions than using fossil fuel. The results showed that using sugar cane ethanol instead of fossil fuel to make ethylene saved 32 MJ of NRPE, and 1.87 kg CO_2eq per 1 kg. Similarly, using sugar cane ethanol instead of fossil fuel as vehicle fuel saved 27.2 MJ of NRPE, and 1.82 kg CO_2eq per 1 kg (when the yield was less than 96%) [32].

This gives an insight to the possibilities and complications that can arise in the cradle-to-gate phase. Here we saw that not only can the ethanol be used for a variety of applications, but that each application has its own merits and flaws. The possibility might also arise that one application may be over or underused, leading to an issue with supply and demand. For instance, if too much material is assigned for polymerisation, but a sudden shortage of fuel arises, the priorities might need to change for the use of the sugar cane ethanol, as supply might not be able to keep up with demand, causing a short supply of valuable materials.

2.2.4 Cumulative Energy Demand

When performing a life cycle assessment, energy demand is an important factor to consider, as well as the differences between delivered energy and primary energy. The term 'Gross Energy Requirements' (GER) refers to the entire process chain, where energy requirements are considered from the moment raw materials are extracted from the environment, right up to where a product is made, or a service is delivered, such as electrical energy. However, GER has been misused in the past when only partial systems of various process chains have been investigated, and energy requirements were not properly traced back to primary material extraction. As a result, the term 'Cumulative Energy Demand' (CED) was introduced to clarify that the system has traced all materials back to raw materials from the earth.

Although these two definitions originally refer to the same system boundaries, GER always refers to the gross calorific values (GCV) whereas CED can refer to either gross calorific values or net calorific values (NCV), or alternatively, higher and lower heating values respectively. This complicates the use of CED somewhat as the difference between higher and lower heating values can sometimes differ by up to 50% for certain chemical products. For this reason, it is important to keep the assumptions made for CED constant when conducting an investigation, which can be difficult since all of CED data required may not be available from a single source. Another problem being that sometimes the CED data simply does not exist.

To aid the lack of data, a study was performed to provide data on several plastics like PE and PVC, as well as organic intermediates. It focused on finite energy sources (NRPE) and dismissed renewable sources as being negligible. It also focused on 'Cumulative CO_2' (CCO_2) originating from fossil-based fuels. The boundaries covered the extraction of resources, and ended after the useful materials were produced, essentially forming a cradle-to-gate study.

Whilst the data calculated for these polymers and intermediates aren't of great use for the Novatein® LCA, the methods of calculating the CED is important. The CED in the study refers to NCV, and was calculated using data from the same database, and values for energy use from the same topographic region. The CCO_2 was derived using common emission factors for materials like hard coal, natural gas, refinery gas, etc. In conclusion, by taking care to use the same values for emissions, feed stocks and energy use, the result allowed for an accurate database to be established, allowing for the comparison of various different fossil-based polymers regarding energy consumption and emissions [11].

This serves as a reminder that once the delivered energy of a system is obtained, it is part of the LCI, and to convert the data into an LCIA, the method of calculating the CED must be carefully selected, and the energy and emission factors applied to the delivered energy to gain the final NRPE and GWP values.

2.2.5 Novatein®

Novatein® is a thermoplastic protein which uses bloodmeal as a base to form a bio-polymer. The proteins in bloodmeal are used to create a thermoplastic by breaking disulphide bonds, disrupting hydrophobic bonds, and creating linear chains. This is achieved through the addition of SS and SDS and urea, as well as adding TEG and water as plasticisers to allow the polymer to be physically manipulated without becoming too brittle. Once all of the ingredients are mixed, the Novatein® powder consolidates when extruded, enabling it to be granulated and injection moulded [5].

Since the primary feedstock is bloodmeal, its acquirement is one of the most important subjects that needs to be covered when performing a life cycle analysis on Novatein®. Bloodmeal is a product that can also have alternative uses than just fertiliser. Since Novatein® is the subject of this study, and has previously been investigated from cradle-to-gate, it is vital to understand the methods used to obtain the results leading up to the gate-to-grave section.

The Novatein® resin LCA was broken into three parts. The first part covered obtaining blood, the drying process, and allocation methods for blood production. The two main impacts considered were NRPE use and GWP. The allocation scenarios that were investigated included a simple mass based impact allocation for a live animal, and a more advanced mass based allocation which excluded wastes and losses, with blood being allocated as a fraction of all animal products. The third method used was an economic allocation based on the price of bloodmeal as a fraction of the price of a carcass. Lastly, blood was considered as a waste product, with no impacts allocated to blood production, however blood drying to form bloodmeal was still included in the LCI and LCIA as there are other options available for the use of blood. A system expansion case was also investigated to consider the use of urea to replace bloodmeal as a fertiliser. However, as this case is the least justifiable, it will be ignored.

Bloodmeal production has four major GWP and NRPE use impacts; farming, transport of animals, meat processing, and blood drying. In the simple mass based allocation case, farming and meat processing require an enormous amount of

NRPE, however farming has by far the largest amount of GHG emissions associated with it due to the methane production by cattle. Due to these factors, not only does simple mass based allocation have a higher NRPE use than the other cases, but the GHG emissions are much higher than the rest (Figure 5 and Figure 6).

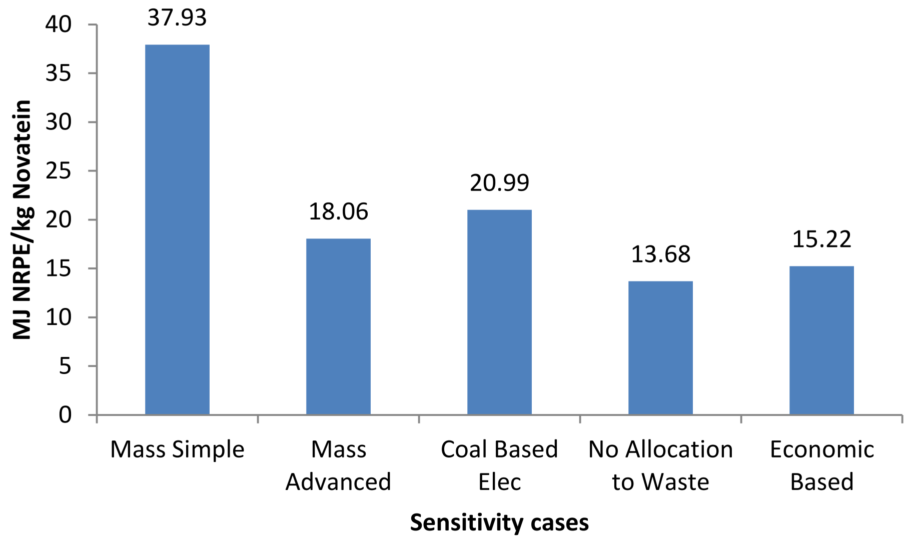

Figure 5 – NRPE used to produce bloodmeal per 1 kg of Novatein® (MJ)

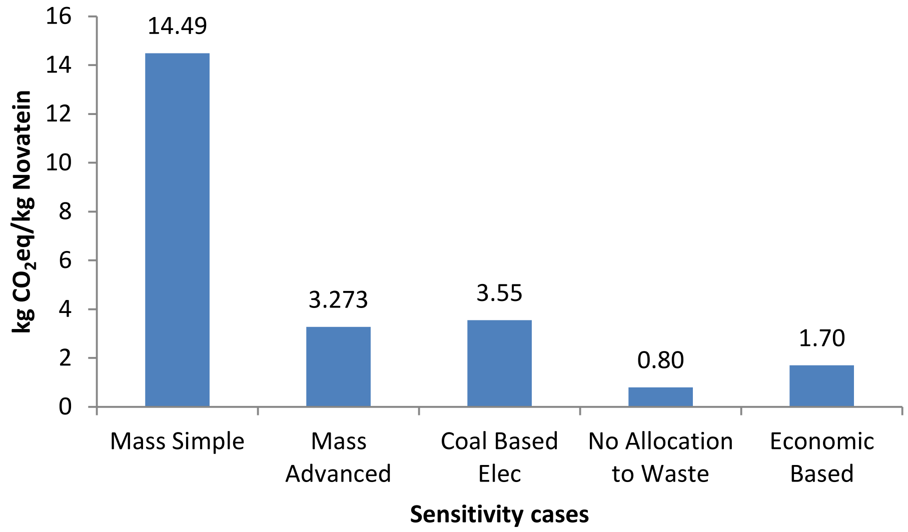

Figure 6 – GWP emissions to produce bloodmeal per 1 kg of Novatein® (kg CO_2eq)

For the advanced mass and economic allocation cases, the NRPE use is lower, with a substantial decrease in GHG emissions. Mass based allocation still has the largest NRPE use at 18.06 MJ/kg Novatein®, and also has the largest GHG emissions at 3.27 kg CO_2eq/kg Novatein®, compared to the economic allocation at 15.22 MJ/kg Novatein® and 1.70 kg CO_2eq/kg Novatein®. When bloodmeal was considered to be a low value by product, with no impacts being allocated to low value or waste products, the GHG gas emissions dropped to 0.80 kg CO_2eq/kg Novatein®, and NRPE use was only 13.68 MJ/kg Novatein®. These impacts were the lowest of any of the cases, due to fact that only blood drying and a small fraction of transport made up the impacts. This showed that allocation needs to be very carefully considered, along with justification, as large variances can occur [1].

Lastly, using advanced mass allocation as a base, the CED was calculated using only coal based electricity, instead of a grid mix of hydro and coal electricity. This increased the NRPE to 20.99 MJ/kg Novatein®, and recalculating the GWP resulted in 3.55 kg CO_2eq/kg Novatein® being emitted to atmosphere. The increases were due to the fact that coal based electricity required 2.77 MJ NRPE/MJ delivered energy, compared to just 2.36 MJ NRPE/MJ delivered energy for the grid mix. Additionally, only 42.2% of the NZ grid mix electricity counts as NRPE. To further increase the GWP, the NZ grid mix only produces 0.02797 kg CO_2eq/MJ CED, whereas coal based electricity produces 0.09788 kg CO_2eq/MJ CED. While the NRPE use and GWP values are only a slight increase in terms of the mass allocation case, they would have much more of an impact is they were applied to the case where there is no allocation to wastes and low value by products.

The second part of the eco profile study investigated the impacts of polymer production. This meant calculating the impacts from the additives used, as well as the energy consumption and GHG emissions from processing. The additives had a total NRPE consumption of 8.89 MJ/kg Novatein ® resin, with GWP adding a further 0.4 kg CO_2eq/kg Novatein® to all the cases studied. The processing steps had a NRPE use of 1.16 MJ/kg Novatein ®, and a GWP value of 0.084 CO_2eq/kg Novatein® for all the cases expect for coal based electricity generation. Its processing operations required 3.06 MJ/kg Novatein ® and a GWP value of 0.31 CO_2eq/kg Novatein® (Figure 7 and Figure 8). Again this was due to the way that impacts are calculated for coal based electricity.

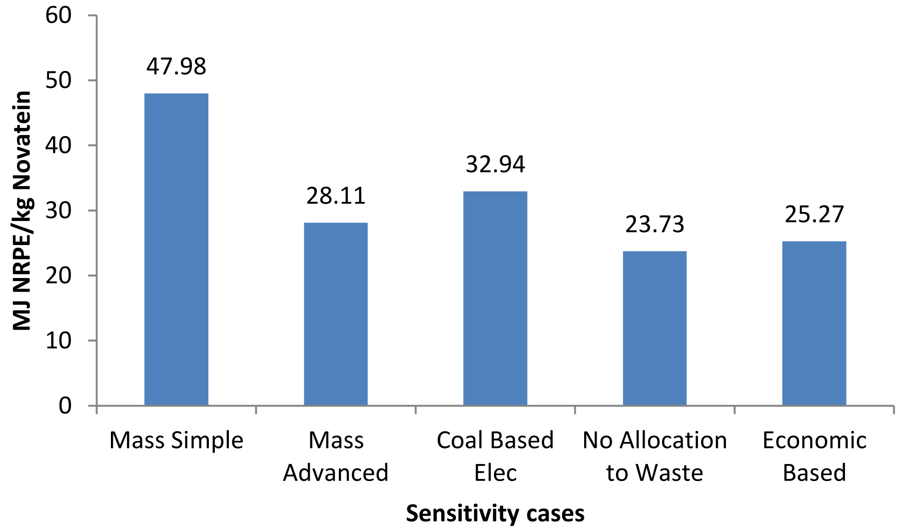

Figure 7 – NRPE used to produce 1 kg of Novatein® resin (MJ)

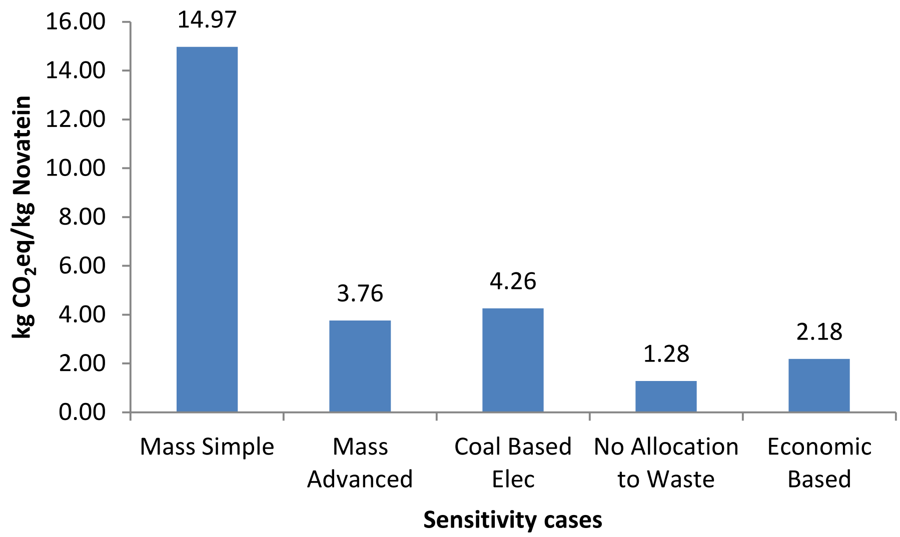

Figure 8 – GWP emissions to produce 1 kg of Novatein® resin (kg CO_2eq)

It was concluded that blood production had much higher impacts than Novatein® production when the basic mass based allocation was considered. However, for all the other cases, blood drying had the largest impact. Because of the large impact of blood production and drying, impacts that were significant during production became insignificant in the overall cradle-to-gate. The final conclusion drawn was that Novatein® production is justified if viewed from a point of turning waste into a product [33].

The final part of the Novatein® cradle-to-gate study looked at the applications and issues of performing life cycle assessments on bio-based polymers, and explained difficulties with comparing bio-polymer LCAs. These difficulties include allocation, energy assumptions, and differences in cradle-to-gate and cradle-to-grave assessments. Using a renewable feedstock cannot always guarantee a lower impact than using fossil fuel based polymers, and energy sources (NRPE) also have a big impact and should be kept constant for different materials. It mentions that allocation decisions can make large changes in outcomes, and also that a cradle-to-gate assessment does not provide a full picture, and is just a preliminary insight [34].

2.2.6 Novatein Commercial Feasibility

The Novatein® ecoprofile study was based on an economic feasibility study of setting up a resin production facility next to a rendering plant in the Taranaki region. In the report, the costs of buying land, setting up a plant, purchasing & installing the equipment, hiring staff, and the production process were included. The production plant was based on a 10 year life span, would consume 10% of New Zealand's bloodmeal supply to create 3600 tonnes of resin annually, with a discount factor of 15%, and an estimated accuracy for capital costs of ±20%.

The capital costs for all the equipment were calculated by first receiving a quote for the purchase of the machines, then applying Lang factors to the purchase costs [35]. Land purchase and building costs were also included based on an average building cost per square metre of floor space, fencing, road works, etc. The machines were also valued for a sales price at the end of 10 years, and the end of life costs were added to the NPV. Operating costs primarily included the raw material, utilities, labour salaries, maintenance, distribution, and administrative expenses.

The cost to produce 1 kg of Novatein® resin isn't mentioned explicitly; however the sales price for breaking even in a 2 year period was calculated at $2.03. The recommended sales price for the resin was estimated to fall between $2.90 and $3.80, based on commodity plastic prices (ranging from $1.17-13.20 per kg). At the specified sales prices, the venture was estimated to achieve a NPV of $30 million after the plant was shut down at the end of 10 years, provided that all the resin was sold at $3.80/kg [35].

The sales price is the most important part of the study, as any economic study involving Novatein® resin will need to use the sales prices of Novatein®, not the cost to manufacture, even when Aduro Biopolymers wants to use its own resin for parts production.

3 The Port Jackson

The meat industry in New Zealand slaughters and processes a combined total of 25 million beef and sheep carcasses a year [36]. Whether exported or sold nationally, this equates to a very large amount of income on a national scale. However, the slaughter process has a lot of health and safety requirements that need to be met [37], while the slaughter and dressing of carcasses are carried out at a very fast pace.

The process begins with the animal arriving at the abattoir and being held in a pen, usually for one day. Once the process starts, the animals enter the abattoir single file, where each animal is stunned. Stunning can be done in a variety of ways, ranging from electric shock, to the use of a bolt gun, which pneumatically drives a pen into the animal's head, rendering it instantly brain dead. The animal is then hoisted up by its hind legs to hang upside down, and moved along the line for bleeding. Bleeding is the act of severing the carotid artery and jugular vein with a knife, to allow the blood to drain from the carcass. This process may differ, as there are several rules to follow when slaughtering an animal to comply with Halal standards. The general idea is than an animal must be alive when bleeding is started, therefore stunning is allowed, as long as the animal is not killed via stunning. After the bleeding is started, the animal can then be hoisted up by its hind legs to be bled dry [38].

When the carcass has been thoroughly bled, the head and feet are removed, and the animal moves down the line to be gutted and skinned. At this point the carcass and organs are inspected for signs of contamination or disease. When all the safety inspections are passed, the carcass may be decontaminated further, chilled, and sent for primal cuts, usually halved or quartered, before being distributed.

The waste products (not including faecal matter) are sent to the rendering plant. The rendering process heats the waste to separate the fats or tallows from water and protein residues to produce edible lards and dried protein residues. This is where bloodmeal, meat & bone, and animal fat are produced. The rendering process can be done in several ways, and with high or low temperatures [39].

When the head and intestines of the animal is removed, there is a chance that some of the faecal matter or paunch grass may spill out of the oesophagus or anus.

This waste matter often comes in contact with the edible meat on the carcass, thus causing contamination that does not adhere to the health and safety regulations [40].

As faecal waste contamination cannot simply be washed off the carcass, the contaminated areas of meat needs to be cut off and disposed of properly. When the meat is trimmed, it means that some of the most valuable parts of the carcass are going to waste. Prior to plugs being used, the preferred technique of reducing faecal contamination was to tie the rectum shut, additionally adding a plastic bag over the top to catch any leakage. When this system was introduced in Norway in 1994 for the slaughter of pigs, the occurrence of Yersiniosis in the population decreased by 25% in the following year [40]. The United States Centres for Disease Control and Prevention (CDC) describes Yersiniosis as an infectious disease caused by a bacterium, that can lead to right-sided abdominal pain and fever, which may be confused with appendicitis in older children and adults [41]. This, and other enterobacteriaceae (pathogenic bacteria including Salmonella and E. coli), can be reduced significantly via the use of rectal tying or stopping.

This is where the rectal plug plays a vital part. By inserting the plug into the anus of a carcass, faecal matter cannot escape. It is a more effective method than tying the rectum, and the plug can be put in place before the anus is excised. There are several types of plugs on the market, but all of the current plugs rely on a simple bung being inserted into the rectum using a push rod (Figure 9 and Figure 10). This idea has been suggested for use since 1989. The original idea was to insert a frozen stainless steel plug that would expand and seal the rectum before excision [42]. However these days the plugs are made from polypropylene, designed to be inserted with force, and to fit snugly. A study into the effectiveness of this process showed that the percentage of carcasses where Enterobacteriaceae was not detected (measured around the anuses of carcasses) increased from 2.9% for unplugged carcasses, to 23.5% [43]

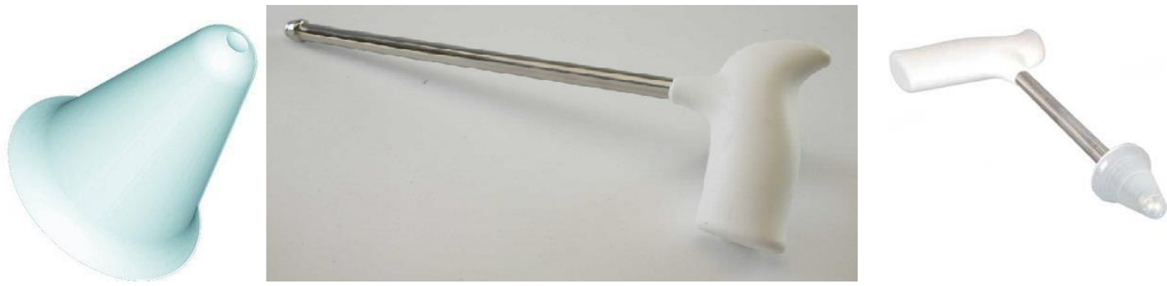

Figure 9 – lamb rectal plug and rodder [44]

Figure 10 – Beef rectal plug [44]

In 2006, Colin Plant form Bestaxx Innovation designed a new plug to reduce waste contamination during the sheep slaughtering process. The plug was completed and tested in 2010 with the help of Andrew Simpson and Fletcher International Exports (Figure 11). It has gone through 14 different phases of development, is currently being used in 6 Australian abattoirs, and is being trialled in New Zealand. The designs used by Bestaxx helped to eliminate two problems with the current plugs, which is applied with a pneumatic gun, pushing the plug into the animal’s rectum, and fires the barbs into the surrounding tissue to close the lid over the top, thus sealing the anus (Figure 11).

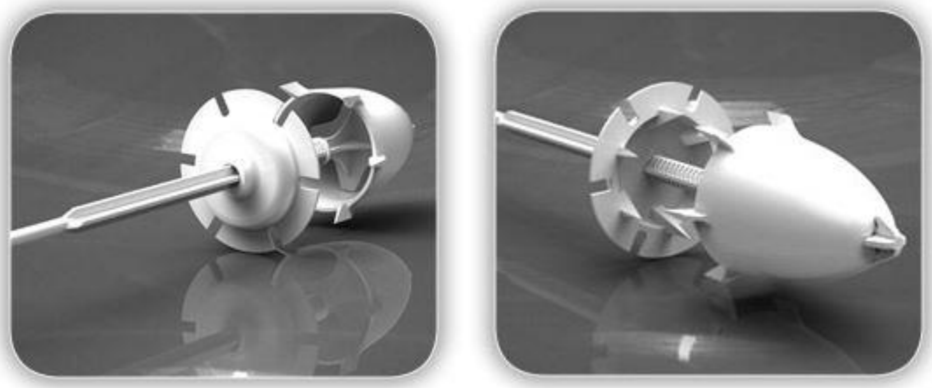

Figure 11 – Bestaxx Innovation's 14th Rectal plug [45]

The newest plug is the 15th phase of the Bestaxx Innovation plug design (Figure 12). The new plug has an easier to use design, and has reverted back to the push rod paradigm. It has a helical screw design for easy insertion and a tight seal, and the selection of Novatein® as the production material will allow for rendering without contaminating the product stream. The life cycle assessment of this study will be carried out on the new design, now named the "Port Jackson". The plug will be used primarily on smaller stock, like sheep, pigs, goats, and bobby calves.

The most important factor included in the plugs' design is processability. Abattoirs process hundreds of carcasses every hour, and time would be wasted if the plugs were removed before rendering. Because of the time constraints, the plugs are actually entered into the rendering process along with the entrails, which causes contamination. The latest Bestaxx plug aims to be processed with the rest of the waste without causing contamination, making the rendered material safe for animal consumption should ingestion occur, and won't interfere with the rendering process. This is a very important factor in the new plug's design, as reducing the contamination of the rendered products will increase their value and applicability. Material selection is crucial, with current materials of choice including wheat based plastics and cellulosics [46]. Blood-meal based polymers are the latest in the line of biodegradable polymers being researched for the plug, which is where this study comes in.

In the financial year spanning 2011-2012, 23.1 million sheep carcasses were slaughtered for sale and export in New Zealand alone [36]. This means that if the rectal plug is made mandatory in every NZ abattoir, over 23 million units can be sold annually when considering sheep alone. At the moment, basic plugs can be bought at various companies in NZ including Argus, and Adept and range in price from \$0.04 to \$0.15 (Figure 9). The current Bestaxx Innovation plug weighs 5.6 g, is made of polypropylene, and has a market value of \$0.15 AUD, or \$0.16 NZD.

Figure 12 – Latest Bestaxx Innovation plug made from Novatein®, the Port Jackson

4 Methodology

4.1 Process Description

This study investigates the life cycle of an ovine rectal plug formed from Novatein® resin. A previous study of Novatein® resin production [1, 33] will function as the cradle-to-gate section of the study, whilst the gate-to-grave section will be modelled using GaBi6 Education. A block flow diagram for the life cycle of a plug is shown in Figure 13. This block flow diagram shows the four main boundaries of the plug's life, but should not be confused with the boundaries used for the LCA (Figure 14), which breaks the unit operations into important sections for the benefit of analysis. It should also be noted that the LCA will be performed on a hypothetical production scheme, and several assumptions will need to be made.

4.1.1 Bloodmeal Production

Bovine blood (plus other additives) is required to produce Novatein®. Blood is a by-product produced during farming by rearing either milk or beef cattle. Once cows are sent to the slaughter house, they are killed and the animals' blood is drained. The blood is collected and dried to form bloodmeal, by which point it is ready to be turned into Novatein®. The inputs into this boundary are blood, and energy from electricity and natural gas (NG), and the outputs are bloodmeal, and CO_2eq emissions to atmosphere.

4.1.2 Novatein® Production

Bloodmeal, along with sodium dodecyl sulphate, sodium sulphite, triethylene glycol, urea, and water are blended and extruded, to form Novatein®. Once granulated, the plastic is ready to be used. Once the granulated pellets are produced, they are packaged and ready to be transported to their next destination. Along with the ingredients and polyethylene (PE) bags used for packaging, the only other inputs into Novatein® production is the electricity required to heat, blend and extrude Novatein®. The outputs from resin production include packaged resin, and CO_2eq emissions to atmosphere.

4.1.3 Plug Production

Resin is transported to an injection moulding factory where the plugs can be produced. The plugs (when formed) must be conditioned for seven days at 23°C and 50% relative humidity, because Novatein® is hydrophilic, and reduced moisture content is required for the plugs to acquire the necessary physical properties. If the moisture content in any plug is excessive, it will become soft and unable to hold its form, thus being ineffective at sealing the ovine's rectum after slaughter. Once conditioned, the plugs will be packaged in an air tight PE bags, and placed in cardboard boxes to avoid moisture being absorbed from the humid environment, and shipped to the meat processing facility. The inputs into this boundary include resin, fuel for transport, cardboard boxes, PE bags, and electricity. The outputs include packaged Port Jackson plugs, PE bags, and CO_2eq emissions to atmosphere.

4.1.4 **Use and End-of-Life**

Novatein® plugs will be inserted individually into the rectum of a sheep after it has been slaughtered (one plug per sheep). The plug is effectively only in use until the carcass is dressed and the intestines and organs are removed; after this point, the plug will pass through the rendering process along with the intestines. During the rendering process, the plug will break down and be separated out, becoming part of the meat and bone meal stream. This is the end of life (EOL) phase, and it is also the final boundary of this LCA. The inputs are packaged Port Jackson plugs, electricity, and natural gas, while outputs include PE bags, cardboard, meat and bone meal, and CO_2eq emissions to atmosphere.

Figure 14 shows the full process flow diagram, and includes mass and energy flows. The cradle-to-gate incorporates the blood collection, drying, and the Novatein® production in a black box configuration, since the mass and energy balances have been completed in a previous study. The packaging, transport, injection moulding, conditioning, and rendering operations all have their relevant mass and energy balances presented here. It is important to note that the boundaries used for the life cycle assessment are represented here, and differ slightly from the production boundaries. The life cycle boundaries are Cradle-to-gate (bloodmeal & resin production), packaging, transport, plug production, and use & end-of-life, and are separated in this fashion for a more organised assessment.

To analyse the product's life cycle, the functional unit must be specified. The function of the plug is to prevent excrement escaping from the intestines of a slaughtered animal. Therefore, the plug's function can be defined as: "preventing faecal matter from escaping a single carcass after slaughter”, and the functional unit will be the use of a single plug for this purpose. However, to prevent large errors accumulating, the overall mass balance of the system will not be performed on a single plug. The mass balance will instead be performed on the hypothetical target market for NZ. Doing so will reduce the error from capital emissions (such as the base weight of transport trucks). The results will then be scaled to represent the inventory and impact of a single plug.

The target market for Novatein® plugs is set for sheep that are slaughtered within New Zealand, where 23.1 million sheep are slaughtered annually [36]. The target chosen is 10% of the NZ market, or 2.31 million plugs per annum (one plug per sheep). Assuming 300 working days (6 days a week, 50 weeks a year), 7,700 plugs are required to be produced per day. Plug production will be over four week periods, with 184,800 plugs produced during each four week block. These assumptions will be the basis on which the modelling will be conducted.

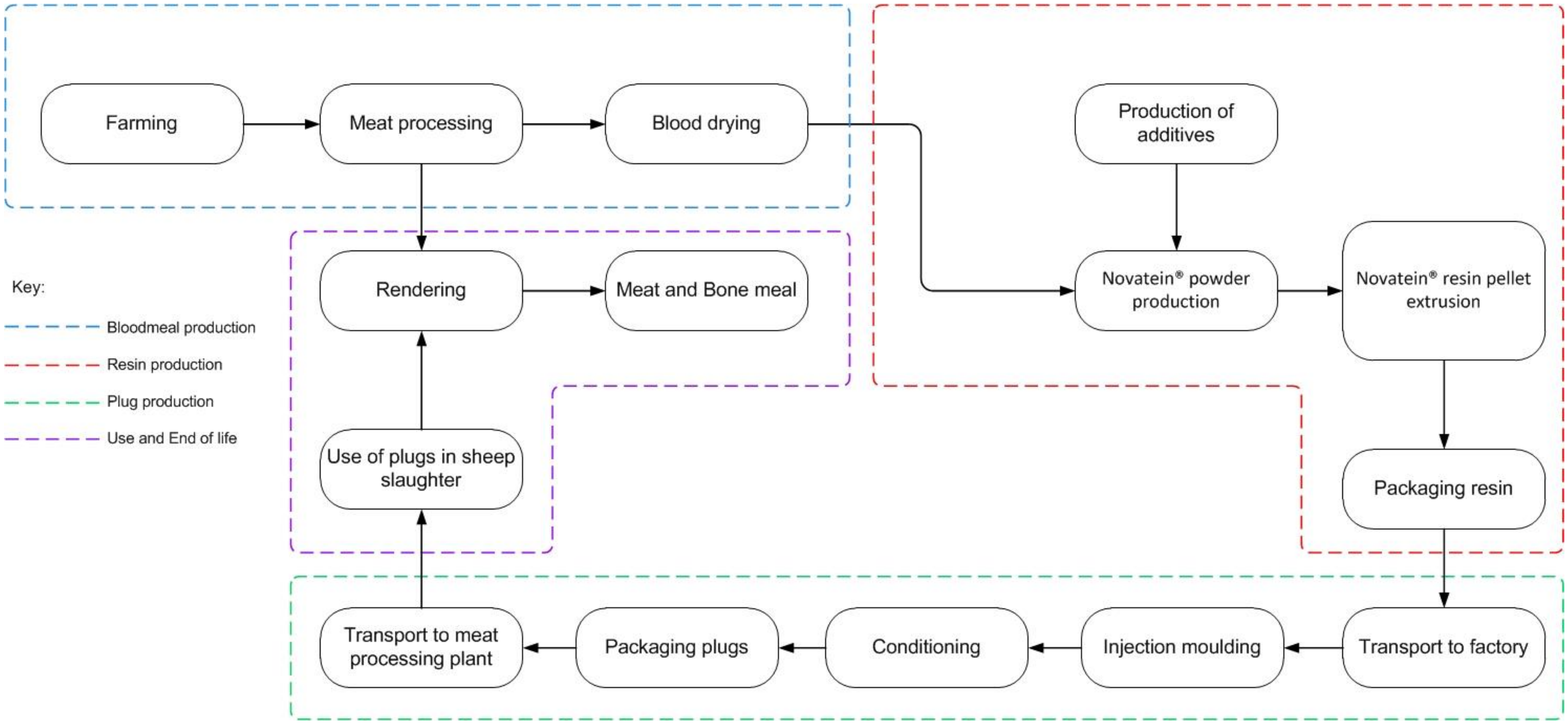

Figure 13 – Block flow diagram of plug Life cycle (with boundaries)

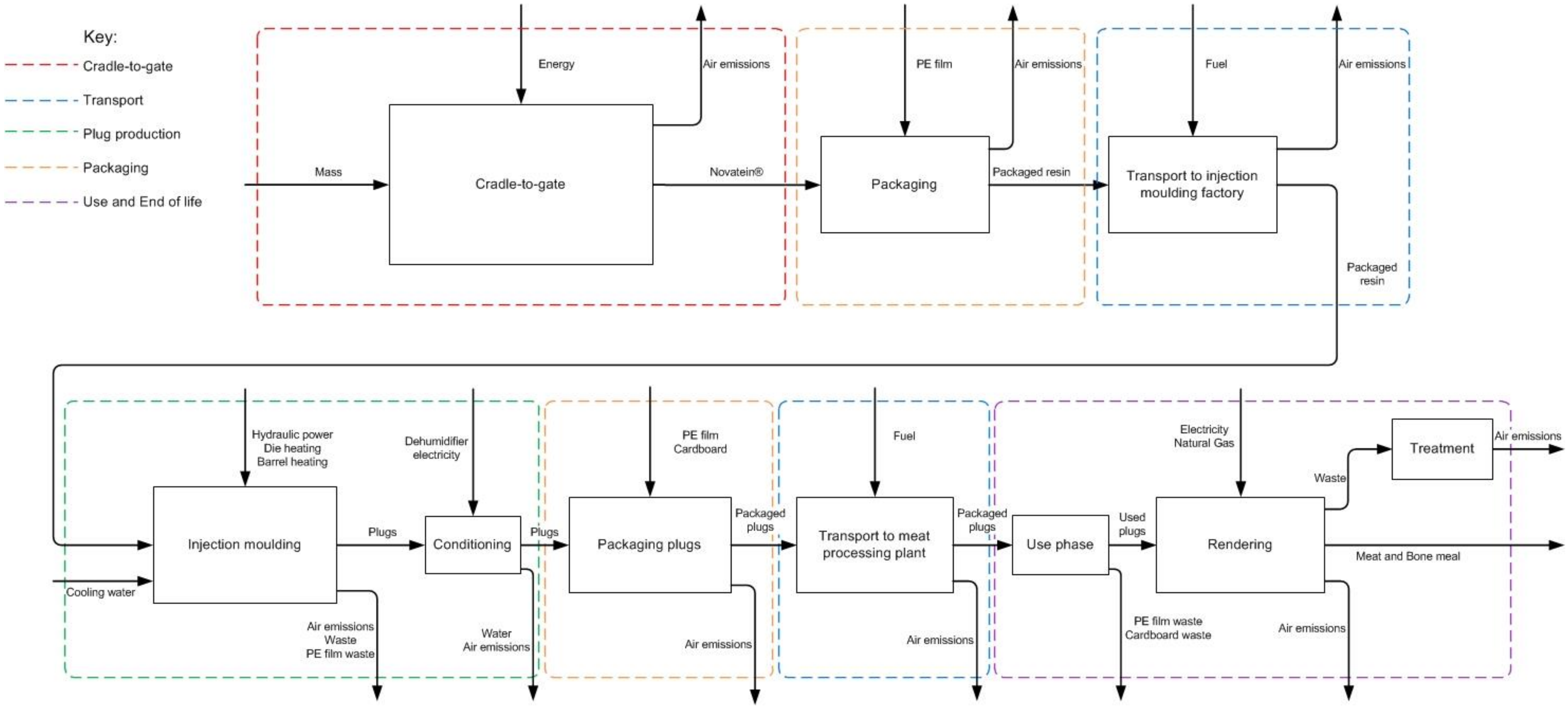

Figure 14 – Process flow diagram of a plug life cycle assessment, with life cycle boundaries

4.2 Goal of the study

This study is a life cycle assessment of a rectal plug designed by Bestaxx Innovation. The plug will be produced from Novatein® resin, and the LCA's results will be compared to current polypropylene design. This report is concerned with internal product evaluation, and will not be presented for public inspection.

4.3 Scope

This study will be both objective and comparative; NRPE and GWP will be determined for the Port Jackson, manufactured form Novatein®. These results will then be compared to the previous design that uses polypropylene for its production. The initial case will be based on the assumption that low value by products have no allocation of impacts, and thus blood has no impacts allocated to it until it is collected for drying. The system boundary starts when the raw materials are produced and ends immediately after the rendering process. The boundaries on the farming side starts after the cow has been slaughtered. However, different allocation methods for farming impacts will be investigated as part of the sensitivity analysis. The functional unit for this study will be one plug produced, as the function of the process is to seal one sheep rectum, before the plug is disposed of. For the initial case, only mass based allocation is used.

4.4 LCI Assumptions and Justifications

The scope of this study is defined via the system boundaries, and thus these boundaries will be explained, along with any assumptions and justifications that apply. There are five main sections to the study, including: cradle-to-gate, packaging, transport, production, and the combination of use and EOL.

4.4.1 Cradle-to-gate

For the cradle-to-gate section, the three main assumptions required are mass of Novatein® required per plug, NRPE requirement per kg of Novatein®, and also the GWP per kg of Novatein®. The quantity of resin needed to produce 2.31 million plugs per annum is required, but it is not the sum of the mass of plugs produced.

To calculate the amount Novatein® required for plug production firstly requires the mass of each plug. As tested, Novatein® plugs weigh an average of 9.36g each, however, this is not the final weight of the plug. Novatein® plugs require conditioning to remove water content, thus the mass must be calculated after conditioning, at the point which it is ready for use. The large amount of water loss from the Novatein® between being powdered mix, and being a final, conditioned product must be determined. Novatein® powder contains 28% moisture content on a per-gram basis, with extrusion lowering the moisture to 27.5 weight-%, and injection moulding bringing the moisture content down to 23.5 weight-%. Finally, conditioning further decreases total moisture content to 8.4 weight-% (Figure 15) [47].

A simple mass balance calculation determined that the mass of resin required to produce each plug is 9.87 g, and that after conditioning, each plug weighs 7.81g. After adding 2% to compensate for waste, the total mass of resin required is 10.1 g. In total, 77.55 kg of resin is required per day to produce the daily requirement of 7,700 plugs. This includes 2% waste, as it is assumed that the runners and sprues will be reground for reuse.

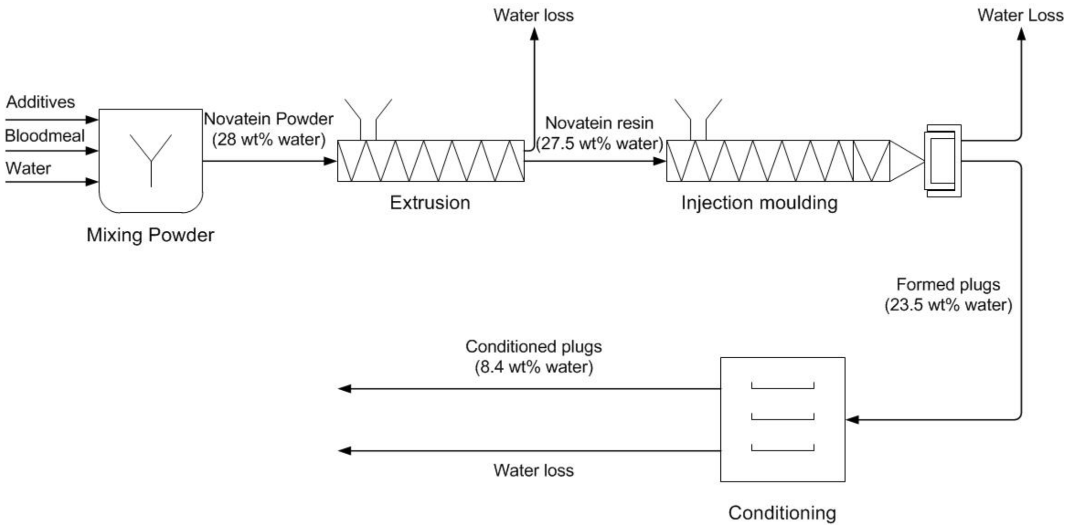

Figure 15 – Water loss during production

The energy use and emissions per kg of Novatein® produced have previously been calculated [1, 33]. However, since there were several sensitivity cases in the cradle-to-gate study, the base case for the initial assessment needs to be selected. This study will be based on the assumption that no impacts from farming are allocated to blood, as it is a waste product. Due to this, blood is only considered to have an impact once it has been collected, and has entered the drying process. Based on this assumption, the NRPE use is assumed to be 23.73 MJ/kg Novatein®, and GWP is 1.28k kg CO_2eq/kg Novatein®.

4.4.2 Packaging

The hydrophilic nature of Novatein® makes packaging an important component of the life cycle. Novatein®'s mechanical properties will change if the moisute content increases, and requires prompt packaging after the resin is produced, or once the plugs leaving the conditioning chamber. An adequately water-proof barrier is required for the packaging, and will be provided by 0.1 mm thick polyethylene bags.

Resin pellets can be packaged in 25 kg bags. Loose Novatein® granules has a density of about 480 kg/m^3, requiring 75 bags every four weeks. If each bag is 0.500 m x 0.350 m x 0.300 m, and the density of polyethylene is 940 kg/m^3, each bag will weigh 0.0806 kg. The total weight of PE film required every four weeks will be 6.04 kg, bringing the total weight of the resin shipment to 1867 kg.

Plugs will be sealed in PE bags, and the PE bags will be packaged in cardboard boxes. The total four-weekly load of conditioned plugs will be 184,800 plugs, with a weight of 1444 kg. Using boxes that measure 0.600 m x 0.280 m x 0.180 m with a 3 mm wall thickness, the box volume will be 0.0302m^3. Assuming each plug occupies a rectangular space of 0.055 m x 0.035 m x 0.035 m, 450 plugs can fit in each box, and the total number of boxes required over four weeks is 411. Each box weighs 0.476 kg, bringing the total four week load of cardboard boxes required to 196 kg. Assuming PE bags with the same dimensions as the boxes are used, 25.2 kg of PE film will be required.

The total packaged mass for plugs is 1665 kg, including plugs, boxes, and PE film. LCA results for cardboard packaging indicated that 21.29 MJ of non-renewable primary energy (NRPE) is used to produce 1kg of cardboard, and 1.01 kg CO_2eq is produced [48]. These numbers will be used to calculate the environmental impact of packaging.

4.4.3 Transport

The hypothetical locations of the resin and plug production plants have been established. The production of Novatein® requires Aduro Biopolymers purchasing bloodmeal from Wallace Corporation Ltd. The installation of production facilities in proximity to their rendering plant would be logical as this minimises the transportation of bloodmeal whilst obtaining relatively cheap real estate.

Two scenarios were considered in the production of plugs: first, the production of the plugs can be contracted out; second, the plugs could be produced in-house (by Aduro Biopolymers), next to the Novatein® production facilities. These plugs will be stored at on site at the resin plant, ready to be shipped to their final destinations. Production locations were proposed to minimise transport, and to minimise the cost of purchasing land for production facilities (where appropriate). When contracting out, the transport required involves moving the resin from Waitoa to Hamilton to be turned into plugs, followed by the transportation of the plugs from Hamilton back to Waitoa for storage. If the plugs were manufactured in-house, the plug manufacturing facility would be next to both the Novatein® production plant and the Wallace Corporation Ltd. rendering facility, so the transport of both the resin and the plugs would be eliminated.

Two factors are considered when analysing the transportation of the resin and plugs. Firstly, the economic aspect of transport; and secondly, the emissions and energy use of the truck will have some global warming potential. When contracting out production of the plugs, the average distance required to be travelled (each way) is 48 km. This involves driving from Avalon Dr, where the industrial section of Hamilton is, to Wallace Corp.'s rendering plant at 266 D Wood road near Waitoa (Figure 16).

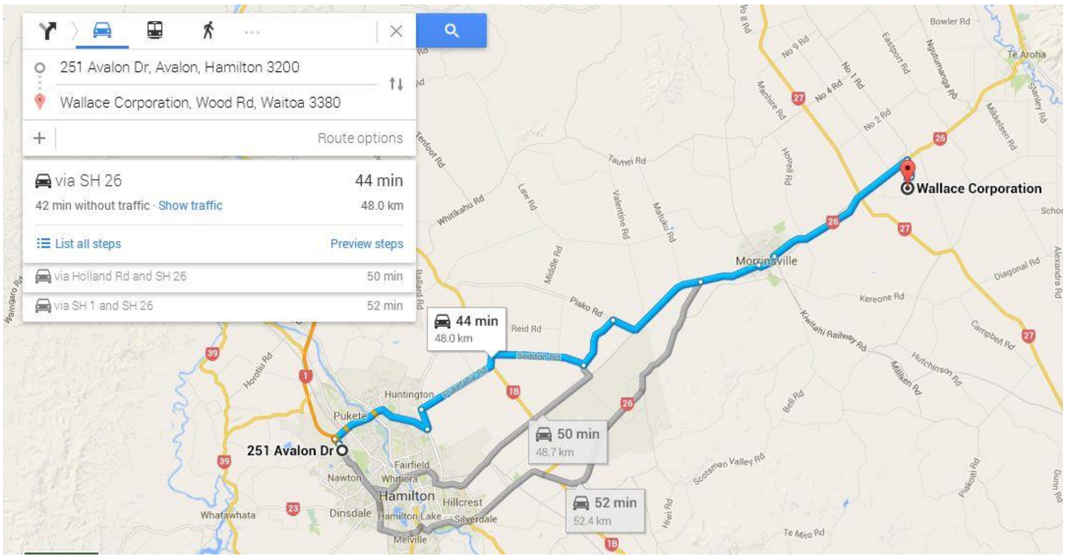

Figure 16 – Suggested transport route to and from Hamilton's industrial centre

Transport was modelled on Gabi6, utilising the formulas for a 7.5 ton truck with a 3.3 ton maximum payload. The fuel consumption of a truck is based on three primary factors: the weight of the cargo, the predicted utilisation of the truck capacity, and the distance travelled. The weight of the cargo and distance travelled are easy to measure, but the utilisation factor requires greater exposition. If a truck is loaded to full capacity and does a return trip with a full cargo hold, the utilisation factor would be 1.0 as the truck is being 100% effective. However, if a truck is fully loaded on an outgoing trip but returns empty, the utilisation factor is 0.5.

By default, all trucks are assumed to be commercial freight operators carrying goods for multiple companies, which yields a high (0.85) default factor. Once the truck is carrying goods for one company only, the utilisation is likely to drop as it may spend some part of the journey with an empty or partially full cargo hold.

A further influence is the amount of cargo in a truck, from a specified system. If the truck is carrying a full load of 3.3 tons, but only 1.8 tons of cargo goods are from the relevant system, the truck will be operating at full efficiency with fuel consumption allocated to the fraction of cargo from the relevant system. However, if a truck with a 3.3 ton capacity carries only 1.8 tons of cargo, the efficiency decreases and fuel consumption increases.

Suppose that a 7.5 ton truck (gross vehicle weight) travels 48 km with a payload of 1.8 tons, and achieves a high utilisation (0.85-1.0) during both the outgoing and return journey. If so, the diesel consumption can increase if: (i) increasing the distance; (ii) decreasing the total payload (causing a lower fuel efficiency); and (iii) decreasing the utilisation[1].

A truck carrying resin from the rendering plant to the injection moulding factory and returning empty yields a utilisation factor of 0.5; the same will apply for picking up plugs, as the truck will be empty for the first half of the trip. It is possible (and desirable) for a truck to carry resin from Waitoa to the factory in Hamilton, and (in a single trip) carry plugs back to Waitoa. The organisation of transport in such a way would increase the utilisation factor and minimise the costs and environmental impact of trucking resin and plugs between facilities. For modelling purposes, since there is limited data it is safest to leave utilisation at a default setting of 0.85, and the payload at 3.3 tons, assuming that the transportation would be organised to maximise efficiency.

[1] This leads to a greater number of trips to move the same mass. 50% utilisation would essentially be a full outward journey and an empty return journey.

4.4.4 **Production**

Production consists of forming and conditioning the plugs, at which point they will be ready for use. The energy requirements for the injection moulder will be modelled in GaBi using an injection moulding process, which employs its own methodology when calculating the energy required. For the calculations to be accurate, the shot sizes need to be between 0.2 kg and 2 kg.

Currently, the cycle times for injection moulding range between 30 and 60 seconds. These cycle times are pre-specified when producing 12-13 gram samples (not including sprue and runner) one at a time in a 35 tonne injection moulder. When producing the plugs commercially, the shot sizes will be much larger than 12g; however, the large surface area of the plugs will allow for faster heat dissipation, allowing cycle times to remain within the boundary of 30-60 seconds. The cavities for the die can also range between 4 and 16 cavities.

From Table 3, a four cavity mould can only meet the daily quota if the cycle times is 40 seconds or below and the IM is operated 24 hours a day. This excludes start up, shut down, and maintenance. Once the cycle times increase to 60 seconds, two machines will be required. Increasing the cavity size to eight will meet the daily quota, even at the maximum cycle time of 60 seconds. Ideally, a 16 cavity die with a 40 second cycle time will be used, fitting the daily production into a 5 hour 20 min slot and still providing enough time for start up and shut down within a normal 8 hour 30 min shift. Using 16 cavities will also reduce the amount of waste per shot.

Table 3 – Hours required to meet daily quota

	Cycle times (s)		
Number of cavities	30	40	60
4	16.0	21.4	32.1
8	8.0	10.7	16.0
16	4.0	5.3	8.0

The component weight for the injection moulder will be (16 x 0.00936 kg) x 2. This accounts for 16 plugs per shot, and the material required is doubled to account for runners and the sprue. The runners will be reground and reused, with only 2% of Novatein® going to waste. The total shot size will be 0.3 kg, which is ideal for applying the formulas used by GaBi to calculate energy use.

The plugs need to be conditioned at a standard of 23°C, at 50% relative humidity (RH). A standard air conditioner/dehumidifier produces air at 23°C and 30% RH. Over the four week period, 285 kg of water must be removed at a rate of 0.424 kg/hr. The size of the conditioning chamber is 9.32 m^3, a volume three times the volume of boxes required per week. Making the chamber three times larger than the volume of boxes ensures adequate circulation to keep the air in the chamber homogenous. The electrical energy use and emissions will also be modelled in GaBi.

4.4.5 Use Phase and EOL

The use-phase of the plug life cycle is important, as it is here that the plug is inserted into the rectum of a sheep, and serves its purpose from the moment of insertion, until the intestines are removed. The cardboard and PE film becomes waste once all plugs are removed from the packaging. The operator is expected to have no environmental impact, and since the plugs are inserted with a manual rodder, no electricity is required.

When analysing the EOL, several inputs require consideration including the use of electricity and gas. During the cradle-to-gate study, the energy use quoted by the Taranaki By-Products (TBP) rendering plant was given as 2 GJ gas and 90 kWh electricity from the national grid per ton of raw material entering the plant [1, 33]. Since the underlying assumption is that this energy use is directly proportional to bloodmeal production as well as the treatment of all raw material, it can only be assumed that the rest of the rendering process will consume the same amount of energy per kg of raw material processed. It is also assumed that this will be the average energy consumption of rendering the pugs at any plant in New Zealand.

The rendering plant utilizes 2 MJ of gas and 0.09 kWh per kg Novatein® rendered. Converting kWh to MJ, 0.09 kWh equates to 0.324 MJ. Taking into account that this is delivered energy, and using the data from the cradle-to-gate study, the NRPE for the use of natural gas is 2.26 MJ/kg, with the primary energy requirement for the delivered electricity being 0.765 MJ/kg. The electricity is separated into renewable and non-renewable, with consumption at 0.441 and 0.323 MJ/kg respectively.

Additional emissions originate from the material streams in the rendering process, and can be split into air, water, and product streams. The water and air emissions can contain components that are odourus and toxic, but possess low CO_2eq values. On average, 780 tonnes CO_2eq is emitted per year per 100,000 tonnes of raw material rendered in the United States, providing a value of 0.0078kg CO_2eq per kg raw material [49]. These numbers were derived by measuring CH_4 emissions, and multiplying the value by 23 to obtain CO_2eq values on a 100 year basis. It can be assumed that this is similar to emissions in NZ. These mass values are extremely small and can be effectively removed from the air stream via biofilters, reducing the amount of volatiles by 50-80% [50]. However, for the purpose of this study, the full amount of CO_2eq will be used as it is already two orders of magnitude less than that of electricity supply.

In the water stream, there are two other primary emission measurements: BOD and TKN. These two emission measurements equate to 0.0009 kg TKN/kg raw material, and 0.005 kg CBOD/kg raw material rendered. Biological oxygen demand (BOD) is the amount of oxygen required by aerobic biological organisms to break down organic material. BOD is a measurement taken from a body of water to measure water pollution, and although it can lead to small amounts of CO_2eq emissions, it generally contributes to eutrophication.

Total Kjeldahl Nitrogen (TKN) is a method used to measure nitrogen compounds released to atmosphere. As these nitrogen compounds can vary (usually being ammonia or ammonium), it is easier to quantify the emissions as a TKN value. However, it must be noted that TKN normally refers to ground or water leaching, and contributes to eutrophication rather than global warming. The contribution of both TKN and BOD to eutrophication rather than global warming means they are not considered further in this study. If the scope of this study were to be revisited in the future and included eutrophication, the inclusion of both TKN and BOD within the analysis would be essential.

Although there are impacts from this life cycle including acidification, eco-toxicity, and photochemical ozone depletion, etc., they are outside the scope of this study, which will only focus on GWP over 100 years and energy consumption. Since there is very little data for the environmental impacts regarding Novatein® production and EOL, gathering data for NRPE use and GWP is often seen as the two most important impacts to consider first, from the studies investigated, and it is often easier to obtain accurate data for these two impact categories. This is similar to the cradle-to-gate analysis conducted for the production of Novatein® resin [1, 33], and a separate study will be required to perform extensive research into each of the remaining impact categories.

4.4.6 General Assumptions

Energy supply is a factor that is critical throughout the life cycle analysis, and as such, it is important to state and maintain the underlying assumptions made for electricity supplied by the national grid throughout this LCA. The electrical inputs are all assumed to be from the New Zealand national grid mix in the same electricity generation mix that was identified and used in the cradle-to-gate study. This electricity generation mix consists of 57.8% hydro-electricity and 42.2% coal burned.

From the rendering plant data, CO_2eq emissions for electricity equates to 0.214 kgCO_2/kg blood dried. Using this information, the NZ grid mix produces 0.02797 kgCO_2eq/MJ total primary energy (on average). Whilst this is the value of primary energy emissions, it should not be confused with delivered energy. Delivered electricity is the amount of energy required by the unit operations, and will be multiplied by 2.36 to obtain the cumulative energy demand (CED) for the NZ grid. The CED will then be separated into renewable primary energy (RPE) from hydro-electricity, and non-renewable primary energy (NRPE) from coal based electricity.

Natural gas (NG) is also used to produce heat energy during blood drying in the cradle-to-gate and rendering process. During the cradle-to-gate study it was found that every MJ of delivered energy supplied by natural gas actually requires 1.13 MJ of primary energy. The primary energy produced by natural gas has a global warming potential emission value of 0.0539 kg CO_2eq/MJ.

As NRPE provides the most substantial contribution to GWP, it is important to understand how the energy values are derived. Delivered energy are regarded as an LCI input, with cumulative energy demand and non-renewable primary energy being part of the LCIA. If a future study is conducted using the data from this LCA, the delivered energy would be used to calculate the specific NRPE based on the relevant grid mix, or the quality of the NG, for that study. Different electricity grid mixes, as well as the quality of the NG being utilised, will affect the LCIA, but not the LCI.

4.5 LCIA

In essence, the LCIA will be a summary of CO_2eq emissions caused by producing the plugs, and their impact on global warming potential over 100 years. Although some of the CO_2eq emissions have been calculated outside of GaBi, the injection moulding, transport, and polyethylene packaging operations have been calculated using the GaBi database. This might lead to issues of internal consistency (thus leading to errors in the calculation), as the main impact methods used in GaBi are the Centre of Environmental Science of Leiden University method (CML) and the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI). However, the GWP impact from the cradle-to-gate and other sources are based on the IPCC method.

The CML method attempts to avoid discrepancies generated by misunderstandings in LCI data interpretation. The CML methodology extracts the impact assessment factors proposed for the problem oriented approach, and links the data to the ecoinvent database. TRACI was developed by the United States Environmental Protection Agency (EPA). It was designed to use European methodologies, but adjusted for US conditions, as such a tool had not existed before 1996 [51]. TRACI has also been linked into the ecoinvent database. Although GaBi primarily uses these two methods, it does have the option to use standard IPCC impact factors, which will be used during this LCA.

The energy requirements will be separated into NRPE (consisting of fuel, coal, and natural gas consumption) and total energy, to account for renewable electricity generated.

4.6 Polypropylene Comparison

To compare the LCA for Novatein® and its various sensitivity cases to the polypropylene (PP) plug developed by Bestaxx Innovation, the unit operations for the PP plug will be modelled and compared to common data for the GWP and NRPE impacts of producing polypropylene products. An environmental information document for the Australian manufacture report claims an average of 2.17 kg CO_2eq emissions and 73.1 MJ NRPE use per kg of polypropylene production. This data can be extrapolated for the production of 1kg of PP pellets, although it may represent a total product LCA. To ensure that the data used to compare polypropylene to Novatein® is accurate, the life cycle of the PP plug has also been modelled in GaBi. With a few exceptions, the life cycles have been kept as similar as possible for a fair comparison.

The Gabi model starts with a pre-existing database for PP pellets entering an injection moulding unit operation (which is also pre-existing in the database). After the plug is produced, it is packaged into cardboard boxes, assuming the same number of plugs will fit into the boxes specified for the Novatein® plug. The PP plugs do not require PE film, as there is no need for an airtight seal. From this point, the transport, use, and rendering processes are assumed to be identical, with one exception. PP plugs will not cause direct GHG emissions like the Novatein®, as they will not degrade during rendering. This emission stream is minor, so omitting it will have little effect on the net GWP and NRPE impacts. The rendering process is also similar, in that the PP plugs will also be rendered. Although the polypropylene plugs will not break down, they will be heated and transported along with the rest of the raw material, consuming energy during the process. Lastly, the PP plugs do require the use of a pneumatic gun for insertion. The energy use from this is negligible, and hence it is also omitted.

5 Results and Discussion

5.1 Eco-profile

Results were split by their respective boundaries as defined by Figure 14. Once the LCA was concluded, sensitivity cases were presented and their effects were also discussed in further detail. Mass and energy flows are shown in Figure 17, Figure 18, and Figure 19, and their values are displayed in Table 4, Table 5, and Table 6.

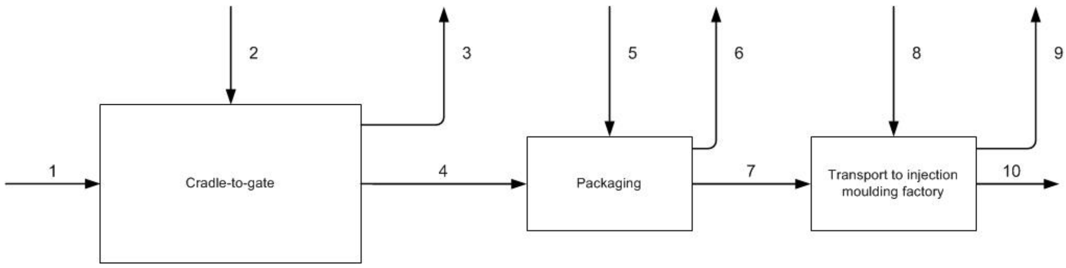

Figure 17 – Cradle to resin transport

Table 4 – Mass and energy flows for cradle to resin transport

#	Flow name	Flow value (per 1000 plugs)
Mass flows (kg/1000 plugs)		
1	Novatein® Powder	10.14
3	CO_2eq emissions	12.9
4	Resin	10.07
5	PE bags	0.0327
6	CO_2eq emissions	0.0786
7	Packaged resin	10.10
9	CO_2eq emissions	0.0630
10	Packaged resin	10.10
Energy flows (MJ/1000 plug)		
2	NRPE	238
5	NRPE	2.36
8	Fuel	0.901

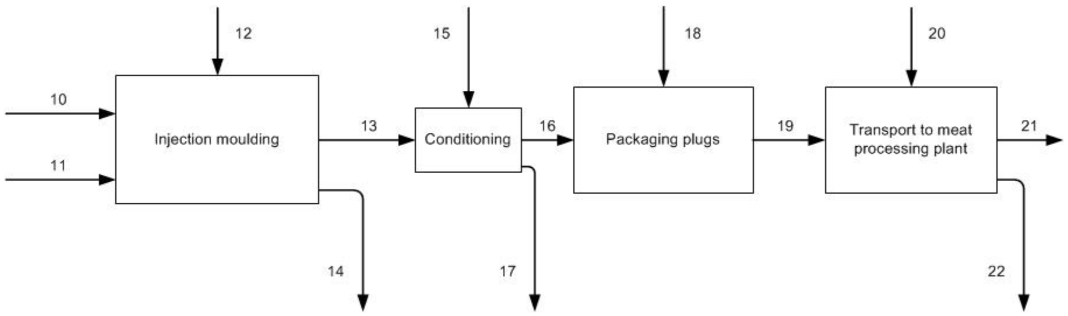

Figure 18 – Injection moulding to plug transport

Table 5 - Mass and energy flows for injection moulding to plug transport

#	Flow name	Flow value (per 1000 plugs)
Mass flows (kg/1000 plugs)		
11	Cold water	0.000715
13	Plugs	9.36
14	CO_2eq emissions	1.48
	PE bags to waste	0.0327
	Waste	0.187
16	Conditioned plugs	7.81
17	CO_2eq emissions	0.484
18	PE bags	0.136
	Cardboard boxes	1.06
19	Packaged plugs	9.01
21	Packaged plugs	9.01
22	CO_2eq emissions	0.0564
Energy flows (MJ/1000 plug)		
12	Electricity	22.3
15	Electricity	7.30
18	PE bags NRPE	9.83
	Cardboard NRPE	22.57
20	Fuel	0.809

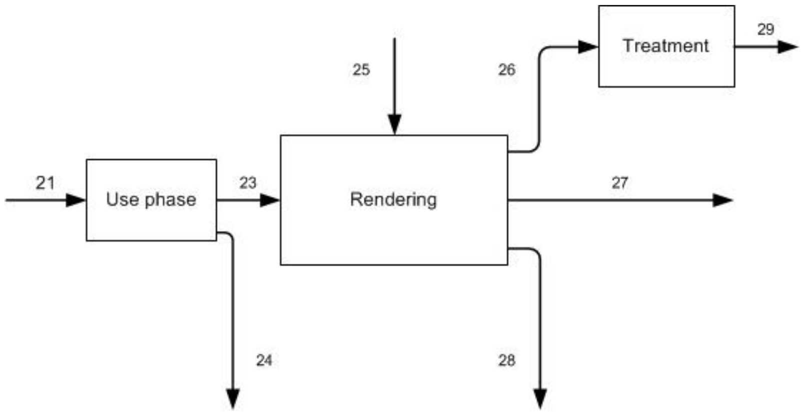

Figure 19 – Use and End-of-Life

Table 6 - Mass and energy flows for use and end-of-life

#	Flow name	Flow value (per 1000 plugs)
Mass flows (kg/1000 plugs)		
23	Plugs	7.81
24	Cardboard waste	1.06
	PE bags waste	0.136
26	Waste water	-
27	Blood and bonemeal	7.75
28	CO_2eq emissions	1.12
29	CO_2eq emissions	0.061
Energy flows (MJ/1000 plug)		
25	Electricity	2.5
	Natural gas	17.7

From analysis of the entire product life cycle, none of the operations have as much GWP as the cradle-to-gate phase (the production of Novatein®) (Figure 20). During plug production (gate-to-grave), injection moulding and packaging showed the largest GWP impact, each comprising 31% of the total gate-to-grave impact (Figure 20). Following this, the next highest impact comes from the rendering process, with conditioning and transport possessing the lowest GWP impact. As the use of the plugs had no impacts, it was not included in the results. Overall, the sum of all boundaries within the entire gate-to-grave phase emitted 36.8% as much GHGs as the production of Novatein® within the cradle-to-gate boundary.

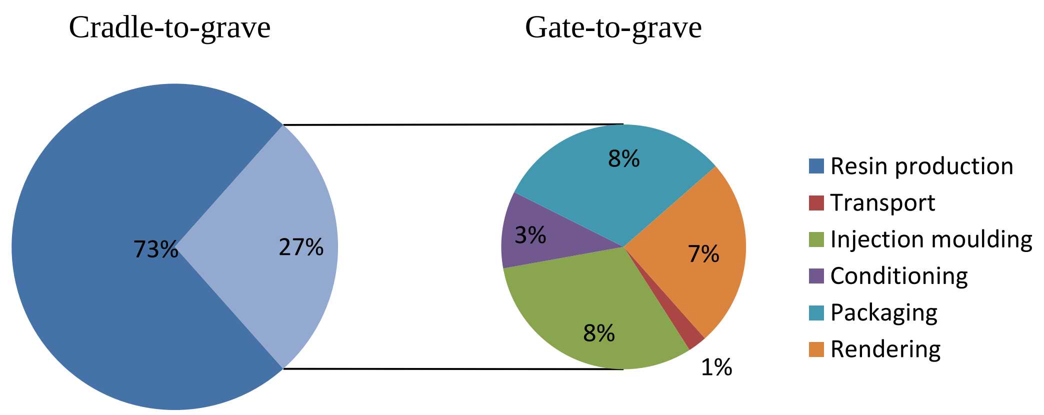

Figure 20 – GWP of the LCA in percentage of CO_2eq per plug

Packaging used the greatest amount of non-renewable primary energy in the gate-to-grave phase and is responsible for 40% of NRPE required for plug production and end-of-life (Figure 21). However, it still only utilises 14.6% as much NRPE as the production of Novatein® resin. The injection moulding process is also energy intensive, and uses the second largest quantity of NRPE in the gate-to-grave phase. The remaining processes follow the trends seen in the GWP results, with rendering using more NRPE than transport and conditioning (Figure 21). It is also important to note that only NRPE has been shown here, and that the total energy use (cumulative energy demand (CED)) is discussed later.

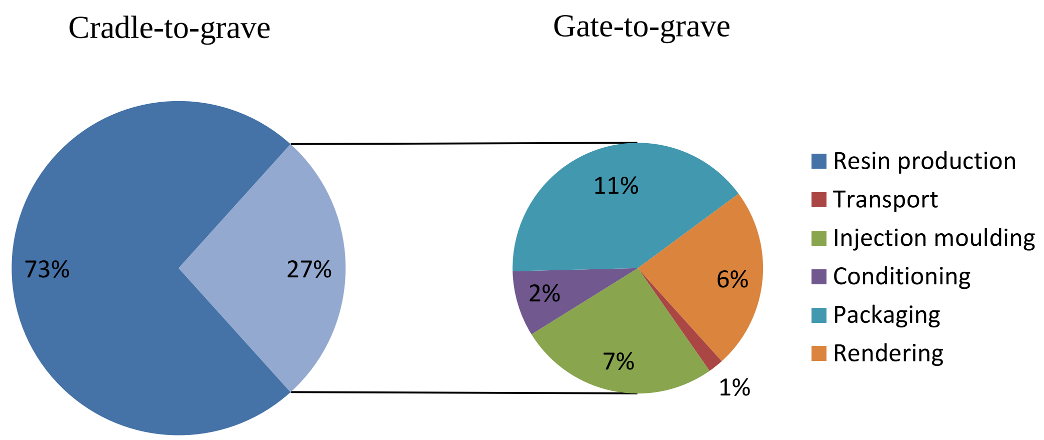

Figure 21 – NRPE use of plug production (percentage of MJ per plug)

To better understand the results, each boundary is discussed in more detail. The results could vary based on the assumptions made, and the areas where results might be sensitive are identified and discussed.

5.1.1 Production of Novatein®

The cradle-to-gate comprises results obtained from the Novatein® eco-profile study [1, 33]. This life cycle assessment has been based on the underlying assumption that bloodmeal is a low value by-product from the farming process, and as such, it has not been allocated any of the environmental impacts associated with farming. The boundary for the initial LCA was before the drying process for bloodmeal production.

The chemical additives for the production process have been analysed in this step, and it is assumed that after the gate they do not have any further carbon dioxide or equivalent emissions to atmosphere. Although the additives can contribute to acidification, eco-toxicity, eutrophication, and several other impacts when released into the atmosphere, these impacts are outside the scope of this study.

The NRPE use and GHG emissions for the production of Novatein® resin were included in the cradle-to-gate. It is important to note that although the life cycle analysis was conducted for the production of 2.31 million plugs a year, the final findings are presented in terms of the functional unit; the production of a single plug. When displaying the findings of the cradle-to-gate, the material waste and water loss must also be accounted for; this leads to the amount of resin required per plug being greater than the weight of a completed plug after it has been injection moulded and conditioned.

Producing 1 kg of Novatein® required 23.73 MJ of NRPE, and created a total of 1.28 kg CO_2eq emissions. Using these figures, the production of one plug required 0.01007 kg of resin, 0.238 MJ of NRPE is expended, and 0.0129 kg of CO_2eq emissions are produced. These results do not include the NRPE requirement or emissions from producing PE film, which is considered in the packaging boundary. Since resin production required 73% of the NRPE and emitted 73% of the GHGs, it would be very important to consider any changes that could be made in the future to decrease these impacts. Farming impacts have also been investigated (see section 5.5.1) to show how allocation for bloodmeal production can influence the whole LCA.

5.1.2 Packaging

The resin will be packaged in polyethylene bags only, while the plugs will be packaged inside cardboard boxes and PE film. The total life cycle emissions for the production and disposal of 1 kg cardboard is 1.01 kg CO_2eq [48], and 2.1 kg CO_2eq for the production and disposal of PE bags [52]. Cardboard requires an NRPE input of 21.29 MJ/kg, and polyethylene requires 72.3 MJ/kg. The CO_2eq and NRPE impacts for PE were calculated using the GaBi database.

Assuming that a human operator packages the plugs, there will be no additional electrical power required for this step of the operation (excluding the energy required in material production). PE bags produced 0.000408 kg CO_2eq per plug, and adding the emissions associated with cardboard, the net CO_2eq emission per plug for these two factors was 0.00148 kg CO_2eq.

The energy required by resin packaging is 0.00236 MJ, and the combined energy requirements of the polyethylene film and cardboard was 0.0324 MJ; this provided a total NRPE input of 0.0348 MJ per plug. Packaging produces 31% of the gate-to-grave's emissions, and utilised 40% of the NRPE (Figure 20 and Figure 21). Due to packaging's high production of CO_2eq emissions whilst simultaneously demanding the highest NRPE use of any operation in the gate-to-grave section of the study, a sensitivity analysis has been performed excluding cardboard boxes altogether to emphasise the significance on this unit operation (see section 5.5.2).

This shows that packaging can well have a large impact for not only plug production, but potentially for any product. Careful consideration to this operation should be given, as packaging is often very cheap (see section 6) and could easily be overlooked in terms of environmental impacts.

5.1.3 Transport

The transport phase resulted in energy use and GWP stemming solely from the production and combustion of diesel fuel. It was assumed the trucks will operate efficiently, by organising cargo loads to avoid empty trips (a 0.85 utilisation factor was chosen for modelling purposes). The distance travelled is relatively small, and thus by combining the distance travelled with the high utilisation factor (which spreads the truck's full CO_2eq emissions across a larger cargo load), the impact from transportation was low. Resin transportation (from the Novatein®

production plant in Waitoa to the plug production contractors in Hamilton) required 0.000901 MJ of NRPE per plug, and plug transport from Hamilton to Waitoa required 0.000806MJ of NRPE per plug. Added together, a total of 0.00171 MJ of non-renewable primary energy was used to transport each plug. CO_2eq emissions were $6.3x10^{-5}$ kg CO_2eq (for Novatein® transportation) and $5.64x10^{-5}$ kg CO_2eq (for plug transportation), a total of $1.19x10^{-4}$ kg CO_2eq per plug. This equated to only 0.53% of the NRPE use and 0.68% of the GWP of the entire cradle-to-grave LCA.

Whilst CO_2eq emissions and NRPE usage are the lowest in the LCA, the results of this phase have the highest chance of varying significantly. There are several factors that can contribute to an increase in the energy use and GWP impact of transportation. By decreasing the extraneous quantity of cargo carried by the trucks (so no other goods except the resin and plugs are transported, thus leaving empty space in the truck), the CO_2eq emissions and NRPE usage is approximately doubled.

Similarly, the utilisation factor could be set at 0.5 instead of 0.85, as the trucks could be empty whilst returning from the resin delivery or departing to pick up the plugs. This would increase the GWP impact and energy use by 70%. If this were the case, the only cargo carried by the trucks would be the Novatein® resin and plugs, thus incurring not only the utilisation penalty, but also the inefficient cargo load penalty.

Finally, the assumed distance travelled could increase greatly if the plugs were to be produced at a location other than Hamilton, or the rendering plant was located away from Waitoa, i.e. at Taranaki By-Products (TBP). If this is the case, the round-trip distance travelled from the resin plant to Hamilton would be almost 500km, leading fuel consumption to be five times greater than the current estimation. Ontop of these factors, the plugs will only be stored on site at the resin production plant, and will need to be transported to meat processing plants around New Zealand. Although NZ is a small country, and transport has a negligible impact in this case, there could be some large variances if it is not conducted properly.

In a worst case scenario, the Novatein® resin plant will be based in Taranaki, injection moulding will be carried out in Hamilton, and the trucks will only carry

Novatein® resin or plugs as their cargo whilst travelling half the journey with an empty truck. In total, this could result in the GWP impacts and energy consumption increasing 17 times larger than the current estimate. If this is the case, transportation will change from showing negligible impact to having a GWP impact 30% higher than packaging or injection moulding, and NRPE use that falls between injection moulding and packaging in magnitude. All before the plugs are delivered to their final destinations. To reiterate, this is a worst case scenario and extremely unlikely to occur. However, it does serve as a reminder that transportation must be considered carefully if changes are made to the setup of this production system, and plugs need to be transported to meat processing plants that are very far away.

5.1.4 Production

The injection moulding and conditioning units were included in the production phase; however, the figures for injection moulding and conditioning were not calculated using an identical methodology and is discussed further.

Injection Moulding

The GaBi software had a non-specific injection moulding unit operation that could be implemented in the analysis. However, for accuracy, the formulas utilised by the injection moulding operation required a shot size between 0.2 and 2.0 kg. The 16 shot size cavity selected had a material shot weight of 0.3 kg, which fell within the parameters of the unit operation and enabled the pre-programmed operation to obtain accurate results.

Electricity demand for production was calculated using the parameters of the unit operation. The shot size included the weight of 16 plugs, along with runners and sprues; after injection moulding, each plug weighed 0.00936 kg. The operation required 2.23 MJ of electrical energy to produce 1kg of injection moulded product, a delivered energy requirement of 0.0224 MJ per plug. However, the production of each plug required a runner that had a weight equal to the plug itself. In reality, half the energy was used during production of the runners and sprue, and half was used to produce the plug. Unfortunately, it is not possible to produce the plugs without the additional material required for the runners. Since the runners will be reground for reuse, all energy used during the process was attributed to the plug.

The cumulative energy demand (CED) of injection moulding is 2.36 times higher than its demand for delivered energy, as discussed during the electricity supply assumptions section. Therefore, the primary energy required to produce a single plug was 0.0529 MJ (0.0224 x 2.36). Of this, only 42.2% is coal-based electricity, so the NRPE demand of each plug was 0.0223 MJ/plug. The GWP for the production of each plug is calculated using the CED value, as hydro-electricity produces a small but important quantity of CO_2eq emissions, bringing the net impact to 0.00148 kg CO_2eq/plug.

The generic injection moulding model is based on commonly used polymers, like polyethylene, and uses a formula for calculating energy use based on the melting temperatures and residence times of commonly used polymers like PE and PP. PE tends to have a melting point between 190-240°C when prepared for injection moulding [53]. Novatein®, by contrast, is formed at a temperature between 120-140°C. From this it can be assumed that the energy required for Novatein® production was overestimated.

It is unlikely that the delivered energy required to produce Novatein® would be twice as high as the energy required to produce polyethylene (240°C compared to 120°C). Novatein® requires a longer cycle time than most common polymers (40 seconds compared to 10 seconds for the PP plug), so residence times are longer for Novatein® products, and therefore the material needs to be kept warm for longer. It is recommended that future studies obtain accurate data for the delivered energy required to produce Novatein® products via injection moulding.

Conditioning Chamber

The conditioning chamber plays an important role in the production process. For the plugs to function with the required physical properties, they must be conditioned for a week at 23°C and 50% relative humidity. Conditioning decreases the plugs' total moisture content to 8.4 wt%. If the plugs reach a moisture content of 10 wt% or above via exposure to humid conditions, the material properties may no longer be sufficient for the plugs to perform effectively [54]. It should also be noted that the plugs will not remain in use long enough for moisture absorption to render them ineffective.

Over the four week period, 285 kg of water will be removed from the plugs. Every hour, 0.424kg of moisture must be removed from the air as moisture evaporates from the plugs. A 0.56 kW dehumidifier can remove 28 L of moisture a day – this more than twice the amount required, and will be sufficient to keep the room at steady state.

For the purpose of this study, it is assumed that the humidifier is constantly running at full capacity, using the maximum amount of electricity to function - under full capacity, 1355 MJ of energy is required over the course of four weeks. This is delivered energy; the cumulative energy demand of each plug is 0.0173 MJ, with NRPE comprising 0.00730 MJ such that CO_2eq emissions are 0.000484 kg CO_2eq/plug.

Conditioning may only utilise 9% of the gate-to-grave's NRPE, and emit 10% of the GHGs (Figure 20 and Figure 21), however using a Novatein® formula that has lower moisture content could reduce or eliminate the need for conditioning. This could not only make a noticeable difference to the over-all impacts, but will also reduce the amount of time required to wait between plug production and when it is physically ready for use. Lastly it could potentially eliminate the need to seal the plug away from any moisture, but this has not been proven yet.

The emissions from the injection moulder and conditioning chamber are exclusively from electrical power production.

5.1.5 Use phase and End-of-Life

Plugs are removed from their packaging and used for a brief period of time. Although the use phase requires no electrical power, it is important to note that the cardboard and PE film do become waste. The emissions from the cardboard and PE film production and disposal have been taken into account during the packaging phase, so no emissions from packaging waste are allocated to this phase.

After the intestines are removed during dressing, the plugs are entered into the rendering system along with the entrails. The rendering process utilises energy from two sources: the electrical grid, and natural gas (burned to turn water into steam). The delivered electrical power was 0.00253 MJ per plug and the energy derived from natural gas was 0.0157 MJ per plug, totalling 0.0182 MJ delivered energy per plug. The CED equated to 0.0237 MJ/plug, bringing the NRPE to 0.0202 MJ/plug.

Emissions from the electrical grid and natural gas were 0.00112 kg CO_2eq per plug, and the GHG emissions from the water stream was $6.10x10^{-5}$ kg CO_2eq per plug; combining these figures, net emissions were 0.00118 kg CO_2eq per plug. As discussed earlier, whilst there are BOD and TKN emissions, these are low and largely attribute to eutrophication rather than global warming potential.

Rendering was responsible for 25% of the GWP for the gate-to-grave phase, and utilised 23% of the NRPE (Figure 20 and Figure 21). This means that the rendering operating was the third highest contributor to both of these impacts, and had a significant effect on the LCA. Unfortunately, much like the drying of blood, this process is the responsibility of the rendering plant, and very little can be done to influence of reduce the impacts of this process. However, since there is a large amount of energy utilised by this processes, any alterations in the grid mix or the quality of the NG being used can cause a dramatic fluctuation in the GWP of this process, which is important to consider during any future applications of this data.

5.2 Global Warming Potential

The relative contributions of each processing step's CO_2eq emissions are shown in Figure 20. The total CO_2eq emissions came to 0.00474 kg per plug, compared to 0.0129 kg CO_2eq for resin production. Essentially, the first half of the Novatein® plug's life cycle contributes 63.2% of its total global warming impact, which appears plausible since the blood drying process is very energy intensive.

It is clear that the impacts from injection moulding and packaging are higher than the rendering process, each comprising 31.2% of the gate-to-grave phase (Figure 20). As a large proportion of the emissions originated from using electrical power, it is important to note how the NRPE was calculated and how much each unit process utilised. Injection moulding used 25.9% of the plug production cycle's NRPE, therefore it can be expected that injection moulding generates a large amount of CO_2eq emissions.

During injection moulding, the energy required to heat the barrel, die, and operate the hydraulics is large. The residence time of material is much longer in the injection moulder than during extrusion (for resin production), which uses a similar heated barrel technique to produce the resin. Similarly, a larger amount of resin resides inside the barrel, requiring more electricity to heat and maintain the resin at the required temperatures of 120-140°C. Additionally, injection moulding requires a heated die, and utilises one or more motors to operate the hydraulics.

As a result, the injection moulder required more electrical power than any of the processing stages. On a mass basis the entire processing phase of Novatein® resin required 1.16 MJ NRPE/kg Novatein®, compared to 2.86 MJ NRPE/kg for Novatein® plugs. It must be noted that this result is based on a fully conditioned plug; if the NRPE consumption of injection moulding for an unconditioned plug is considered instead, the energy use was 2.34 MJ/kg of Novatein® plugs. The results indicate that injection moulding used twice the NRPE of the entire resin processing system (not to be confused with the cradle-to-gate).

When comparing results against the rendering process, there is a different reason for the variances in GWP. The rendering process, although energy intensive, utilises natural gas for a large part of the heating processes. Electrical power would mostly be used for mechanical material transportation, like conveyer belts, mixers & stirrers, and pumps. The use of burning natural gas to provide heat energy in the form of steam is a common method for producing efficient heat energy. When compared to the electrical heaters of the injection moulder, more energy is used by the injection moulder, 0.0224 delivered MJ/plug compared to 0.0182 delivered MJ/plug, on top of which the heat energy produced by the rendering process is obtained in a much more efficient manner through burning natural gas, thus lowering the GWP even further.

One of the most surprising results is the GWP of the cardboard packaging. Its impact was higher than that of rendering but equal to injection moulding during the gate-to-grave portion of the LCA. A potential solution to reduce the impacts of packaging is to remove the cardboard boxes entirely, as the PE bags would be sufficient in both size and physical strength to allow for transportation and storage. This option is discussed later during sensitivity analysis.

Finally, the results from the initial LCA exclude farming as a process, deeming blood as a low value by product and therefore substantially lowering the GWP identified with drying bloodmeal and producing resin. This is a very important factor to consider, as the varying allocation methods for farming's impacts has a significant influence on both GWP and NRPE use, and this issue is therefore convered in further detail during the sensitivity analysis (see 5.5.1)

5.3 Energy Use

Table 7 summarises the primary energy use, including renewable primary energy (RPE), non-renewable primary energy (NRPE), and cumulative energy demand (CED) of producing 1000 plugs for (for easier comprehension). To better understand GWP, the energy use from the different operations must be considered. The total CED sums to 0.368 MJ/plug, with NRPE coming to a total of 0.324 MJ/plug, while the production of 1 kg of conditioned Novatein® plugs requires 41.50 MJ NRPE. However, there are a few very interesting trends among the different process steps which require investigation. Attention should be drawn to just how much higher the energy demand of injection moulding is when compared to the rest of the operations in the gate-to-grave, as it has a large impact during the electrical sensitivity analysis performed later (see section 5.5.4).

The cumulative energy demand of the unit operations in the gate-to-grave had different ratios of NRPE and RPE (Figure 22). When considering injection moulding and conditioning, we know that they only utilise electrical energy, and the rendering process utilises a mixture of electricity and NG. Because of this, ratio of RPE and NRPE for conditioning and injection moulding are different to that of rendering.

Table 7 – Energy use for producing 1000 plugs

	Energy use (MJ)		
	RPE	NRPE	CED
Resin production	N/A	238	238
Transport	N/A	1.71	1.71
Injection moulding	30.6	22.3	52.9
Conditioning	10.0	7.30	17.3
Packaging	N/A	34.76	34.8
Rendering	3.45	20.2	23.7
Total	**44.0**	**324**	**368**

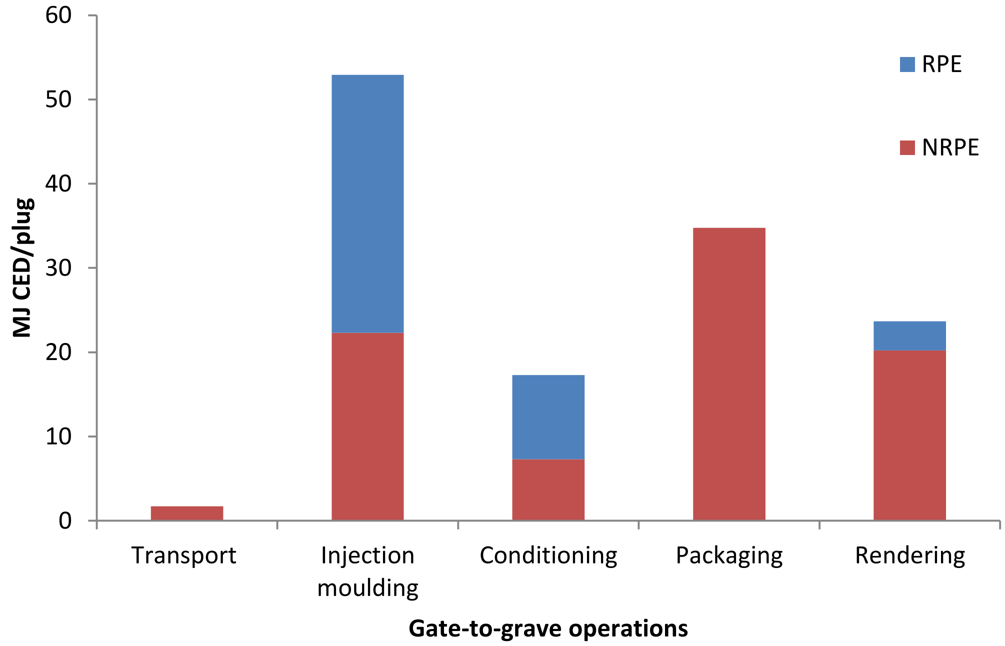

Figure 22 – CED of producing 1000 plugs (gate-to-grave operations)

When comparing conditioning to rendering, conditioning requires only 36.1% of rendering's NRPE demand. However, the CED of conditioning is 73.1% of rendering's total energy demand. This fact becomes much more important later during the electrical sensitivity analysis, when the NZ grid mix will be compared to the use of coal to produce 100% of the electricity requirements for this production system. If the electrical grid mix changes, the CED of conditioning would fluctuate more than that of rendering.

5.4 Comparison to Polypropylene

The primary competition for the Novatein® plug is the previous Bestaxx Innovation design, made from polypropylene. The PP plug weighs 28.6% less than the 7.82 g Novatein® plug, which highlights the need to use the functional unit for comparison

With the data on the process of the PP plug production being limited, the production impacts must be derived from a more ambiguous source. However, since the Bestaxx Innovation plug is produced in Australia, using an Australian source for the average GWP and NRPE, it is possible to draw a reasonable accurate comparison. An environmental information document for Australian manufacture report claims an average of 2.17 kg CO_2eq emissions, and 73.1 MJ NRPE used per kg of PP production. Converting this data to reflect the impact of a single plug, the GHG emissions are 0.01235 kg CO_2eq/plug, and requires 0.4161 MJ of NRPE/plug, including a 2% increase to account for waste.

When using the GaBi database to produce results with the assumptions made earlier, the GWP is 0.0126 kg CO_2eq/plug, and requires 0.43 MJ of NRPE/plug, including disposal. Since the data is very similar, it may be assumed that the modelling completed for the PP plug using GaBi is more accurate for this study, and thus will be used for the comparison.

Compared to the PP plug, the Novatein® plug emitted 40% more CO_2eq per plug. However, the Novatein plug required only 75.4% of the NRPE utilised by the PP plug. This may seem counter intuitive, however, roughly 0.290 MJ of the PP plug's energy use is accounted for as feed stock, meaning only 0.140 MJ of energy is used during production and transport. The actual production energy used by the Novatein® plug is 132% more than that of PP, including the drying of bloodmeal.Remembering that the initial base case assumed that there is no energy or emissions allocated to farming, the results are based only on the drying of blood and production of Novatein® resin and plugs. Although there is some NRPE to account for in the feed stocks of the additives, it is a negligible amount.

Even though the functional unit of this product is based on a single plug, it is interesting to note that the results seem reasonable when compared to other materials on a weight basis. When considering the base case, including cardboard but not including any faming impacts, 1kg of conditioned plugs have a CO_2eq emission of roughly 2.26kg/kg Novatein® plugs. This is more just over twice the amount of emissions produced from corrugated cardboard at 1.01 kg CO_2eq/kg cardboard, and is only slightly more than the impacts from PE film at 2.10 kg CO_2eq/kg, and PP at 2.17 CO_2eq/kg.

When NRPE use is considered on a mass bases however, there is a different trend. To produce and dispose of 1kg of Novatein® plugs requires just 41.5 MJ/kg of NRPE, compared to 77.1 MJ/kg for PP. This means that 1 kg of conditioned, ready to use Novatein® products only requires 53.9% of the NRPE that 1kg of PP products do. If there were any cases where the functional unit of these polymers were based on mass, the Novatein® products could well hold an advantage over petroleum based polymers. However, this does exclude any allocation of impacts to blood production, although the NRPE use for mass and economic based allocations still comes to 85.6% and 79.1% respectively when compared to PP.

Finally, the designs of the plugs should be kept in mind, as the current PP plug cannot be made from Novatein®, but the new design can be made from either Novatein® or PP. If the new plug were to be manufactured using PP, the larger design could lead to a higher impact from PP which maybe be very comparable in terms of GWP.

Whilst the mass based conclusions cannot be used as outright references in future cases, they do lend more credibility to the results gained in this study, as the emission values of commonly used counter parts for Novatein® are very similar to the results obtained, and the NRPE is actually lower on both a plug and mass basis. It should also be mentioned that a less moisture rich Novatein® formula would reduce or eliminate the need for conditioning, but may require a larger amount of bloodmeal, thus it would reduce the impact from conditioning, but may increase impacts from resin production per plug, and per kg of Novatein® plugs.

The base case proves that Novatein® plugs use less NRPE, however they also have a larger GWP, meaning that from this data, there is no clear indicator as to which design is better for the environment. Novatein® does have one advantage over PP in the fact that it not only breaks down during the rendering process, but is also non-toxic, becoming part of part of the meat and bone meal when rendered. This means that it will not become a choking hazard or contaminate the meat and bone meal in such a way that it is unfit for animal consumption. Unfortunately, this study did not include insight into the overall animal toxicity of PP or Novatein®, however none of the ingredients used during Novatein® production is toxic when ingested.

5.5 Sensitivity Analysis

Several factors may influence the results of an LCA, and a sensitivity analysis should be included to highlight potential changes and major assumptions. As such, there are four major points to consider during this study. The largest possible variances lie with the allocation methods of farming impacts, how electricity is generated and distributed, producing plugs in-house, and also the inclusion of cardboard boxes during packaging.

5.5.1 Mass and Economic Allocation for Blood Production

The two most justified allocation methods for farming impact have been considered for comparison to demonstrate how the allocation methods can vastly change the results from this study. The allocation method for blood in the cradle-to-gate study covered mass and economic allocation methods, as well as the method used in the base case, which treats blood as a low value by product, and is therefore considered to have no impacts prior to the blood being collected for drying. By allocating some impacts from farming to bloodmeal, the results from the cradle-to-gate do change quite significantly, therefore the selected allocation method must be justified.

If blood production were to have impacts allocated to it from the farming process on a simple mass basis, where allocation is based on blood being a fraction of the live animal weight, it greatly increases the GWP and NRPE. The impact from Novatein® production increased from 1.28 to 14.97 CO_2eq/kg Novatein®, and NRPE use increased from 23.73 to 47.98 MJ/kg Novatein® [1]. However, a more suitable method is to apply mass based allocation where waste and losses are excluded, and blood is allocated as a fraction of all animal products, bringing the total impact to 3.76 CO_2eq/kg Novatein®, and results in NRPE consumption dropping to 28.11 MJ/kg Novatein® resin produced. This data represents the impacts of blood production, blood drying and resin production. When implementing the advanced mass based allocation, not only does the NRPE use increase by 18.5% for resin production, but the CO_2eq emissions increase by 193.0% per plug.

When these results are compared to the entire cradle-to-grave analyses, the total impact per plug increased to 0.0425 kg CO_2eq/plug, a 141% increase for a single plug. The NRPE increase is then 13.6% over the initial case. When compared with the PP plug, advanced mass based allocation leaves the Novatein® plug with a CO_2eq emission of 238% higher than PP, and using 85.7% of the total NRPE that the PP plug uses. These results are again significantly increased when compared to the base case, which had 40.0% more CO_2eq emission than PP, but only used 75.4% of the NRPE. These increases are from including farming impacts during resin production.

If blood production were to have impacts allocated to it from the farming process on an economic basis, it would also increase the CO_2eq emissions and energy used. The impact from Novatein® production in the cradle-to-gate phase increased from 1.28 to 2.18 CO_2eq/kg Novatein®, and NRPE use increased from 23.73 to 25.27 MJ/kg Novatein® resin produced [1]. NRPE use increased by 6.49% per plug, but again there is a large increase in the CO_2eq emissions at 32.6% over the cradle-to-gate. When these results are compared to the entire cradle-to-grave analyses, the total impact per plug increased to 0.0218 kg CO_2eq, a 23.8% increase for a single plug. The total NRPE increase is then 4.93% over the initial case. When compared with the PP plug, economic based allocation leaves the Novatein® plug with a CO_2eq emission that is 73.3% higher, but using only 79.1% of the NRPE.

It is not always fair to assume that low value by-products are waste. For example, blood is a waste from meat processing, but bloodmeal is an important product of the rendering process. If this study had to be compared to other bio-polymers in the future, the justifications used during allocation of impacts may not allow for the same assumptions made during this study. The comparisons may need to be drawn on a more equal basis by making the same assumptions throughout comparable studies. Due to this it is important to include the two most important allocation scenarios for the impact of blood production, as it may be crucial for this data is to be referenced in the future.

5.5.2 Removing Cardboard

One of the unit operations that can be drastically altered in this LCA is the packaging phase, which would lead to a decrease in both CO_2eq emissions and energy use. Packaging required the highest amount of energy in the gate-to-grave phase at 40% (Figure 21), and is also emitted the same amount of CO_2eq emissions to the atmosphere as injection moulding at 31% (Figure 20). Therefore, a plausible way to decrease the impact of the plug's life cycle is to remove unnecessary packaging in the form of cardboard.

By removing the cardboard boxes, the plugs will only be packaged in PE bags, which may be robust enough to keep the plugs sealed in during the transport operation and storage. Another possibility is to further reduce the impacts by maximising the number of plugs in each bag before moisture sorption becomes a problem after the bags are opened. This means taking into account how long the plugs can be exposed to humid conditions before moisture content will affect the physical properties too much, and then sizing the packaging so that the plugs are used before the plugs lose their effectiveness. This result in a reduction of the total amount of PE film that is required. However, for the purpose of this sensitivity, the plastic bags will remain the same size, and only the elimination of cardboard will be inspected.

CO_2eq emissions from cardboard boxes equated to 22.6% of the gate-to-grave, and 6.07% of the entire LCA. The NRPE used by the cardboard packaging equated to 26.1% of the gate-to-grave, and 6.95% of the total LCA. By removing the use of cardboard packaging all together, not only does the NRPE use and CO_2eq emissions decrease, but the impact from transport decreases as well. Although transport has a negligible emission of 0.68% CO_2eq of the entire LCA, and only utilises 0.53% of the NRPE, if the locations of the resin and production plants changed drastically and increased the distances travelled, removing cardboard could well help to decrease transport impacts significantly.

If cardboard packaging were to be removed from the life cycle, the total CO_2eq emissions would drop to 0.0166 kg CO_2eq/per plug. Compared to the PP plug, the Novatein® plug would only emit 31.5% more CO_2eq per plug, compared to 40.0%. The Novatein plug NRPE requirements would be only 70.2% of that utilised by the PP plug, compared to 75.4%. Although the CO_2eq emissions do drop, the Novatein® plug still has a significant amount of emissions compared to

PP. However, the most important factor to concentrate on is the fact that NRPE can be brought down to be much lower than PP plug's, which puts the Novatein® at an advantage in regards to energy use.

5.5.3 Producing Plugs In-house

When considering the environmental impact of producing the plugs in-house, resin packaging is no longer required, and transport is also removed completely from plug production. Although there needs to be additional facilities built to house the injection moulder and conditioning chamber, it may be predicted that the impacts of constructing such a small facility will be negligible over the 10 year life span of the project.

The most interesting result is that the in-house case uses only a little less NRPE than the base case, and a similar result is seen for GWP. The in-house case lowers GWP to 98.9% of the original. NRPE has a similar disparity between the two, with in-house plug production using 98.7% of the NRPE of the base case. Although two entire boundaries are removed from the LCA, they have the lowest impacts of the gate-to-grave, so their removal had little effect. When compared to PP, the in-house scenario only has a 38.4% higher GWP, and an NRPE use of 74.5% of PP's energy use. Based on this, contracting out plug production without the use of cardboard boxes still had the lowest GWP an NRPE use of the Novatein® plug production scenarios.

5.5.4 Coal Based Electricity

The NZ grid electricity mix is based on 42.2% coal based electricity and 57.8% hydro-electricity. Delivered energies must be converted into primary energies, or CED, and require further calculation to determine the actual RPE and NRPE that is consumed during an LCA.

It is useful to consider the data for delivered energy (Table 8), in case the study needs to be adapted for different regions or countries that produce their electricity in different ways. For resin production, one of the sensitivity cases investigated was using 100% coal based electricity for the production of Novatein® resin. This is another very important case to adapt for the full LCA, however, it has a much larger influence than simply increasing the NRPE use and GWP for the cradle-to-gate study.

For the purpose of this sensitivity analysis, it was assumed that transport and packaging production are outside of the control of our system, and would remain at their original values. However, resin production, injection moulding, conditioning, and rendering were calculated using the NZ grid mix, and therefore their impacts would be altered.

The most striking observation is that injection moulding now has a larger NRPE use and GWP than the rest of the operations in the gate-to-grave (Figure 23 A and B), and has increased by 178% and 311% respectively when compared to the base case. Similarly, the conditioning chamber had a GWP increase of 178% and a NRPE use increase of 311%. This can be expected as both of these operations had NRPE and GWP impacts based purely on electricity consumption (Table 8) therefore it makes sense that their values should increase by the exact the same ratio.

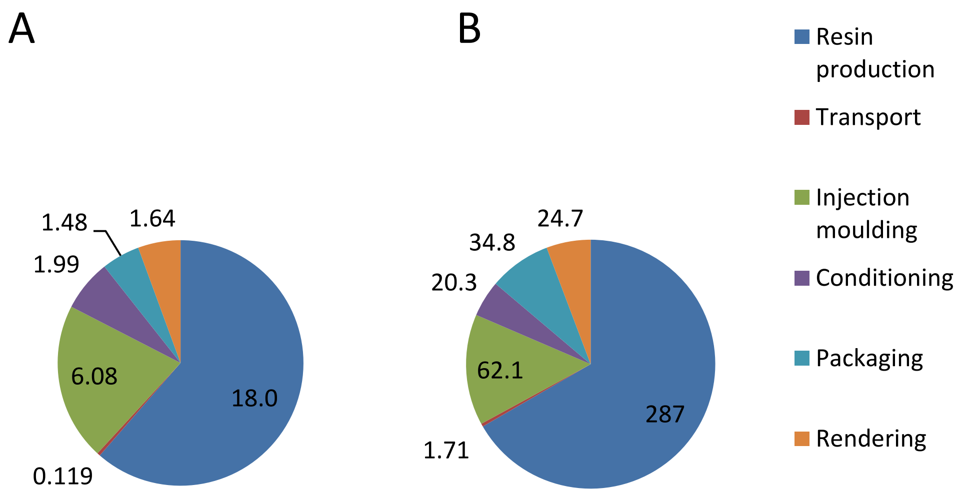

Figure 23 –

A: GWP of coal based electricity case (kg CO_2eq/1000 plugs)

B: NRPE use of coal based electricity case (MJ/1000 plugs)

Table 8 – Delivered energy for plug production (MJ/plug) (1000 plugs)

	Energy use (MJ)		
	Electricity	Natural Gas	Total
Injection moulding	22.4	0	22.4
Conditioning	7.33	0	7.33
Rendering	2.53	15.7	18.2

The resin production and rendering processes both include the use of natural gas for blood drying, and to process the plugs at the end of their lives. The cradle-to-gate had a NRPE use increase of only 20.6%, with GWP increasing by just 39.5%. The rendering process had an NRPE increase of 22.3%, with GWP increasing by 38.9%. They do not show the same increase, as rendering is a unit operation on its own, and resin production includes several process steps which do not utilise natural gas. As this sensitivity case only affects electrical energy supply, this is expected. Additionally, both of these processes have emissions that do not stem from energy use, but are related to vapour mass streams that are released into the atmosphere.

Both conditioning and rendering have an increase in the amount of NRPE use, but packaging still uses the most, followed by rendering, then closely by conditioning. However, conditioning now has the highest impact of the three, followed by rendering, then packaging, which is the reverse of their energy use. This is understandable when the conversion of delivered energy is explained. For the delivered energy to be converted to the standard NZ grid mix of hydro and coal based electricity, it must be multiplied by a factor of 2.36. Once this is done, only 42.8% of the final CED is coal based NRPE. On top of this, the CO_2eq emissions for the grid mix come to just 0.02797 kg CO_2eq/MJ CED. However, for coal based electricity, to convert delivered energy into CED, it must be multiplied by a factor of 2.77, and 100% of this CED is considered to be NRPE. Additionally, the CO_2eq emission for coal based electricity is 0.09788 CO_2eq/MJ CED. So, not only is the CED higher for coal based electricity, but 100% of the CED is NRPE, and the impact per MJ is also much higher.

For this reason, the processes that purely use electricity for their energy consumption have a NRPE increase of 178%, along with a very high GWP penalty. This explains why conditioning might have a lower NRPE use than rendering and packaging, but a higher GWP than both. Additionally, it may also be concluded that the production phases for cardboard and PE may incorporate renewable energy, or may also use more energy efficient production methods, since conditioning has a lower NRPE use, but a higher GWP when electricity generation is varied.

When the recalculated impacts of the cradle-to-gate, injection moulding, conditioning, and rendering processes are added together, along with packaging and transport, the final GWP equates to 0.0293 kg CO_2eq/plug, and the NRPE reaches a total of 0.431 MJ/plug. The GWP is 66.1% higher than the base case, and 132.6% higher than the GWP for PP (using the NZ grid mix). NRPE is 32.8% higher than standard when substituting the NZ grid mix with coal based electricity, but surprisingly it is only 0.14% higher than the NRPE consumed by PP, making their NRPE use practically equal per plug.

5.5.5 Sensitivity Comparison

The factors considered affected GWP the most (Figure 24 and Figure 25). It would appear that NRPE was less sensitive to the scenarios considered. This is mainly due to the fact that allocation methods do not incur such a large increase in the overall NRPE consumption, however, GWP can change quite significantly with just a minor change to allocation, process alteration, or energy generation methods.

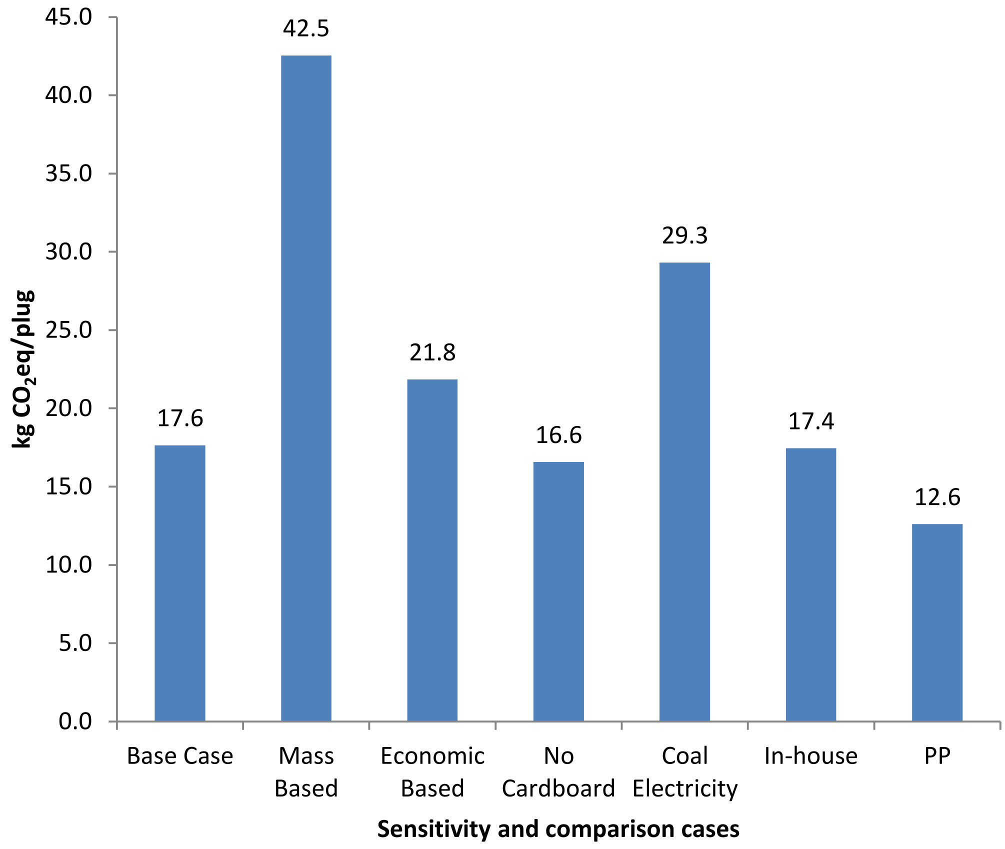

Figure 24 –GWP for the production of 1000 plugs (kg CO_2eq)

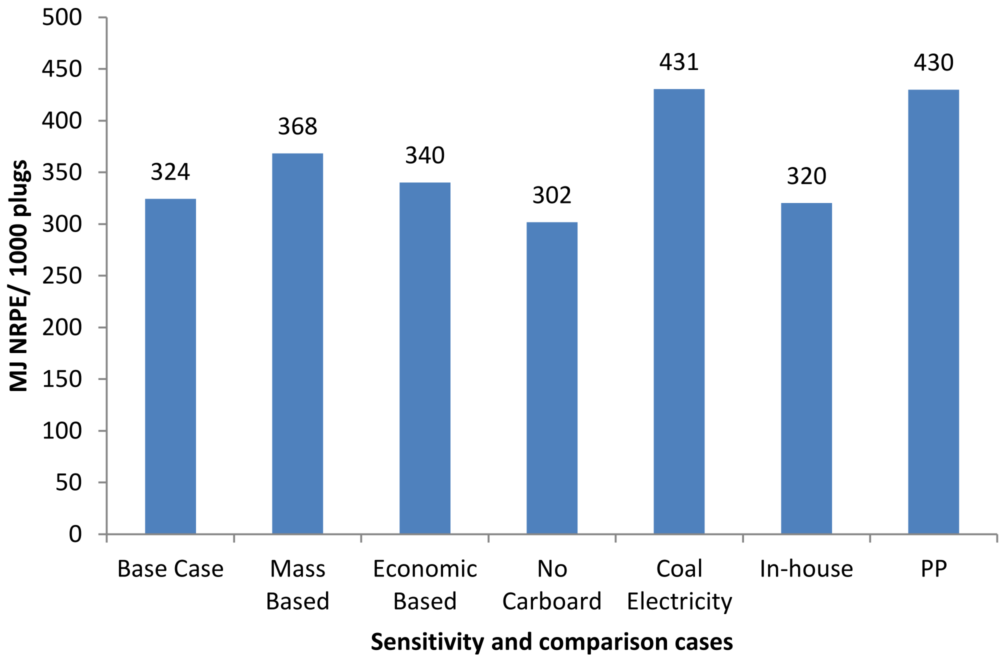

Figure 25 – NRPE required producing 1000 plugs (MJ)

It is clear that the best case scenario in this study is to produce Novatein® plugs without packaging them in cardboard boxes. The NRPE is much lower than that of PP, however even with the lowest GWP of the investigated scenarios, it still has almost a third more of an impact than PP plugs. This is due to the energy intensive blood drying process. If a lower moisture content recipe was used to produce the Novatein® plugs, and an in depth energy balance was performed around the injection moulder, it could decrease NRPE use and GWP due to lower conditioning requirements, and a lower energy use by the injection moulder. This could allow for the Novatein® plugs to have a GWP much more similar to that of PP, with a substantially lower amount of energy use.

Novatein® plug production is a very energy intensive process, and all effort should be made to reduce the energy use surrounding blood drying, injection moulding, and conditioning. It must also be noted that the coal based electricity analysis was performed on the basis that bloodmeal had no impact prior to dying. If the mass or economic allocation methods were selected for further comparison, adding the use of coal based electricity to their impacts would increase GWP and NRPE even more, placing both well above the impacts from PP.

Packaging can have reduced impacts from not only removing cardboard boxes, but also from sizing the PE bags to hold the optimal amount of plugs before moisture sorption will affect physical properties. Although transport is almost negligible in all of the cases, it could increase if it is not organised in an efficient manner, or the distances between production plants increase. It is also important to keep in mind that the packaged plugs will be stored on site, and additional transport will be required to ship them out to various meat processing plants. Lastly, there is little that could be done to improve the rendering blood drying processes, since the rendering plants are under the control of the meat processing companies, which would already be trying to work as efficiently as possible.

Although Novatein® plugs had a higher GWP in all cases, compared to PP, they do have the advantage of requiring much less NRPE (excluding coal based electricity). This trade off occurs due to the fact that the main feedstock for Novatein® is bloodmeal, which is a low value by-product of the beef and dairy farming process, and does not directly require the extraction of large amounts of raw material from the ground. Unfortunately the energy use to transform blood into Novatein® does have a large amount of emissions, as well as the fact that the Novatein® plug weighs more due to having a different design from PP, increasing GWP impacts even further for the functional unit. If the Port Jackson plugs were to be manufactured using PP, then GWP and NRPE will both increase due to the larger size of the new design, which could potentially narrow the margin of GWP between Novatein® and PP, and increase difference between the NRPE use in favour of Novatein®.

A very large advantage for the Novatein® plug is the fact that it breaks down during the rendering process to become a non-toxic part of meat and bone meal, which is often used in pet food, and sometimes burned as a renewable energy source. When PP plugs go through rendering, they consume energy, but do not break down, and become pollutants in the meat and bone meal. This could increase the toxicity of the meat and bone meal or even pose as a choking hazard when ingested, potentially reducing the amount of applications for this product. Using Novatein® will avoid contaminating the meat and bone meal, allowing for safe ingestion when used in pet food. Although this factor does not directly come across in this LCA, it could be investigated further if the goal and scope of this study were broadened to include eutrophication, eco-toxicity, acidification, photochemical ozone creating potential, and especially human and animal toxicity.

6 Economic Analysis Results and Discussion

6.1 Assumptions

6.1.1 Economic Model

To perform the costing analysis, two scenarios were selected for investigation. The first scenario models the plug production being contracted out to a third party, and the plugs being transported to Aduro Biopolymers' resin production plant near Waitoa. The second scenario involves leasing land next to the Novatein® resin production plant, as well as purchasing, shipping and installing an injection moulder. The critical assumption around costing this project was to treat the production of the plugs as a separate, stand-alone enterprise, and not as part of the Novatein® production plant (although sharing management could be beneficial as a way to co-ordinate and reduce overheads). If the plug production is a separate, stand-alone enterprise, then the resin should be purchased from the Novatein® production plant at market value, and not at the cost of production. This assumption is critical to the profitability of the enterprise, and will be discussed in more detail in section 6.1.2.

The costing analysis for the plug will take place only within the production boundary (Figure 13). Once the Novatein® resin is purchased, it must be packaged before it can be shipped to the plug production factory in Hamilton. Packaging resin is not part of the plug production phase and is not included in this costing analysis, because the Novatein® production process must package the resin before it can be sold. Packaging of the resin becomes absorbed within the Novatein® production process, and will be reflected in the price of the resin. The only direct cost of packaging to the plugs stems from packaging the completed plugs in Hamilton.

When contracting out production of the plugs, the conditioning chamber required to dry plugs was priced by summing the purchase of materials and the labour required to erect the structure. A storage space for 4 weeks' worth of plugs is also required. The floor area required for both the conditioning chamber and storage facility will be priced on a per-year basis, derived from industrial rental rates in Hamilton. The plugs are then transported back to the resin plant; after this point, the costs to use and render the plugs are not relevant to this study.

In the second scenario, plugs would be produced in-house on the same site that the Novatein® resin is manufactured. An injection moulder would need to be purchased, imported, and installed, and additional land and buildings leased to house the IM and conditioning chamber. The plugs are sealed and packaged after conditioning, ready for transport nationwide.

Whilst manufacturing the plugs in-house would remove the impact of transport, it may be assumed that the financial impact of transport is low, and removing this element would have a negligible effect on costing. It is also important to note that several key assumptions about the creation and operation of the resin plant set-up are carried over from the resin commercial feasibility study [35].

6.1.2 Resin supply

The resin required to produce the plugs will be purchased at the market value of Novatain®, because plug production is a separate project. Secondly, the resin production project requires its own profit margin to stay at a positive net income. If the resin was assumed to be acquired at the cost of production, then the cost to produce each plug would be much lower, making profits higher within the separate economic entity (production of plugs). From an accounting point of view, the net profit for Aduro Biopolymers is comprised of the production of Novatein® resin, plus the production of plugs. The total net profits of Aduro Biopolymers would require adding the net profits from the production of Novatein® resin to the net profits derived from the production of the plugs (Figure 26). If the gate-to-gate production of plugs purchased Novatein® resin at the cost of production, profits would simply be shifted from the resin production to plug production. However, this accounting manipulation would distort both the profits of Novatein® production (by understating them), and the profits of the plug production (by overstating them).

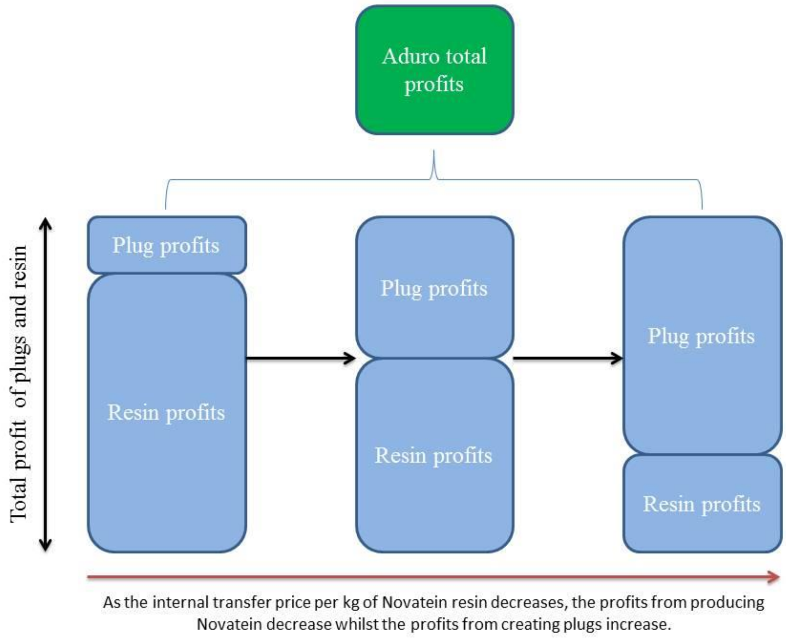

Figure 26 – Comparing how the internal trasfer pricing affects overall profits

The market value of the Novatein® resin is currently expected to be between $2.90 and $3.80 per kg. For competitive purposes, it is assumed that for plug production the market value of the resin is on the lower bound of this estimate. This means that every kg of Novatein® resin is projected to be purchased at $2.90/kg. This assumption stays constant whether the production of plugs is contracted out, or performed in-house.

6.1.3 Transport

The plug production process will use Novatein® resin, which is produced at the same facility as Wallace Corp's rendering plant in Waitoa. When contacting out the production of plugs, the resin must be transported to Hamilton and the completed plugs transported back to Waitoa. To transport the products, a commercial truck will be hired every four weeks. Included in the price of truck hire is the daily hiring cost plus an additional cost per km travelled.

The truck will be driving from its depot to the injection moulding plant (in Hamilton) to pick up the plugs, drop the plugs off in Waitoa at the resin plant, and return with a load of resin via the injection moulding factory. Since a 3.3 ton truck requires a Class 2 licence in New Zealand, a skilled driver will need to be hired for 3 hours to make the round trip. Labour for loading and unloading the truck is assumed to be covered by workers at the injection moulding factory, and the workers at the rendering plant.

6.1.4 Production

Injection Moulding

Whether contracting out the production of the plugs or manufacturing them in-house, the capital and operating costs must be identified. When contracting out production, the injection moulding process will be based on a per-hour cost through a third party in Hamilton. The major capital cost will be for the manufacture of the die, whilst the major variable cost is the rental rate at which the machine will be hired to produce plugs. The cost of labour to run the injection moulder is included in the per hour rental rate of the injection moulder.

When plugs are manufactured in-house, there are more capital and operating costs to consider. The capital costs include purchasing, shipping, installing an injection moulder, and manufacturing the die. The ongoing costs include leasing land and buildings to set up the plant and conditioning chamber, electricity, and hiring a full time labourer to operate the machine and do basic maintenance. Electricity will be calculated using the price per kWh from the commercial feasibility study [35] and adjusted for inflation in electricity prices in NZ. The kWh required will be calculated using the delivered energy of the injection moulder from the LCI.

Included in the price of purchasing the injection moulder is the cost of set-up, calculated via Lang factors [35]. These factors will account for electrical, item erection, piping and ducts, instruments, civil, structure and building, and lagging costs.

Conditioning

Construction of the conditioning chamber will be required for both scenarios, whether the production of plugs are contracted out or produced in-house. The capital costs include the materials required for the walls, roof, and floor, as well as the joining material. The conditioning chamber will be constructed of 5mm thick Perspex sheeting, to allow for the chamber to be mobile, and easily relocated or removed if required. Due to the relatively simple nature of this task, construction of the conditioning chamber is estimated to require 32 hours of skilled labour. An industrial dehumidifier is also required, plus shipping to the relevant sites. In either scenario, an area of floor space will be rented to install the conditioning chamber and store at least four weeks' worth of plugs.

The last ongoing cost that will be equivalent for both scenarios is the cost of electricity, which will be priced on a per kWh basis as of time zero.

6.1.5 Packaging

Packaging, comprised of cardboard boxes and PE film, will be relevant and identical between both scenarios. The cardboard boxes will be purchased in bulk, but the estimate could be inaccurate because box sizes vary greatly. PE film will also be bought in bulk, because the annual quantity required would be lower than the minimum order quantity. This is not a problem, since PE film will not degrade over a year and a half when stored properly.

6.1.6 Manager

A manager is needed to oversee the entire process. The requirement is not for a full-time manager, but for an experienced engineering manager to work part time on this project. It is expected that since the plug production is a straight forward operation and the majority of the time required is during set-up, it would only require a fraction of an existing manager's week to ensure that production is running smoothly. The same salary for the manager will be used from the commercial feasibility study, with a smaller percentage of the salary being allocated to running this project. The cost of this manager time is uniform across both scenarios.

10 hours per week of management time is allocated to maintaining and continuing the production of plugs, derived from a manager with an annualised salary of $100,000 per annum. If the volume of production is scaled up, the additional management time required will be scaled up incrementally. Rather than a doubling of production demanding double the management time, the incremental factor applied to increasing management time is 1/4. Hence, 2x the volume will require 12.5 hours per week, and 3x the volume will require 15 hours per week.

6.1.7 Sensitivities

The aim of the economic analysis is not just to find the production cost of each plug, but also to gain insight on the financial viability of the project. This can be further split into a comparison of the financial viability of contracting out production of the plugs verses manufacturing them in-house. The profit of the plug will be calculated over the course of ten years (the life of the project), and will then be adjusted by the appropriate discount factors to gain the net present value (NPV). However, to obtain a figure for the NPV, the discount rate needs to be determined and it needs to appropriate, because a wildly wrong discount rate can lead to spurious results, dependent on both the pattern of the ongoing cash flows and the magnitude of the up-front costs. The results and the overall NPV of the project is also sensitive to the price at which the plugs will be sold to different meat processing plants. To determine an appropriate discount rate, a risk-profile of being on the low end of 'high' is attached to this project. The discount rates that other, large companies apply to their internal environmentally friendly ('energy efficient') projects are found, and then compared on a risk-profile basis. The applicable rate for investments of a similar nature is 30%-50% [55].

In terms of pricing, existing Bestaxx PE plugs currently sell for approximately $0.15 AUD each – at the current exchange rate of 1.04:1, this equates to $0.16 NZD (the existing market for plugs range from $0.04-$0.15 AUD each). Slightly undercutting the NZD cost per plug by $0.01 leads to an expected price per plug of $0.15 NZD each. Due to the competitive nature of the product, it is important to keep pricing approximately within this range.

A sensitivity analysis is conducted to examine changes in NPVs according to movements in discount rates, plug prices, market share attained, and the cost of resin on per kg basis.

6.2 Discussion

After conducting an NPV analysis under the two scenarios, contracting production of the plugs out via a third party was found to provide a higher NPV over the life of the project for the most likely plug sales price ($0.15), discount rate (35%), market share (10%), and resin cost ($2.90 per kg). This is primarily due to the high capital outflows at time zero (t_0) when producing plugs in-house; these capital costs include buying, shipping, and installing an injection moulder. Secondly, the ongoing cost of hiring a full-time operator for the injection moulder is not cost effective, because the contractors can spread the cost of each operator over multiple injection moulders whereas this project is unable to do so due to the limited product range (Table 9 and Table 10).

Underpinning the concept of NPV is the time value of money, which is especially important to this project due to the high discount rate attached. Discount rates exponentially reduce future cash flows when converted to a time-zero value. To observe this, note that a cash flow of $100,000 in 10 years' time is worth $4,973.50 today (when discounted at 35%), whereas a capital expenditure at time zero of $100,000 still has a present value of $100,000.

Table 9 – Costing estimates for contracting out plug production (per 1000 plugs)

Overhead costs of plug production				
	Item description	**Cost ($)**	**Units**	**Cost per 1000 plugs ($)**
Ongoing management of the project				
Production manager	10 hours p/w	25000	$ per annum	10.823
Conditioning and conditioning chamber	Dehumidifier purchase	1633	$ total	0.071
	Materials for chamber	23117	$ total	1.001
	Labour to build chamber	1440	$ total	0.062
Injection moulding	Manufacturing die	130000	$ total	5.628
Operating costs of plug production				
Fixed costs per plug	**Item description**	**Cost ($)**	**Units**	**Cost per 1000 plugs ($)**
Truck hire	Truck hire fee (once per month)	155	$/day	0.839
Distance travelled (km)	104 km travelled	46.80	$ cost per round trip	0.253
Driver	Round trip labour cost	180	$ cost per round trip	0.974
Rent for chamber		300	$ per annum	0.130
Rent for floor space to store 4 weeks' worth of plugs		600	$ per annum	0.260
Variable costs per plug				
Resin	$ 2.90	3.80	$/kg Novatein resin	29.408
Cardboard	Cardboard boxes, 500, 598L X 344W X 231H mm	2359.80	$/500 boxes	10.488
Polyethylene film	25.2 kg of 0.1mm PE film	10.50	$/ kg	1.433
Renting the injection moulder		45	$ per hour	31.250
Electricity for chamber		0.19	$ per kWh	0.377

Table 10 – Costing estimates for in-house plug production (per 1000 plugs)

Overhead costs of plug production				
	Item description	**Cost ($)**	**Units**	**Cost per 1000 plugs ($)**
Production manager	10 hours p/w	25000	$ per annum	10.823
Conditioning and condition chamber	Dehumidifier purchase	1633	$ total	0.071
	Materials for chamber	23117	$ total	1.001
	Labour to build chamber	1440	$ total	0.062
	Industrial rental (floor space) for conditioning chamber	1680	$ per annum	0.727
Injection moulding	Manufacturing die	130000	$ total	5.628
	Buying and installing the injection moulder	316989	$ total	13.722
	Shipping the injection moulder (delivery)	38164	$ total	1.652
	Industrial rental (floor space) for injection moulder	8320	$ per annum	3.602
Operating costs of plug production				
	Item description	**Cost ($)**	**Units**	**Cost per 1000 plugs ($)**
Fixed operating costs				
Full time operator for IM		31.17	$ per hour labour ($50k salary)	21.645
Variable operating costs				
	Item description	**Cost ($)**	**Units**	**Cost per 1000 plugs ($)**
Resin	$ 2.90	3.80	$/kg Novatein resin	29.408
Cardboard boxes	Cardboard boxes, 500, 598L X 344W X 231H mm	2359.80	$/500 boxes	10.488
Polyethylene film	25.2 kg of 0.1mm PE film	10.50	$/ kg	1.433
Electricity for chamber		0.19	$ per kWh	0.377
Electricity (IM)		0.19	$ per kWh	1.152

6.2.1 Analysis of individual factors

Cost factors are split by boundary (i.e., production of Novatein® resin, packaging, transport, injection-moulding, and conditioning). These are analysed both on an NPV and non-NPV basis, for a time-zero perspective on the relative importance of costs.

6.2.2 Contracting out the production of the plugs

Clearly, the most influential costs (as a percentage of total costs) are the injection-moulding phase and the resin cost (Figure 28). In the first instance, the costs are not reported as NPV figures; rather, they are non-NPV adjusted (meaning that a cost of $1,000 in 10 years is weighted equally to a $1,000 cost at time zero). The transition from non-NPV to NPV figures leads those phases with higher up-front costs (at t_0) to become relatively more important than those phases with costs that are spread equally over the 10 year life of the project. As an example of this, consider the injection-moulding phase; broken down, this involves the creation of the die ($130,000) and an ongoing cost of $45 per hour to run the injection-moulder. When contracting out the production of the plugs, the creation of the die is the most significant up-front cost in the entire project, and this leads to the injection-moulding phase becoming more significant on an NPV basis than a non-NPV basis. This can be compared to the Novatein® resin, which is required evenly over the 10 year project lifespan and thus becomes relatively less important on an NPV basis.

The higher the discount rate used, the larger the transition of costs from a non-NPV to an NPV basis becomes. On a non-NPV basis, the cost of Novatein® resin is 31.6% of the total cost of each plug; whilst on an NPV basis (discounted at 35%) the cost of Novatein® resin decreases to 27.1% of the cost of each plug (Figure 27 A and B). A third scenario was analysed, which is the cost breakdown on an NPV basis if the resin cost is $3.80 per kg (Figure 27 C).

Other costs that are surprisingly high include the cardboard boxes used to transport the plugs from the contractors in Hamilton to Wallace Corp.'s rendering plant in Waitoa. The cost here amounts to 9.73% of the total cost per plug on an NPV basis, driven by the cost per box and the number of boxes required. Practical ways to reduce this cost per plug involves re-using each box multiple times; even if each box is used only twice instead of once, total cost per plug on an NPV basis will decrease by almost 5%.

Dividing the costs of injection-moulding even further, on an NPV basis the cost of the die equates to 19.1% of the total cost per plug, and renting the injection-moulder comprises 28.8% of the total cost per plug. The cost of the die is extremely high compared to other dies due to its complexity and its size. The difficulty lies in the machining of the die, as a 5 or 6 axis machine is required to cut the special spiral grooves, as well as the die requiring a removal core for each plug. Outsourcing the machining of the die is also unlikely to reduce costs, and the additional shipping that would be required. The cost of international shipping is projected to be high, because it would be extremely heavy and large (constructed from a large block of high-quality stainless steel). Secondly, the cost of renting the injection-moulder could be reduced by entering into a longer term agreement with the contracting company, who may be willing to decrease the cost per hour in return for a longer term guarantee of continuing business. Similarly, discussing this option with multiple contracting companies would enable the management team identify the contractor who provides the best balance of cost per hour and product quality (perhaps based on the previous business reputation of the contractor – reliability will be a major concern).

Reducing the cost of the Novatein® resin by negotiating lower prices with the Novatein® production plant is not of utmost concern, even though the cost of Novatein® resin comprises 27.1% of the total NPV cost per plug. If the cost of purchasing Novatein® is reduced, this increases the NPV of the plug creation, but it decreases the NPV of the Novatein® production plant by an equal and offsetting amount. Since both the Novatein® production plant and the plug production is owned by Aduro, there is no benefit to the holding company from negotiating Novatein® prices that are lower than what the resin could otherwise be sold for to outside parties.

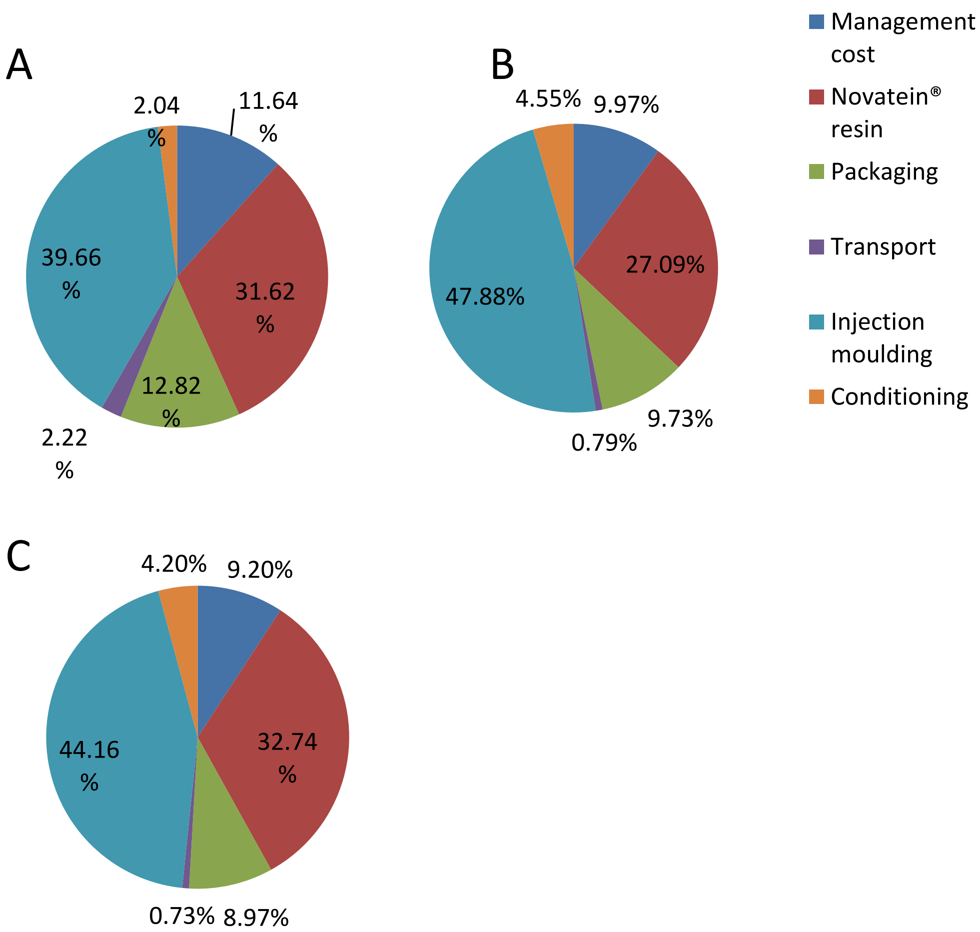

Figure 27 –

A: Contracting out: non-NPV basis, costs as a % of total production of plugs. Resin cost of $2.90/kg

B: Contracting out: NPV basis, costs as a % of total production of plugs. Resin cost of $2.90/kg

C: Contracting out: NPV basis, costs as a % of total production of plugs. Resin cost of $3.80/kg

6.2.3 **Producing the plugs in-house**

This involves purchasing, shipping, and installing an injection-moulder in facilities next to the Novatein® production plant and Wallace Corp.'s rendering facilities.

Major costs are again split by boundary, and converted from a non-NPV to an NPV basis (which provides a more accurate estimate of the real economic effect of the timing of costs). Together, the cost of buying, shipping, and installing an injection-moulder is $355,153. Lang Factors were used to calculate the estimated installation cost, and were based on the same calculations used for the Novatein® economic feasibility study [35]. These included the main plant item erection, piping, ducting and chutes, instrumental, electrical, civil, structure and building, and lagging costs (see section 9). The Lang factor for the injection moulder is 2.51.

These up-front and ongoing costs lead to injection moulding comprising 61.7% of total costs per plug on an NPV basis, compared to only 47.6% on a non-NPV basis (Figure 28). Clearly, the total NPV of the project will be extremely sensitive to the IM phase; practical considerations include the requirement for a detailed due diligence analysis when purchasing, shipping, and installing the IM. It should be noted that the cost of purchasing the injection-moulder was not $355,153 in itself; rather, (excluding shipping) the injection-moulder cost $152,657 to which Lang factors were applied to account for installation. As part of the sensitivity analysis, the impact of increasing resin purchase price from $2.90/kg to $3.80/kg was considered. When taken into account, resin increases from 19.6% to 24.2% of the total costs of production (on an NPV basis).

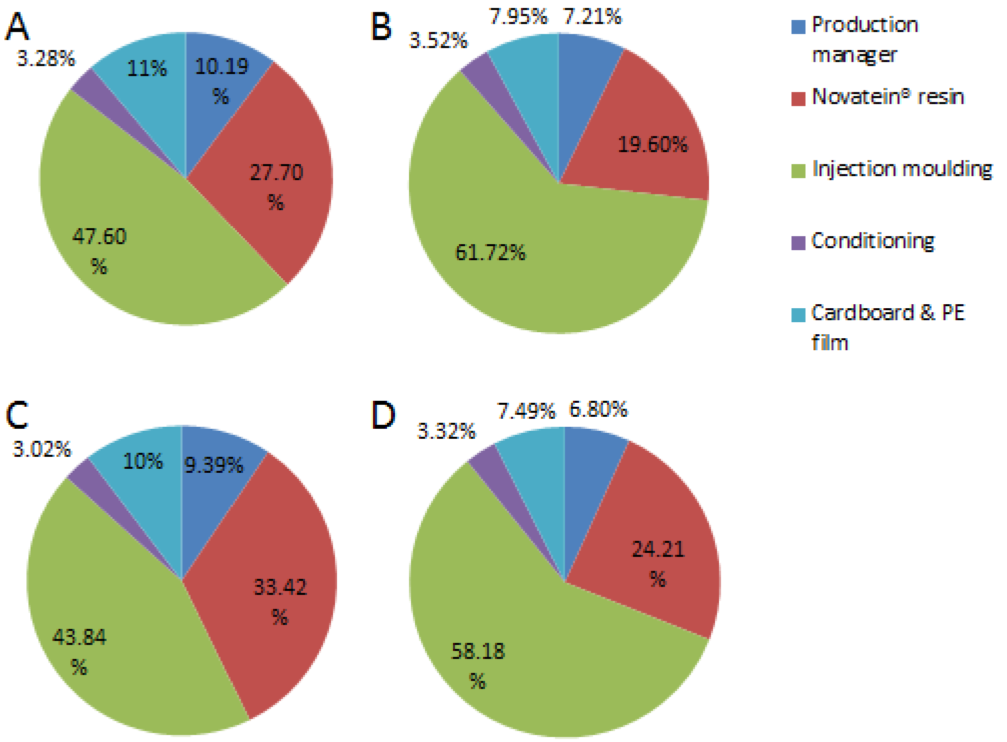

Figure 28 –
A: Manufacturing in-house: non-NPV basis, % total costs. Resin cost of $2.90/kg
B: Manufacturing in-house: costs, NPV basis, % of total costs. Resin cost of $2.90/kg
C: Manufacturing in-house: non-NPV basis, % of total costs. Resin cost of $3.80/kg
D: Manufacturing in-house: NPV basis, % of total costs. Resin cost of $3.80/kg

6.2.4 Sensitivity analysis

The sensitivity analysis of the plug production was conducted by first finding influential factors in determining the NPV of the project. These include: (1) the sales price of the plug; (2) the discount rates applied to the cash flows in the projects; (3) the market share gained (% of total sheep slaughtered in NZ per annum); and (4) the cost of resin, per kg.

The baseline scenario was a sales price of $0.15 per plug, a discount rate of 35%, a 10% market share, and $2.90 per kg resin.

6.2.5 Contracting out the production of the plugs

In Table 11, the potential sales price of the plug ranged from $0.11 to $0.19 NZD, and the discount rate applied ranged from 25%-45% (increasing in increments of 2.5%). At a discount rate of 35%, the lowest price the plugs could be sold at whilst still generating a positive NPV for the project is $0.12 each. Considering that other high quality plugs sell for around $0.16 NZD each (against which the Port Jackson plug will be competing), it is important to keep the pricing of the plug in roughly the same range. The economic viability of the project is high when contracting out, with even a sales price of $0.13 per plug providing a positive NPV at the highest modelled discount rate of 45%.

Table 12 analyses the NPV of the project by varying the market share achieved (% of sheep slaughtered annually) against the sales price of the plug. The market share varies from 10% to 30%, in 2.5% increments. The most influential capital cost when contracting out is production of the die; this die need only be produced once, even with volume up to 3x higher than projected. Scaling up production is a method to spread the cost of the die across a larger number of units, reducing the cost of the die on a per plug basis. This leads the NPV of the project to increase substantially. At a sales price of $0.15 per plug and a market share of 30%, the NPV of the project increases to $744,428.

Table 11: Contracting out, NPV sensitivity to price of plug and discount rate

NPV sensitivity to price of plug and discount rate										
		Discount Rate								
		25.0%	**27.5%**	**30.0%**	**32.5%**	**35.0%**	**37.5%**	**40.0%**	**42.5%**	**45.0%**
$ per plug sales price	**0.11**	$ 558	-$ 10,612	-$ 20,469	-$ 29,209	-$ 36,997	-$ 43,967	-$ 50,232	-$ 55,886	-$ 61,007
	0.12	$ 59,943	$ 44,540	$ 30,950	$ 18,898	$ 8,159	-$ 1,451	-$ 10,090	-$ 17,885	-$ 24,947
	0.13	$ 119,327	$ 99,693	$ 82,368	$ 67,005	$ 53,316	$ 41,065	$ 30,053	$ 20,116	$ 11,114
	0.14	$ 178,712	$ 154,846	$ 133,787	$ 115,112	$ 98,472	$ 83,580	$ 70,195	$ 58,116	$ 47,174
	0.15	$ 238,096	$ 209,998	$ 185,205	$ 163,219	$ 143,629	$ 126,096	$ 110,338	$ 96,117	$ 83,235
	0.16	$ 297,481	$ 265,151	$ 236,624	$ 211,326	$ 188,786	$ 168,612	$ 150,480	$ 134,118	$ 119,295
	0.17	$ 356,866	$ 320,304	$ 288,042	$ 259,433	$ 233,942	$ 211,128	$ 190,623	$ 172,118	$ 155,355
	0.18	$ 416,250	$ 375,456	$ 339,461	$ 307,540	$ 279,099	$ 253,644	$ 230,765	$ 210,119	$ 191,416
	0.19	$ 475,635	$ 430,609	$ 390,879	$ 355,647	$ 324,255	$ 296,160	$ 270,908	$ 248,120	$ 227,476

Table 12: Contracting out manufacture of plugs. Sensitivity of NPV to market share and plug price

NPV sensitivity to volume (market share) and sales price per plug (35% discount rate, resin cost of $2.90/kg)										
		Market share (% sheep slaughtered annually)								
		10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	27.5%	30.0%
$ per plug sales price	**0.11**	-$ 36,997	-$ 7,054	$ 22,889	$ 52,832	$ 82,776	$ 112,719	$ 142,662	$ 172,605	$ 202,549
	0.12	$ 8,159	$ 49,392	$ 90,624	$ 131,856	$ 173,089	$ 214,321	$ 255,554	$ 296,786	$ 338,018
	0.13	$ 53,316	$ 105,837	$ 158,359	$ 210,881	$ 263,402	$ 315,924	$ 368,445	$ 420,967	$ 473,488
	0.14	$ 98,472	$ 162,283	$ 226,094	$ 289,905	$ 353,715	$ 417,526	$ 481,337	$ 545,147	$ 608,958
	0.15	$ 143,629	$ 218,729	$ 293,829	$ 368,929	$ 444,028	$ 519,128	$ 597,283	$ 669,328	$ 744,428
	0.16	$ 188,786	$ 275,175	$ 361,564	$ 447,953	$ 534,342	$ 620,731	$ 707,120	$ 793,509	$ 879,898
	0.17	$ 233,942	$ 331,620	$ 429,299	$ 526,977	$ 624,655	$ 722,333	$ 820,011	$ 917,689	$ 1,015,367
	0.18	$ 279,099	$ 388,066	$ 497,033	$ 606,001	$ 714,968	$ 823,935	$ 932,903	$ 1,041,870	$ 1,150,837
	0.19	$ 324,255	$ 444,512	$ 564,768	$ 685,025	$ 805,281	$ 925,538	$ 1,045,794	$ 1,166,050	$ 1,286,307

A set of IRR calculations were performed based on differential sales prices of the plugs. It is found that even at a sales price of $0.11 per plug, the IRR is 21%; this increases to an IRR of 67% at a sales price of $0.15 per plug (Table 13). Based on initial estimates this project appears to yield substantial enough cashflows to be resiliant to large changes in both the price per plug and the discount rate applied to the cash flows.

Table 14 performs a sensitivity analysis on the NPV of the project to $0.10 increments in the cost of resin per kg. The NPV of the project is relatively robust to changes in the resin input costs, and remains positive for the highest expected price of $3.80/kg.

Table 13 – IRR based on sales price (contracting out)

IRR based on sales price	
$ per plug sales price	**IRR**
$ 0.11	21%
$ 0.12	33%
$ 0.13	45%
$ 0.14	56%
$ 0.15	67%
$ 0.16	77%
$ 0.17	88%
$ 0.18	99%
$ 0.19	110%

Table 14: NPV sensitivity to the cost of resin (contracting out)

NPV sensitivity to resin input price	
Resin cost ($/kg)	NPV
$ 2.90	$143,629
$ 3.00	$139,050
$ 3.10	$134,471
$ 3.20	$129,891
$ 3.30	$125,312
$ 3.40	$120,733
$ 3.50	$116,154
$ 3.60	$111,574
$ 3.70	$106,995
$ 3.80	$102,416

6.2.6 **Producing the plugs in-house**

When the plugs are produced in-house, not only are the NPV estimates sensitive to both the price of the plug and the discount rate applied to the cash flows, but the NPV estimates are also sensitive to the purchase price of the injection moulder.

When producing the plugs in-house, the capital costs are substantially higher than when contracting out. For example, whilst both scenarios require production of the die, when manufacturing in-house there is also the requirement to buy, ship, and install an injection moulder. Not only is this difference substantial in itself, but it contributes to the NPV of the project substantially due to the capital costs' timing being required at time zero (where all other inflows during the life of the project are discounted at a compounded rate of 35%). This high discount rate makes the up-front costs very important to the total feasibility of the project. The injection-moulding phase comprises 61.72% of the total cost per plug on an NPV basis, and the result of these high capital expenses is that under the baseline assumptions, the NPV of the project is -$96,813 (Table 15).

Table 15 evaluates the sensitivity of the project to changes in prices and discount rates. Manufacturing the plugs in-house does not provide a positive NPV in the majority of the model. The most relevant part of the sensitivity analysis is when prices are $0.15 per plug or below. Even a discount rate of 25% barely yields a positive NPV at this level.

Table 16 evaluates the changes in the NPV of the project against the percentage share of the market captured. Spreading the high capital costs over a larger volume produced enables the cost of the injection moulder per plug to decrease, and this significantly increases the NPV of the project when higher shares of the market are captured. Tripling the volume (from 10% market share to 30% market share) increases the NPV of the project from -$96,813 to $595,937.

Table 15: Manufacturing in-house, NPV sensitivity to price of plug and the discount rate

NPV sensitivity to price of plug and discount rate										
		Discount Rate								
		25.0%	**27.5%**	**30.0%**	**32.5%**	**35.0%**	**37.5%**	**40.0%**	**42.5%**	**45.0%**
$ per plug sales price	**0.11**	-$ 225,796	-$ 241,157	-$ 254,710	-$ 266,730	-$ 277,439	-$ 287,024	-$ 295,639	-$ 303,413	-$ 310,455
	0.12	-$ 166,411	-$ 186,004	-$ 203,292	-$ 218,623	-$ 232,282	-$ 244,508	-$ 255,496	-$ 265,412	-$ 274,395
	0.13	-$ 107,027	-$ 130,851	-$ 151,874	-$ 170,516	-$ 187,126	-$ 201,992	-$ 215,354	-$ 227,411	-$ 238,334
	0.14	-$ 47,642	-$ 75,699	-$ 100,455	-$ 122,409	-$ 141,969	-$ 159,476	-$ 175,211	-$ 189,411	-$ 202,274
	0.15	$ 11,742	-$ 20,546	-$ 49,037	-$ 74,302	-$ 96,813	-$ 116,960	-$ 135,068	-$ 151,410	-$ 166,214
	0.16	$ 71,127	$ 34,607	$ 2,382	-$ 26,195	-$ 51,656	-$ 74,444	-$ 94,926	-$ 113,409	-$ 130,153
	0.17	$ 130,512	$ 89,759	$ 53,800	$ 21,912	-$ 6,500	-$ 31,928	-$ 54,783	-$ 75,409	-$ 94,093
	0.18	$ 189,896	$ 144,912	$ 105,219	$ 70,019	$ 38,657	$ 10,588	-$ 14,641	-$ 37,408	-$ 58,032
	0.19	$ 249,281	$ 200,065	$ 156,637	$ 118,127	$ 83,814	$ 53,104	$ 25,502	$ 592	-$ 21,972

Table 16: Manufacturing plugs in-house. Sensitivity of NPV to market share and plug price

NPV sensitivity to volume (market share) and sales price per plug										
		Market share (% sheep slaughtered annually)								
		10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	27.5%	30.0%
$ per plug sales price	**0.11**	-$ 277,439	-$ 236,002	-$ 194,565	-$ 153,128	-$ 111,690	-$ 70,253	-$ 28,816	$ 12,621	$ 54,058
	0.12	-$ 232,282	-$ 179,434	-$ 126,830	-$ 74,103	-$ 21,377	$ 31,349	$ 84,076	$ 136,802	$ 189,528
	0.13	-$ 187,126	-$ 123,110	-$ 59,095	$ 4,921	$ 68,936	$ 132,952	$ 196,967	$ 260,982	$ 324,998
	0.14	-$ 141,969	-$ 66,665	$ 8,640	$ 83,945	$ 159,249	$ 234,554	$ 309,858	$ 385,163	$ 460,468
	0.15	-$ 96,813	-$ 10,219	$ 76,375	$ 162,969	$ 249,562	$ 336,156	$ 422,750	$ 509,344	$ 595,937
	0.16	-$ 51,656	$ 46,227	$ 144,110	$ 241,993	$ 339,876	$ 437,758	$ 535,641	$ 633,524	$ 731,407
	0.17	-$ 6,500	$ 102,673	$ 211,845	$ 321,017	$ 430,189	$ 539,361	$ 648,533	$ 757,705	$ 866,877
	0.18	$ 38,657	$ 159,118	$ 279,579	$ 400,041	$ 520,502	$ 640,963	$ 761,424	$ 881,886	$ 1,002,347
	0.19	$ 83,814	$ 215,564	$ 347,314	$ 479,065	$ 610,815	$ 742,565	$ 874,316	$ 1,006,066	$ 1,137,817

The cost of resin per kg is an important input into the NPV analysis, but does not change the outcome under this analysis. In all expected cases (resin cost $2.90/kg to $3.80/kg) the NPV is substantially negative.

Table 17: Manufacturing in-house NPV sensitivity to cost of resin per kg

NPV sensitivity to resin input price	
Resin cost ($/kg)	NPV
$ 2.90	-$96,813
$ 3.00	-$101,392
$ 3.10	-$105,971
$ 3.20	-$110,550
$ 3.30	-$115,130
$ 3.40	-$119,709
$ 3.50	-$124,288
$ 3.60	-$128,867
$ 3.70	-$133,447
$ 3.80	-$138,026

Contracting out the manufacturing of the plugs yields a better financial result under each sensitivity analysis. Splitting the factors that differ between the two scenarios, manufacturing the plugs in-house incurs high capital costs, so that the majority of the costs per plug (on an NPV basis) are incurred at the inception of the project at time zero. Analysing this on a discounted cash flow basis, at very low discount rates manufacturing in-house becomes relatively more attractive; however, it is not reasonable to apply a discount rate low enough to reach this outcome, because the riskiness of this venture is high.

The critical factor that will cause manufacturing in-house to be more financially viable is how low the cost of purchasing, shipping, and installing the injection moulder can be. The difference between the NPV of the projects (under baseline assumptions) is $240,442, and the current estimated total cost of buying, shipping, and installing the injection moulder is $355,153. If the total cost of the IM can be reduced to $114,711, the two scenarios become equal. Because manufacturing in-house has a higher ongoing cash inflow per year, this scenario will also benefit more from scaling up volume above the 10% market share threshold.

Considering these factors and that manufacturing in-house has a marginally lower environmental impact (due to removing transport), the recommendation is that Aduro Biopolymers manufactures in-house as long as they can purchase, ship, and install an injection moulder for $114,711 or below. This option also provides the largest NPV if a larger market share is captured. If Aduro is unable to purchase, ship, and install an injection moulder for under $114,711, an objective judgement based on the estimated market share to be captured will have to be made.

7 Conclusions and Recommendations.

The objective of this thesis was to investigate the feasibility of producing of the Port Jackson plug from Novatein® resin. The primary focus was to estimate the non-renewable energy use and greenhouse emissions that are attributed to the production of the plug from creation to disposal, as well as the economic viability of undertaking the plug production. These results were then compared to the current market competitor, a plug made from polypropylene.

Two cases were considered for the life cycle of the Port Jackson, but these were not significantly different in terms of their environmental impacts (GWP and NRPE). However, within the life cycle, the unit operations varied considerably.

Plug production contributed only 27% of both GWP and NRPE use for the entire life cycle. During plug production, both injection moulding and packaging had the highest GWP, with packaging requiring the most NRPE. Packaging should be carefully considered as it will have a large impact on the environmental profile of the Port Jackson. The operations with the lowest impacts included conditioning, and transport, collectively contributing to less than 4% of the entire LCA impacts.

The life cycle impacts were particularly sensitive to packaging, the allocation method used for farming impacts on bloodmeal production, and the ratio of the electricity grid mix. It would be sensible to consider removing cardboard from the plug packaging, while allocation methods are not under the control of the manufacturer, and is a limitation of the assumptions made in this study. The importance of the ratio of renewable to non-renewable energy used to generate electricity is that if the product is manufactured outside of NZ, impacts from electricity use could change noticeably.

The cost of purchasing, shipping, and installing the injection moulder is critical to the financial feasibility of producing the Port Jackson. The two scenarios can be equal if the injection moulder can be purchased at a reasonable cost, and/or if a great market share can be obtained.

Currently, the Novatein® plug has a higher GWP than the PP plug, however, it requires less NRPE, and if contracted out, can be sold competitively at a matching market value of $0.15 or $0.16 per plug. If absolutely necessary, the price may be lowered even further, to as low as $0.12. Based on the LCA and financial feasibility study, producing the Port Jackson from Novatein® is only slightly in favour over PP. Novatein's biggest advantage over PP is the fact that it not only breaks down during the rendering process, but is also non-toxic, so simply becomes part of part of meat and bone meal. It was concluded that PP only had a lower GWP, however Novatein® can be deemed as a more suitable plug to use since it has a lower NRPE use, the ability to be successful at a lower price, and being much less contaminating when rendered, thus not affecting the quality of meat and bone meal.

Some possible inaccuracies within the study need to be addressed in the future, with each requiring in depth investigation. The first is the energy requirement of injection moulding. Although the calculations are deemed to be within the specified parameters, Novatein® is unlike common polymers like polyethylene and polypropylene, and has a lower melting temperature, but also has a longer residence time. Another factor that must be considered is the transportation impact of shipping plugs from storage to meat processing plants around the country, or even overseas. Lastly, the allocation methods for the impacts of farming must always be considered when comparing the Port Jackson plug to other products in the future, as they can increase the impacts from production significantly.

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9 Appendix

The appendix is provided as a PDF document on the enclosed disc.

Appendix

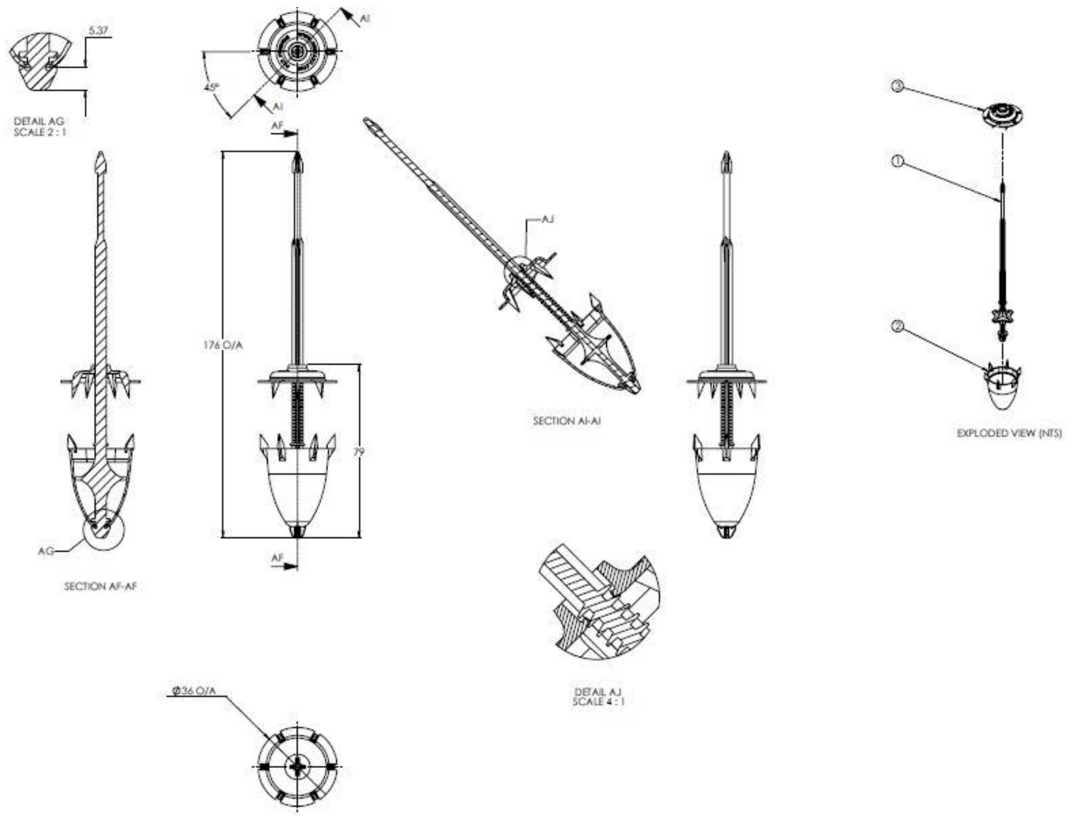

Figure A: 1 – Schematics for polypropylene plug

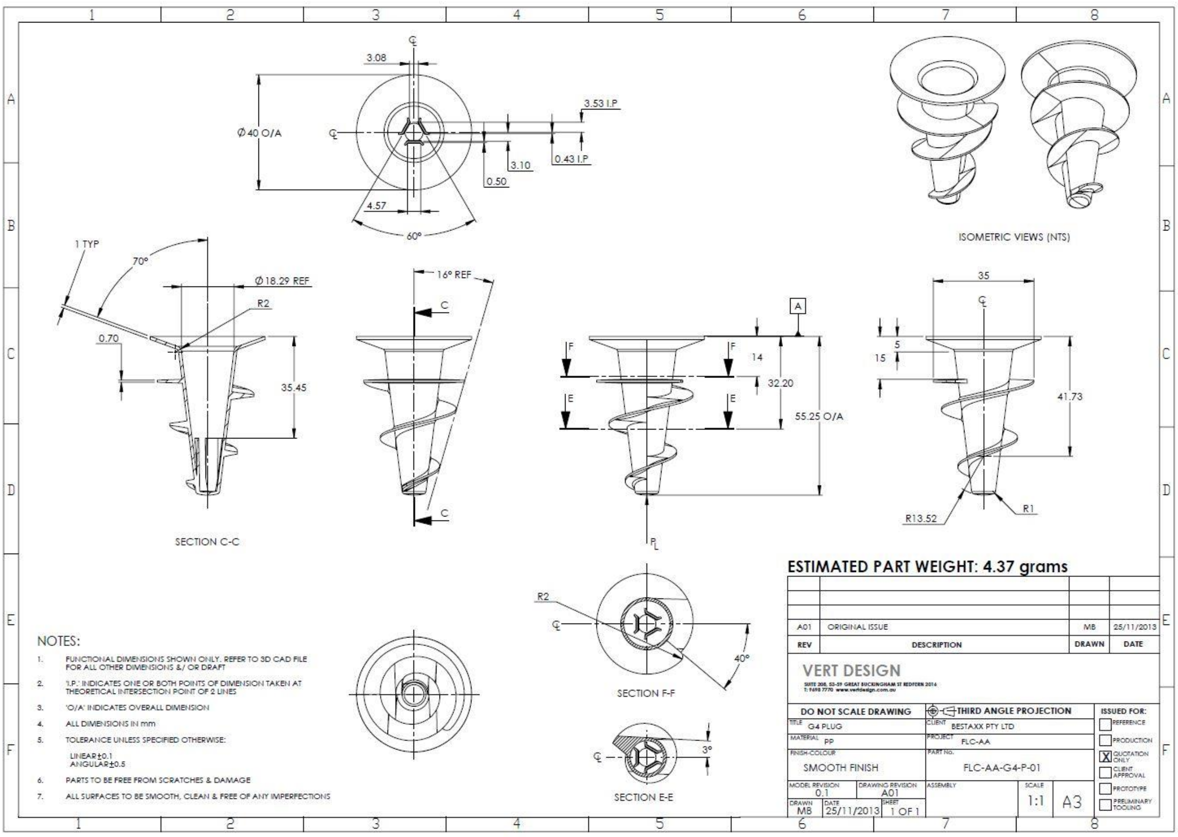

Figure A: 2 – Schematics for the Port Jackson

Table A: 1 – Lang factor scenarios for installing the injection moulder

Lang Factor	Scenario	Value of Individual Main Plant Item							SENZ TABLE	Injection moulder		
MPIC		>$960K	$320K to $960K	$130K to $320K	$64K to $130K	$19K to $64	$9.6K to $19K	<$9.6K	current	152657.43		
Cost Category		1	2	3	4	5	6	7		3		
Main Plant Items (delivered)		1	1	1	1	1	1	1	2	1	1	1
Main Plant Items erection (*fer*)	Much of the erection included in purchase cost of equipment such as large tanks	0.013	0.03	0.04	0.06	0.075	0.09	0.25	3	1	0.04	0.04
	Average erection	0.05	0.08	0.1	0.11	0.13	0.15	0.38	4	0	0.1	0
	Equipment involving some site fabrication such as large pumps requiring lining up and serpentine coolers	0.08	0.1	0.13	0.15	0.18	0.2	0.48	5	0	0.13	0
	Equipment involving much site fabrication of fitting such as large distillation columns and furnaces	0.3	0.38	0.4	0.56	0.67	0.77	1.13	6	0	0.4	0
									7			0.04
Piping, ducting and chutes including erection (*fp*)	Ducting and chutes	0.03	0.05	0.1	0.18	0.28	0.43	0.59	8	0	0.1	0
	Small bore piping or service only	0.06	0.13	0.26	0.43	0.69	1.04	1.4	9	1	0.26	0.26
	Average bore piping and service piping such as predominantly liquid piping	0.16	0.26	0.4	0.66	0.98	1.4	1.76	10	0	0.4	0
	Large bore piping and service piping such as predominantly liquid piping or Average bore piping with complex system such as manifolding and recirculation	0.2	0.33	0.49	0.78	1.11	1.58	1.94	11	0	0.49	0
	Large bore piping with complex system such as manifolding and recirculation	0.25	0.41	0.61	0.96	1.38	1.96	2.43	12	0	0.61	0

									13			0.26
Instrumental (*fi*)	Local instruments only	0.03	0.04	0.06	0.13	0.24	0.43	0.75	14	1	0.06	0.06
	*one controller and instruments	0.09	0.13	0.22	0.34	0.49	0.65	1	15	0	0.22	0
	*two controllers and instruments	0.13	0.2	0.33	0.45	0.6	0.79	1.14	16	0	0.33	0
	*three or more controllers and instruments	0.18	0.33	0.43	0.6	0.77	0.96	1.38	17	0	0.43	0
									18			0.06
Electrical (*fel*)	Lighting only	0.03	0.03	0.03	0.06	0.1	0.13	0.19	19	0	0.03	0
	Lighting and power for ancillary drives such as conveyors, stirred vessels and air coolers	0.1	0.14	0.2	0.26	0.34	0.41	0.6	20	1	0.2	0.2
	Lighting and power excluding transformers and switchgear - e.g. Equipment off site - or machines drives such as pumps, compressors and crashes	0.13	0.18	0.25	0.33	0.43	0.51	0.63	21	0	0.25	0
	Lighting and power including transformers and switchgear for machine main drives such as pumps, compressors and crushes	0.19	0.25	0.34	0.46	0.6	0.74	1	22	0	0.34	0
									23			0.2
Civil (*fc*)	Average civil work, including plant and structures foundations, floors and services	0.08	0.1	0.14	0.17	0.22	0.28	0.35	24	1	0.14	0.14
	Above average civil work, complicated machine blocks, special floor protection, elevator pits in floors and considerable services	0.15	0.21	0.31	0.4	0.5	0.6	0.85	25	0	0.31	0
									26			0.14
Structures and buildings (*fsb*)	Negligible structure work and buildings	0.012	0.025	0.025	0.04	0.05	0.06	0.08	27	1	0.025	0.025
	Open air plant at ground level with some pipe bridges and minor buildings	0.06	0.08	0.1	0.14	0.17	0.21	0.26	28	0	0.1	0
	Open air plant within a structure	0.14	0.24	0.31	0.41	0.5	0.59	0.74	29	0	0.31	0
	Plant in a simple covered building	0.19	0.29	0.39	0.48	0.56	0.69	0.85	30	0	0.39	0

	Plant in an elaborate building or a major structure within a building	0.35	0.48	0.63	0.76	0.9	1.06	1.38	31	0	0.63	0
									32			0.025
Lagging (*fl*)	Lagging for service pipes only	0.012	0.03	0.04	0.06	0.1	0.15	0.23	33	1	0.04	0.04
	Average amount of hot lagging on pipes and vessels	0.03	0.04	0.08	0.14	0.21	0.31	0.38	34	0	0.08	0
	Above average amount of hot lagging on pipes and vessels	0.04	0.06	0.1	0.17	0.26	0.35	0.4	35	0	0.1	0
	Cold lagging on pipes and vessels	0.06	0.1	0.15	0.25	0.31	0.41	0.56	36	0	0.15	0
												0.04
							Total Lang Factor					1.765
							Total cost of injection moulder ($)					316988.7

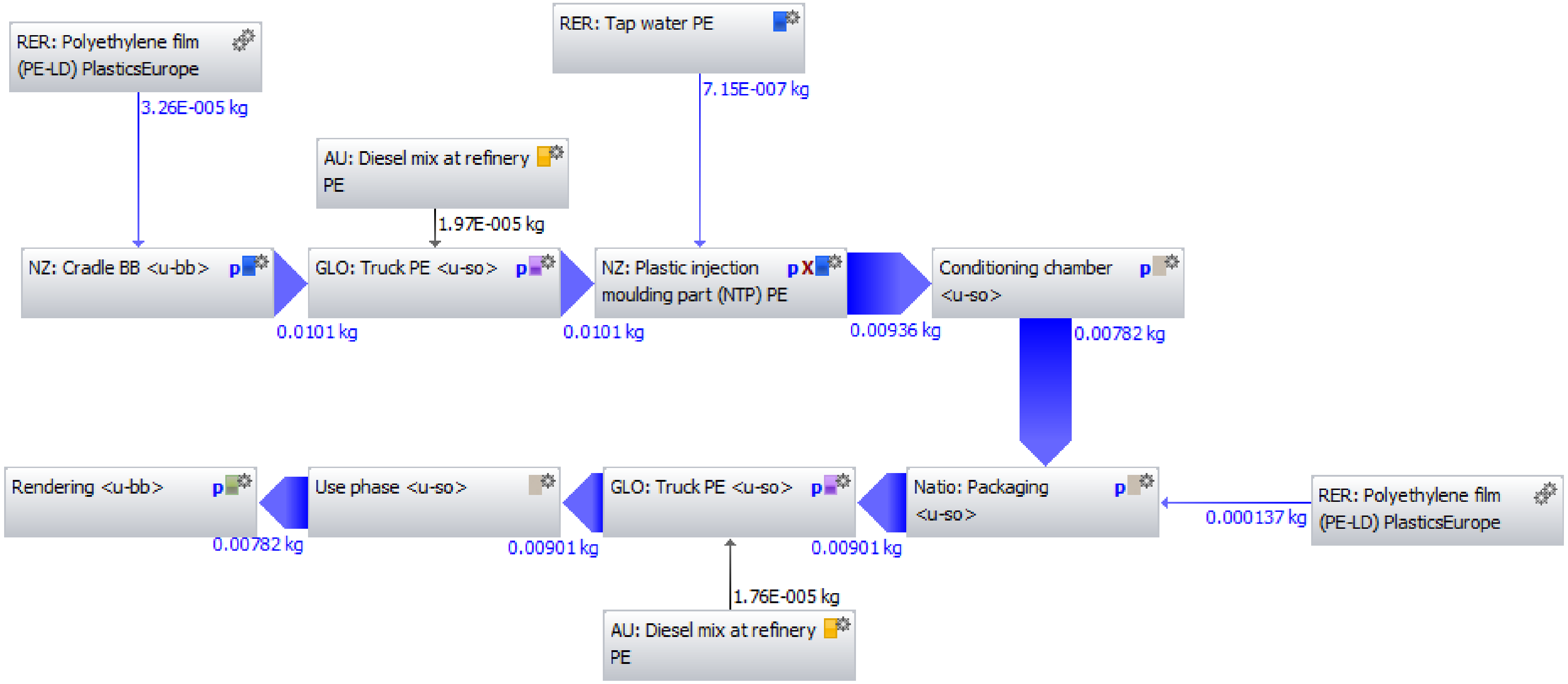

Figure A: 3 – Gabi mass flow diagram (1 plug)

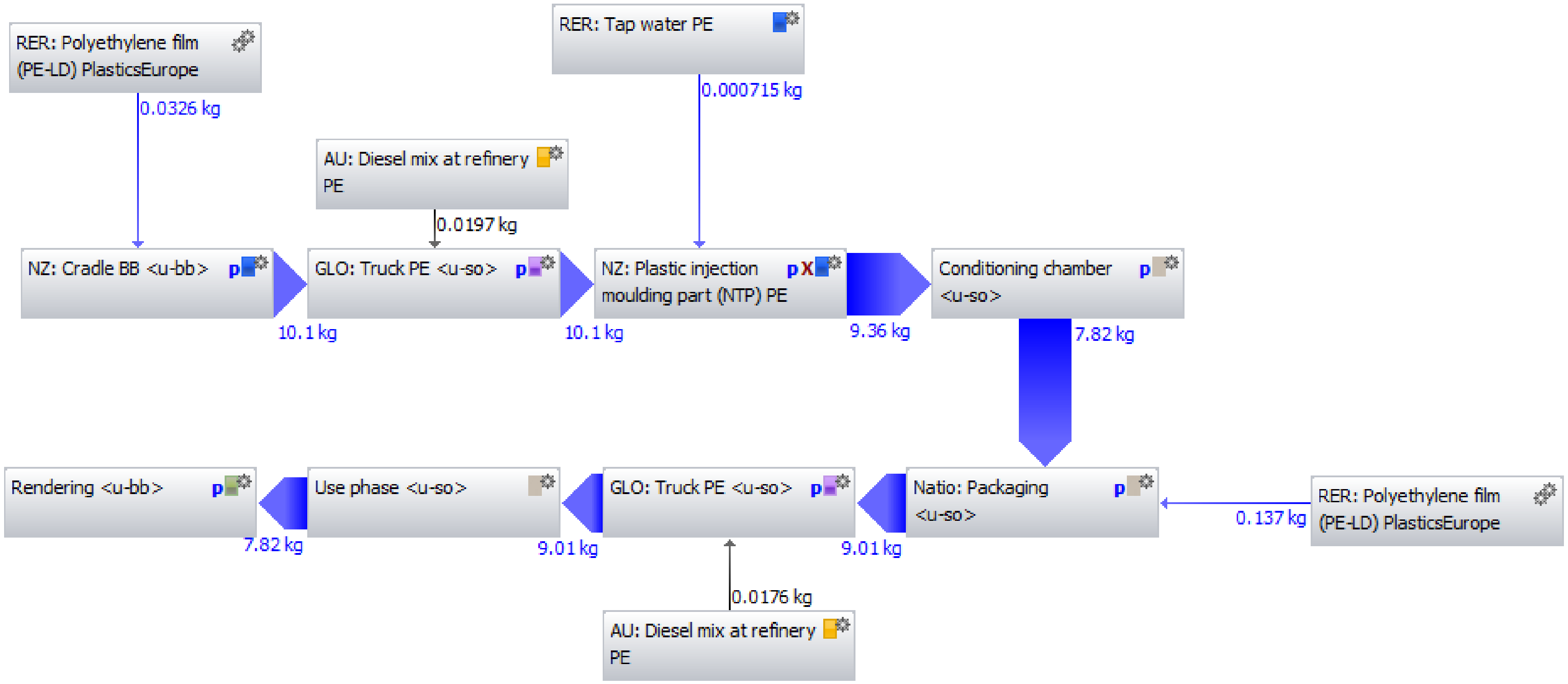

Figure A: 4 - Gabi mass flow diagram (1000 plugs)

Free parameters

Parameter	Formula	Value	Minimum	Maximum	Standard	Comment
bloodmeal		1.06E003			0 %	
pe_film		6.04			0 %	

Fixed parameters

Parameter	Formula	Value	Minimum	Maximum	Standard	Comment
co2_emission	Ntp_resin*1.28	2.38E003				
Gas_elec	Total_elec*0.35	8.91E003				
Hydro_elec	Total_elec*0.65	1.65E004				
NRPE	Ntp_resin*23.73	4.41E004				
Ntp_resin	bloodmeal*1.747	1.86E003				
PE_energy	pe_film*72.3	437				
Total_elec	Ntp_resin*13.68	2.54E004				
total_weight	Ntp_resin+pe_film	1.87E003				
waterloss	bloodmeal*0.013	13.8				

Inputs (Show all flows)

Parameter	Flow	Quantity	Amount	Unit
PE_energy	Electricity [Electric power]	Energy (net calorific value)	2.36	MJ
NRPE	Electricity [Electric power]	Energy (net calorific value)	238	MJ
pe_film	Polyethylene-film (PE) [Plastic parts]	Mass	0.0326	kg

Outputs (Show all flows)

Parameter	Flow	Quantity	Amount	Unit	Tracked flows
total_weight	NTP resin packaged [Plastics]	Mass	10.1	kg	X
waterloss	Water vapour [Inorganic emissions to air]	Mass	0.0747	kg	
co2_emission	Carbon dioxide [Inorganic emissions to air]	Mass	12.9	kg	

Figure A: 5 – Gabi parameters, inputs, and outputs for the cradle-to-gate (1000 plugs)

Scaling factor: 0.00541 ☑ Fixed

Free parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
ntp_resin		1.86E003			0 %	
plug_weight		0.00936			0 %	

Fixed parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Comment, units, defaults
CO2_elec	total_elec*0.02797	273				
coal	total_elec*.35	3.42E003				
Componentv	16*plug_weight*2	0.3				[kg/part] Default 0,2 kg - 2 kg; Do not use outside of this scope
coolingwater	88.2*Componentweight*0.005	0.132				[kg] Cooling water losses
Electricity	6.305*Componentweight+0.3372	2.23				[MJ] Power per kg part
hydro	total_elec*.65	6.35E003				
Material	(plug_weight+Waste)	0.00955				[kg] Material per kg part
ntp_inj	ntp_resin*0.9477	1.76E003				
plugs_prod	ntp_inj/material	1.85E005				units
total_elec	ntp_resin*Electricity*2.36	9.78E003				
total_waste	ntp_resin-weight_allplugs	132				
total_water_	coolingwater+waterloss	97.5				
Waste	0.02*plug_weight	0.000187				[kg] plastics waste
waterloss	ntp_resin-ntp_inj	97.3				
weight_allpl	plugs_prod*plug_weight	1.73E003				

Inputs Show all flows

Parameter	Flow	Quantity	Amount	Unit
total_elec	Electricity [Electric power]	Energy (net calorific value)	52.9	MJ
ntp_resin	NTP resin packaged [Plastics]	Mass	10.1	kg
coolingwater	Water (tap water) [Operating materials]	Mass	0.000715	kg

Outputs Show all flows

Parameter	Flow	Quantity	Amount	Unit	Tracked flows
total_waste	Industrial waste for municipal disposal [Consumer v	Mass	0.714	kg	
weight_allplugs	NTP plug [Plastics]	Mass	9.36	kg	X
	Polyethylene (PE, unspecified) [Consumer waste]	Mass	0.0327	kg	*
CO2_elec	Carbon dioxide [Inorganic emissions to air]	Mass	1.48	kg	
total_water_los	Water vapour [Inorganic emissions to air]	Mass	0.528	kg	

Figure A: 6 – Gabi parameters, inputs, and outputs for the injection moulder (1000 plugs)

Free parameters

Parameter	Formula	Value	Minimum	Maximum	Standard	Comment
pntp_in		1.73E003			0 %	
pntp_out		1.44E003			0 %	

Fixed parameters

Parameter	Formula	Value	Minimum	Maximum	Standard	Comment
CO2_power	0.02797*power_use	89.4				
power_use	1354.8*2.36	3.2E003				
water_loss	pntp_in-pntp_out	285				

Inputs (Show all flows)

Parameter	Flow	Quantity	Amount	Unit
power_use	Electricity [Electric power]	Energy (net calorific value)	17.3	MJ
pntp_in	NTP plug [Plastics]	Mass	9.36	kg

Outputs (Show all flows)

Parameter	Flow	Quantity	Amount	Unit	Tracked flows
pntp_out	ntp plug conditioned [Plastics]	Mass	7.82	kg	X
CO2_power	Carbon dioxide [Inorganic emissions to air]	Mass	0.484	kg	

Figure A: 7 – Gabi parameters, inputs, and outputs for conditioning (1000 plugs)

Free parameters

Parameter	Formula	Value	Minimum	Maximum	Standard	Comment
cardboard		195			0 %	

Fixed parameters

Parameter	Formula	Value	Minimum	Maximum	Standard	Comment
CO2_card	cardboard*1.01	197				
energy	cardboard*21.29+PE_energy	5.98E003				
PE_energy	25.2*72.3	1.82E003				

Inputs (Show all flows)

Parameter	Flow	Quantity	Amount	Unit
PE_energy	Electricity [Electric power]	Energy (gross calorific value)	9.86	MJ
	ntp plug conditioned [Plastics]	Mass	7.82	kg
	Polyethylene-film (PE) [Plastic parts]	Mass	0.137	kg
cardboard	Cardboard (packaging) [Materials from rer	Mass	1.06	kg

Outputs (Show all flows)

Parameter	Flow	Quantity	Amount	Unit	Tracked flows
	Cargo [Others]	Mass	9.01	kg	X
CO2_card	Carbon dioxide [Inorganic emissions to air]	Mass	1.07	kg	

Figure A: 8 – Gabi parameters, inputs, and outputs for packaging (1000 plugs)

Inputs (Show all flows)

Parameter	Flow	Quantity	Amount	Unit
	Cargo [Others]	Mass	9.01	kg

Outputs (Show all flows)

Parameter	Flow	Quantity	Amount	Unit	Tracked flows
	ntp plug conditioned [Plastics]	Mass	7.82	kg	X
	Cardboard [Consumer waste]	Mass	1.06	kg	*
	Polyethylene (PE, unspecified) [Consumer waste]	Mass	0.137	kg	*

Figure A: 9 – Gabi parameters, inputs, and outputs for plug use (1000 plugs)

Free parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
ntp		1.44E003			0 %	

Fixed parameters

Parameter	Formula	Value	Minimum	Maximur	Standar	Commer
BOD	ntp*0.005	7.22				
CO2_total	E_and_G_em+volatile_em	218				
coal_co2	coal_elec*.09788	127				
coal_elec	ntp*.898	1.3E003				
E_and_G_em	ntp*(0.1219+0.0214)	207				
gas	ntp*2.26	3.26E003				
gas_elec	ntp*0.323	466				
hydro	ntp*0.441	637				
TKN	ntp*0.0009	1.3				
total_co2_coal	(ntp*0.1219)+coal_co2	303				
total_elec	gas_elec+hydro	1.1E003				
volatile_em	0.0078*ntp	11.3				

Inputs Show all flows

Parameter	Flow	Quantity	Amount	Unit
total_elec	Electricity [Electric power]	Energy (net calorific value)	5.97	MJ
ntp	ntp plug conditioned [Plastics]	Mass	7.82	kg
gas	Natural gas New Zealand [Natural gas (re	Energy (gross calorific value)	17.7	MJ

Outputs Show all flows

Parameter	Flow	Quantity	Amount	Unit	Tracked flows
CO2_total	Carbon dioxide [Inorganic emissions to air]	Mass	1.18	kg	

Figure A: 10 – Gabi parameters, inputs, and outputs for rendering (1000 plugs)