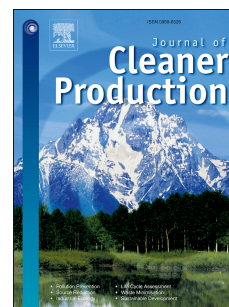


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# A life cycle assessment data analysis toolkit for the design of novel processes – A case study for a thermal cracking process for mixed plastic waste

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## Abstract

The earlier in the development of a process a design change is made, the lower the cost and the higher the impact on the final performance. This applies equally to environmental and technical performance, but in practice the environmental aspects often receive less attention. To maximise sustainability, it is important to review all of these aspects through each stage, not just after the design. Tools that integrate environmental goals into the design process would enable the design of more environmentally friendly processes at a lower cost. This paper brings together approaches based on Life Cycle Assessment (LCA) including comparisons of design changes, hotspot analysis, identification of key impact categories, environmental break-even analysis, and decision analysis using ternary diagrams that give detailed guidance for design while not requiring high quality data. The tools include hotspot analysis to reveal which unit operations dominate the impacts and therefore should be the focus of further detailed process development. This approach enables the best variants to be identified so that the basic design can be improved to reduce all significant environmental impacts. The tools are illustrated by a case study on the development of a novel process with several variants: thermal cracking of mixed plastic waste to produce a heavy hydrocarbon product that can displace crude oil, naphtha, or refinery wax or be used as a fuel. The results justified continuing with the development by confirming that the novel process is likely to be a better environmental option than landfill or incineration. The general approach embodied in the toolkit should be applicable in the development of any new process, particularly one producing multiple products.

## Highlights

- A simple LCA toolkit has been developed for application to process design
- The toolkit was applied to a case study: thermal cracking of plastic waste
- The improved process has a better environmental performance than the alternatives
- The toolkit can be applied generally in the development of new processes

## Keywords

Life Cycle Assessment, Process Design, Pyrolysis, Plastic waste, Thermal cracking.

## Abbreviations

Term	Explanation
<b>ADP (elements)</b>	Abiotic Depletion Potential based on the use of Elements
<b>ADP (fossil)</b>	Abiotic Depletion Potential based on the use of Fossil resources
<b>AP</b>	Acidification Potential
<b>EP</b>	Eutrophication Potential
<b>FAETP</b>	Freshwater Aquatic Eco-toxicity Potential
<b>GCV</b>	Gross Calorific Value
<b>GWP</b>	Global Warming Potential
<b>HTP</b>	Human Toxicity Potential
<b>LCA</b>	Life Cycle Assessment
<b>MAETP</b>	Marine Aquatic Eco-toxicity Potential
<b>NCV</b>	Net Calorific Value
<b>ODP</b>	Ozone Layer Depletion Potential
<b>POCP</b>	Photochemical Ozone Creation Potential
<b>RT700</b>	The 1/10 scale pilot plant under construction by Recycling Technologies Ltd
<b>RT7000</b>	The commercial scale plant under construction by Recycling Technologies Ltd
<b>SCR</b>	Selective catalytic reduction
<b>SME</b>	Small and Medium sized Enterprise
<b>TETP</b>	Terrestrial Eco-toxicity Potential

## Nomenclature

Symbol	Definition
$N$	Normalised LCA score
$W$	Weighting factor
$I$	LCA impact
$S$	Maximum value of rating scale
Subscripts	
$1$	For technology option 1
$2$	For technology option 2
$A$	For selected LCA impact category A
$B$	For selected LCA impact category B
$C$	For selected LCA impact category C
$i$	For option i
$H$	Highest impact in given LCA impact category
$L$	Lowest impact in given LCA impact category

## 1. Introduction

### 1.1. Life Cycle Assessment (LCA) in the Design Process

Life Cycle Assessment (LCA) is widely considered as the most powerful tool for assessing the environmental performance of a process or product (Clift et al., 2000; Sadhukhan et al., 2014). The concept behind LCA is “cradle-to-grave” assessment of the whole supply chain delivering a product or service. Life cycle thinking avoids the effect known as ‘burden shifting’ where decisions taken to improve one stage act to the detriment of performance in other life cycle stages (Baumann and Tillman, 2004).

This research addresses the use of LCA in process design. The benefits, concepts, and aims of integrating LCA into the design process are well discussed within the literature, see for example studies by Bhandar et al. (2003) and Morales-Mendoza et al., (2012). However, the design process is inevitably characterised by uncertainty (Toniolo et al., 2014). Collingridge (1980) went so far as to articulate the design paradox known as the Collingridge dilemma: at an early stage in a technological development there is wide scope for change but knowledge is sparse, but the possibilities narrow as more information becomes available. There is therefore an incentive to find tools that can be used early in a development when knowledge is limited. Some studies have argued that LCA can only be used appropriately for complete designs or late in the design process, otherwise the results will be compromised (Barton et al., 2002; Millet et al., 2006). Others have argued that environmental concerns should be introduced at the earliest possible stage in the design process, when changes are less difficult or costly to implement and can bring the largest potential environmental and economic benefits (Gasafi and Weil, 2011; Nielsen and Wenzel, 2002).

It has also been suggested that environmental management and the application of LCA are more important for smaller organisations than for larger ones (Hunkeler, 2003; Rebitzer et al., 2004): early consideration of environmental concerns in the design process is especially

important for Small and Medium Sized Enterprises (SMEs) or start-ups designing a new process, because unplanned or late changes may result in significant expenditure or difficulties with the allocation of resources (Rebitzer et al., 2004). However, this implies a need for a simple approach that can be used by non-specialists.

LCA is sometimes criticised for being time consuming, challenging to apply (Azapagic, 1999), or requiring expert knowledge so that it does not meet the needs of the design engineer (Millet et al., 2006), does not provide direct feedback or lacks the flexibility to adjust to design changes in the short term (Bhander et al., 2003). Despite these criticisms, some literature advocates the use of “sophisticated mathematical theories” (Chang et al., 2014) or complex data analysis approaches such as non-linear programming (Hanes and Bakshi, 2015) which are even more open to these criticisms and represent serious barriers to implementation, especially for SMEs and start-ups.

Thus, while they may be useful in decision-making processes in general, complex methodologies such as those presented by Fazeni et al., (2014) and Ribeiro et al., (2008) are not well adapted for informing the design process. This paper sets out the development of a toolkit to overcome the criticisms of complexity by bringing together a number of simple data analysis approaches that are easy to use, quick in application and offer maximum utility to the design engineer. Such a tool must be quick and straightforward so that it can be applied through the rapid changes that typically occur within the design process (Hetherington et al., 2014). Simulation using LCA software such as GaBi allows the LCA analysis to be modified faster (Spatari et al., 2001), so that it can be applied on a live basis with constant updating as design progresses or new data become available. Rather than being designed to support the decision making process itself, this approach uses LCA to provide information needed by the design engineer without significantly increasing the workload or requiring expertise beyond that of a LCA practitioner. The approach may be used in conjunction with the existing methodologies in the literature, rather than in place of them.

A number of concepts from the LCA literature have been brought together to form the toolkit. Designs are commonly developed by evaluation against a base case. Many examples of this can be found within the literature, including application to chemical process design (see for example, Azapagic, 1999 and Chen and Shonnard, 2004) and retrofit of existing processes (Blanco-Davis and Zhou, 2014). The base case can comprise an initial outline design; however, as design progresses, the most recent iteration becomes the new base case. The use of LCA software such as GaBi enables the environmental consequences of changes in the base design to be estimated quickly. Hotspot analysis, such as applied by Nielsen & Wenzel (2002), highlights the sources of emissions within the overall process, to identify where environmental improvements may be most effective. Additionally, once design is complete, the hotspots become of significant interest as targets for future optimisation as part of the usual “debottlenecking” process after construction. Finally, LCA is used in the context of the potential yields of the process to aid in the development of process targets.

## **1.2. Plastic Waste and Thermal Cracking**

The development of the toolkit is supported and illustrated by applying it to a specific process of current interest: recovering value from waste plastics by thermal cracking.

The plastics industry is a major part of the world economy, but the scale of this sector and the predominance of single use plastics mean that it is a major source of waste worldwide. Of the most commonly used plastics, none are biodegradable, resulting in an accumulation in landfill and the natural environment amounting to 60% of all plastics produced to 2015 (Geyer et al., 2017). Globally, 322 million tonnes of plastic were produced in 2015 with a growing trend (PlasticsEurope, 2016). Plastic demand in Europe was 49 million tonnes in 2015 with demand in the UK making up 7.5% of this figure (circa 3.7 million tonnes). An estimated 50% of plastic produced is used in single-use disposable items (Hopewell et al., 2009) with service lives of a year or less (Al-Salem et al., 2010).

Over 90% of the current manufacture of plastic derives from fossil hydrocarbons (World Economic Forum et al., 2016). Single use followed by disposal therefore represents a lost opportunity for reducing fossil fuel usage and deriving utility from the material to improve sustainability. The maximum amount of plastic waste that can be sorted and mechanically recycled is estimated to be 29-45% (Denkstatt, 2014). This leaves 55-71% remaining as mixed waste for which there are limited opportunities for re-use. Globally, 40% of all plastic waste is landfilled (World Economic Forum et al., 2016) and represents a significant source of chemicals leached into the environment (see Teuten et al., (2009) for a detailed review). According to PlasticsEurope (2015), if landfilling of plastics can be eliminated in Europe by 2025, there is a potential cumulative saving of 60 million tonnes of plastic waste by 2037; equivalent to 750 million barrels of oil.

Globally, 32% of plastic produced is estimated to escape collection altogether (World Economic Forum et al., 2016). A significant quantity of this ultimately reaches the ocean where it creates severe environmental problems, including entanglement and ingestion (Gregory, 2009), and concentration of persistent organic pollutants (Teuten et al., 2009). To the point that some authors have called for plastics to be classified as hazardous to the environment (Rochman et al., 2013). The most recent estimation is that between 4.8 and 12.7 million tonnes of plastics entered the oceans in 2010; the flow continues to rise (Jambeck et al., 2015), and, in the absence of effective action, is projected to equal the total mass of fish by 2050 (World Economic Forum et al., 2016).

New processes to recover value from mixed plastic waste are needed to combat these problems. One possibility is thermal cracking; this is the case study used to illustrate the methodological development set out here. The specific process considered is under development by Recycling Technologies Ltd., using low severity thermal cracking in an oxygen-starved atmosphere with the goal of processing plastic streams that cannot be sorted or mechanically recycled. Other processes that apply thermal cracking to plastics, such as those described by Perugini et al. (2005) and Shonfield (2008), yield hydrocarbon products in the diesel or gasoline range, as well as naphtha and aromatics.; The processes examined by Perugini et al. (2005) and Shonfield (2008) include pre-sorting of plastics. By contrast the feedstock for the Recycling Technologies process is a mixed plastic waste and the target product is a heavy hydrocarbon analogous to refinery wax or Heavy Fuel Oil (HFO); the process can also be operated to produce a substitute for Light Fuel Oil (LFO) or natural gas. Although no reported process is exactly comparable to the Recycling Technologies process, it is similar to thermal cracking of



feeds such as biomass (Zhong et al., 2010), tyres (Li et al., 2010) and municipal waste (Al-Salem et al., 2014).

LCA studies assessing thermal cracking as a method for processing mixed plastic waste are relatively scarce in the literature (Astrup et al., 2015). Examples of such studies include Mølgaard (1995); Perugini et al. (2005); Shonfield (2008); and Al-Salem et al. (2014); however, Mølgaard (1995) analyses a high temperature pilot process, Perugini et al. (2005) and Al-Salem et al. (2014) examine the BP thermal cracking process while Shonfield (2008) assesses two different thermal cracking plants including the BP design. LCA studies performed on one thermal cracking plant are not transferrable to another due to significant differences between processes and products. By its very nature, waste is a highly variable feed stream, and differing feeds will result in differing chemical products Pinto et al. (1999) and López et al. (2011) provide examples of such effects by analysing various feed mixtures and comparing their compositions. Al-Salem et al. (2017) and Lopez et al. (2017) review the effects of feed composition and process conditions on the division between solid, liquid and gaseous products. Thus the conclusions from other published studies cannot be carried over to the Recycling Technologies process. A new LCA study has therefore been carried out as part of this work.

## 2. Methodology of Toolkit

The Toolkit consists of a set of techniques that can be effectively applied in early stage design without requiring high data quality. The flow chart in Figure 1 shows how this new toolkit may be applied to any new process during development. The process is iterative as design itself is an iterative process. It can also be applied to a wide range of processes.

*Figure 1: Flow chart of the toolkit along with the major outputs. Sections where the elements of the flowchart are discussed are shown on the diagram*

Cradle to grave LCA is the key component of the toolkit because it forms the basis for all further analysis. The LCA is performed during design, rather than post-hoc as is more common with LCA (see section 1.1). It starts with an LCA of the initial design and is then updated progressively with each prospective design change. The final LCA is carried out on the completed design when the design is frozen. Following the ISO standards (ISO 14040, 2006; ISO 14044, 2006), the LCA comprises four phases: Goal and Scope Definition, Inventory Analysis, Impact Assessment and Interpretation.

- Goal and Scope Definition – The research question is translated into a set of goals and objectives that define the study. The limits of the study, functional units and system boundaries are set, to define what processes are and are not included in the analysis.
- Inventory Analysis – The system diagram from the goal and scope stage is refined. Input and output mass and energy flows are obtained from design data together with test data as they become available; in this specific case, they were obtained from Recycling Technology's laboratory scale rig. Inventory data are then collated for all the input and output flows; in this specific case, they were obtained from EcoInvent 3.0
- Impact Assessment – Data from the Inventory Analysis are processed to express the results in terms of contributions to a recognised set of environmental impacts.

- Interpretation – This phase permeates the entire assessment; in this application of LCA, it is embodied in the progressive reviews of the design strategy and detailed approaches. The process is iterative as interpretation highlights aspects of the design requiring improvement, or those that should be examined further.

### 3. Case Study

#### 3.1. System Boundaries

System boundaries for this study were defined based on the general recommendations by (Baumann and Tillman, 2004) in order to ensure completeness and transparency (Table 1).

*Table 1: System Boundary Considerations*

<b>System Boundary Consideration</b>	<b>Application to this Study</b>
<b>Location</b>	UK. Therefore UK data are used where possible, supplemented where necessary by data from other countries, preferably within Europe.
<b>Interactions with neighbouring systems</b>	Some feeds and wastes have their own life cycle impacts. These are included, but the plastic waste input is assumed to have zero burden, following Clift et al. (2000). The multifunctional nature of this process necessitates the use of system expansion to avoid allocation wherever possible (see section 3.2).
<b>Time Horizon</b>	Defined by CML (Guinée et al., 2002; Oers, 2015): 100-year environmental impact used for GWP; time horizon for toxicity categories is infinite.
<b>Time/Date</b>	Inventory data were obtained from EcoInvent version 3, which includes data up to the year 2013.
<b>Inclusion of capital goods</b>	Capital goods are not included.
<b>Technological</b>	The RT7000 thermal cracking process including material preparation and product usage.

The RT700 is a 1/10 scale pilot plant capable of processing 100 kg/h (dry basis) of mixed plastic waste to produce a waxy hydrocarbon product to be traded under the name 'Plaxx™'. The RT700 has been operated to provide data and experience to guide the design of the commercial RT7000 which will be capable of processing 1000 kg/h. The initial design for the RT7000, shown in figure 2, was a direct scale up of the RT700 (Recycling Technologies Ltd, 2017). Figure 2 also shows the modifications implemented in the design of the RT7000 following application of the toolkit, as set out in section 4.2. It also shows the expanded systems used to account for the Plaxx™ product; as explained in section 3.2.



*Figure 2: Initial and modified designs for the RT7000 commercial plant (Recycling Technologies Ltd, 2017) – Numbers 1-4 represent changes to the initial design, discussed in Table 6. A and B show the system expansions for recycling and fuel applications respectively*

The Recycling Technologies process is compared against two alternatives for treatment of mixed plastic waste: direct incineration to produce electricity displacing energy from the UK grid (represented by the average UK generating mix) and simple landfilling. The environmental impacts of these processes were described by aggregated data from GaBi version 6, based on EcoInvent version 3, derived from Doka, (2003). Swiss data were used in the absence of GB and EU data. for the emissions from incineration and landfilling and for some minor inputs. CHP processes, with heat as well as power output, have very low penetration in the UK and were therefore not considered. For direct incineration, Doka (2003) suggests a typical NCV of mixed plastic of 30.79 MJ/kg (GCV = 34.05 MJ/kg). Also, following Doka (2003), the plastic is assumed to have 15.3% moisture content, with a thermal efficiency of incineration between 15 and 22% based on NCV (Smith et al., 2001). Doka, (2003) models short-term emissions from landfilling over a 100 year timescale, including landfill gas combustion (without energy recovery) and the treatment of landfill leachate. Doka, (2003) also models long term emissions, over a 60,000 year time horizon, to allow for possible failure of landfill liners and containment, but the analysis here only considers the 100-year horizon, consistent with the time-scale over which global climate effects are considered.

### **3.2. Assumptions and Cut-off Criteria**

This LCA is conducted in advance of construction and is thus predictive, based primarily on design data supported by results from the RT700 pilot plant. Assumptions are necessary to fill in missing or incomplete data; the sensitivity of the final results to these data are analysed. The range of feed compositions to a commercial plant cannot yet be defined. This case study is based on an assumed composition for the pyrolysis product representative of that obtained from mixed plastic rich in polyethylene; feed composition is not a design variable and therefore variations in feed composition are not explored. A further study using data from a more detailed process simulation will address this issue.

In order for comparisons to be drawn with alternative waste management technologies, the functional unit for this study is 1 tonne of generic, dry plastic waste processed in the UK in 2015. Plastic waste feed is assumed to start accumulating burdens only from the gate of the Recycling Technologies process; see Clift et al. (2000) and Ekvall et al. (2007) for the rationale behind this assumption. The relatively small-scale process is designed to be located at a site of waste generation or collection; transport from the site is therefore nugatory and is not included in the analysis.

System expansion using the avoided burdens approach to account for the use of co-products (including energy), was used to account for the multiple functions of the process. This approach is described by a number of sources with various terminologies (Azapagic and Clift, 1999; Baumann and Tillman, 2004; Clift et al., 2000; Ekvall and Finnveden, 2001; Eriksson and Bisailon, 2011; Tillman et al., 1994) . Its value lies in simplifying the analysis to retain a single functional unit: the primary product or service. However, it may not avoid some degree of

allocation as the sub-processes included by system expansion may themselves be multifunctional (Azapagic and Clift, 1999). Following Clift et al. (2000), the approach can be summarised as:

$$LC\ Impacts = Direct\ and\ Indirect\ Impacts - Avoided\ Impacts$$

Plaxx™ is intended to be a multipurpose product with both material recycling and energy applications. The specifications of the Plaxx™ product enable it to replace refinery wax, naphtha for plastic manufacture, and crude oil as a refinery feed. For these applications, it is assumed that Plaxx™ is functionally identical to the displaced product so that 1kg of Plaxx™ replaces 1kg of the material. Plaxx™ can also be used as a direct substitute for another fuel, particularly Heavy Fuel Oil (HFO), but possibly also Light Fuel Oil (LFO) or natural gas. In these cases, Plaxx™ is assumed to replace the conventional fuel in an engine with Selective Catalytic Reduction (SCR) of NO<sub>x</sub> on an equivalent energy (GCV) basis. The low sulphur content of plastic used as feed leads to a low-sulphur product: testing of the product Plaxx™ from the pilot plant indicates that it contains approximately 0.02% sulphur. In the inventory analysis, the sulphur is assumed to combust fully to form SO<sub>2</sub>. Average technology mixes for landfill and incineration were also investigated as reference technologies for plastic waste disposal – see section 3.1.

The impact categories and associated characterization factors defined by CML (Oers, 2015) have been selected as they cover a broad range of primary environmental impacts and are in widespread use (Sadhukhan et al., 2014). As noted in section 1.2, over 90% of plastics originate from fossil sources (World Economic Forum et al., 2016). Biogenic carbon in the material input to thermal cracking is therefore assumed to be zero and the category GWP (Excluding Biogenic Carbon) is therefore not included.

## 4. Application of LCA Toolkit to Case Study

### 4.1. Evaluation of Product Scenarios

LCA is conventionally used to compare environmental impacts between different ways to provide a product or service and with alternative technologies. This stage in the toolkit is iterative and repeated for each design or product change, as shown in figure 1. The modifications between the initial and final designs of the RT7000, shown in figure 2, are discussed in detail in section 4.2. We start here with the comparison between different uses of the Plaxx™ product; the associated Life Cycle impacts for the initial and final designs of the RT7000 process are summarised in Table 2 and compared with the two conventional waste processing alternatives. Negative values represent a net environmental benefit; i.e. the burdens arising from the process itself are less than the environmental credit from the product.

Table 2: LCA impacts for the initial and final RT7000 designs with comparative values for Incineration and Landfill; all values per tonne of dry mixed plastic waste processed

	Use/Disposal Phase Scenarios							Alternatives	
	RT7000 Design	Wax	Naphtha	Crude	HFO	LFO	Gas	Incineration	Landfill
ADP elements [g Sb-Equiv.]	Initial	0.56	0.56	0.57	0.85	0.85	0.86	0.37	0.02
	Final	<b>0.54</b>	<b>0.54</b>	<b>0.54</b>	<b>0.84</b>	<b>0.83</b>	<b>0.85</b>		
ADP fossil [GJ]	Initial	-33.3	-32.8	-28.2	-31.8	-33.9	-30.5	-14.9	0.35
	Final	<b>-39.5</b>	<b>-39.1</b>	<b>-34.5</b>	<b>-38.1</b>	<b>-40.2</b>	<b>-36.8</b>		
AP [kg SO <sub>2</sub> -Equiv.]	Initial	-1.10	1.22	2.14	-7.57	3.20	8.51	-2.71	0.28
	Final	<b>-2.55</b>	<b>-0.23</b>	<b>0.69</b>	<b>-8.91</b>	<b>1.85</b>	<b>7.17</b>		
EP [kg Phosphate-Equiv.]	Initial	0.70	0.83	0.87	1.33	1.35	2.42	-0.46	7.43
	Final	<b>0.26</b>	<b>0.38</b>	<b>0.43</b>	<b>0.91</b>	<b>0.93</b>	<b>2.00</b>		
FAETP inf. [tonne DCB-Equiv.]	Initial	0.10	0.10	0.11	0.10	0.12	0.12	0.91	1.68
	Final	<b>0.06</b>	<b>0.06</b>	<b>0.06</b>	<b>0.05</b>	<b>0.07</b>	<b>0.07</b>		
GWP 100 years [tonne CO <sub>2</sub> -Equiv.]	Initial	0.46	0.95	1.14	0.80	0.80	1.57	1.78	0.10
	Final	<b>-0.09</b>	<b>0.40</b>	<b>0.59</b>	<b>0.29</b>	<b>0.30</b>	<b>1.07</b>		
HTP inf. [tonne DCB-Equiv.]	Initial	0.02	0.08	0.11	-0.12	0.13	0.17	0.57	0.60
	Final	<b>-0.04</b>	<b>0.03</b>	<b>0.05</b>	<b>-0.17</b>	<b>0.07</b>	<b>0.12</b>		
MAETP inf. [megatonne DCB-Equiv.]	Initial	0.43	0.44	0.44	0.35	0.47	0.51	0.35	1.57
	Final	<b>0.18</b>	<b>0.19</b>	<b>0.20</b>	<b>0.10</b>	<b>0.23</b>	<b>0.26</b>		
ODP, steady state [mg R11-Equiv.]	Initial	21.1	21.1	21.1	33.1	33.1	33.1	-19.2	3.57
	Final	<b>6.02</b>	<b>6.03</b>	<b>6.03</b>	<b>18.2</b>	<b>18.2</b>	<b>18.2</b>		
POCP [kg Ethene-Equiv.]	Initial	-0.56	-0.11	0.07	-0.44	-0.03	0.38	-0.13	0.03
	Final	<b>-0.66</b>	<b>-0.21</b>	<b>-0.03</b>	<b>-0.54</b>	<b>-0.12</b>	<b>0.28</b>		
TETP inf. [kg DCB-Equiv.]	Initial	-8.31	2.57	4.59	-3.65	3.32	5.66	-0.65	0.96
	Final	<b>-8.78</b>	<b>2.10</b>	<b>4.12</b>	<b>-4.10</b>	<b>2.86</b>	<b>5.20</b>		

As is common in LCA studies, no scenario shows the best performance in all categories. The scenarios can be ranked from best to worst in each impact category, but this does not really convey the nature and extent of the differences between scenarios. Table 3 shows an alternative approach where the impacts for the final plant design with the different product scenarios are reported on a linear 1-100 scale where 1 represents the best option and 100 represents the worst. The ratings were determined according to the following method.

$$\text{Rating of option } i = [(I_i - I_L)(S - 1)/(I_H - I_L)] + 1 \quad (1)$$

where  $I$  represents an LCA impact,  $S$  is the maximum value of the scale (in this case 100), and subscripts  $L$  and  $H$  indicate the lowest and highest impacts in the given impact category.

Table 3: Ratings of LCA impacts for RT7000 final design with alternative product scenarios

	RT7000 Use/Disposal Phase Scenarios						Alternatives	
	Wax	Naphtha	Crude	HFO	LFO	Gas	Incineration	Landfill
ADP elements	63	63	64	99	99	100	43	1
ADP fossil	3	4	15	6	1	9	63	100
AP	40	54	60	1	67	100	39	58
EP	10	12	12	18	18	32	1	100
FAETP inf.	1	1	1	1	2	2	54	100
GWP 100 years	1	27	37	22	22	62	100	11
HTP inf.	18	26	30	1	32	38	95	100
MAETP inf.	6	7	8	1	10	12	18	100
ODP, steady state	68	68	68	100	100	100	1	61
POCP	1	48	67	13	57	100	56	73
TETP inf.	1	78	92	34	83	100	59	70

Although the results shown in Table 2 and the scaled results shown in Table 3 are useful, their significance is unclear without a frame of reference.

#### 4.1.1. Normalisation

Normalisation aids interpretation by highlighting the impact categories with the greatest significance. Each impact is expressed as a fraction of the total impact arising from some body of economic activities (Figure 1). In this work, impacts from the specific process system were normalised against the total impacts for Western Europe (Oers, 2015), with data for 1995 used as the baseline, as recommended by CML (Oers, 2015).

The normalised results for the final design of the RT7000 plant with different product scenarios are shown in Table 4. The most significant impacts are fossil Abiotic Depletion Potential (ADP - fossil), Freshwater Aquatic Eco-toxicity Potential (FAETP), and Marine Aquatic Eco-toxicity Potential (MAETP). The least significant impacts are elemental Abiotic Depletion Potential (ADP - elements), Ozone Depletion Potential (ODP) and Human Toxicity Potential (HTP). Other categories, including Global Warming Potential (GWP), are of intermediate significance. It is of note that MAETP dominates the normalised life cycle impacts by a large margin. However, MAETP normalisation is currently subject to debate with the result of normalisation considered contentious due mainly to problems in modelling the fate and impacts of metals and other persistent pollutants (Heijungs et al., 2007). MAETP is included here for completeness, but in view of this uncertainty, it is not treated as an important category influencing the process development.

Table 1: Normalised LCA results for final RT7000 design expressed as a percentage of EU impacts

Percentage of one billionth of 1995 EU impacts [%/tonne]	Wax	Naphtha	Crude	HFO	LFO	Gas	Incineration	Landfill
ADP elements	0.65	0.66	0.66	1.01	1.01	1.02	0.46	0.03
<b>ADP fossil</b>	<b>-129</b>	<b>-128</b>	<b>-113</b>	<b>-124</b>	<b>-131</b>	<b>-120</b>	<b>-49.0</b>	<b>1.45</b>
AP	-9.38	-0.89	2.47	-33.0	6.33	25.76	-9.85	1.14
EP	1.98	2.94	3.32	6.84	6.99	15.36	-3.49	59.3
<b>FAETP inf.</b>	<b>10.9</b>	<b>11.3</b>	<b>11.5</b>	<b>10.2</b>	<b>13.7</b>	<b>14.0</b>	<b>186.1</b>	<b>340</b>
GWP 100 years	-1.97	8.12	12.0	5.05	5.15	20.9	37.7	2.23
HTP inf.	-0.58	0.33	0.68	-2.31	0.88	1.51	7.71	8.16
<b>MAETP inf.</b>	<b>158</b>	<b>167</b>	<b>173</b>	<b>85.9</b>	<b>200</b>	<b>231</b>	<b>328</b>	<b>1415</b>
ODP, steady state	0.01	0.01	0.01	0.02	0.02	0.02	-0.02	0.01
POCP	-7.96	-2.56	-0.36	-6.59	-1.56	3.37	-1.61	0.45
TETP inf.	-18.6	4.44	8.72	-8.70	6.02	10.97	-1.33	2.16

#### 4.1.2. Key Categories

For further analysis, it is useful to focus on the categories revealed as most significant and open to the greatest improvement by the normalised results in Table 4, guided by consideration of the objectives of the Recycling Technologies process to reduce the problems caused by waste plastics. The three most significant categories are shown in Table 5 along with the reasons for their selection.

Table 5: Selected Categories &amp; Justification

<b>ADP (fossil)</b>	Reduction of fossil fuel usage and recovery of hydrocarbons from waste is a main goal of the process; therefore it is appropriate to include this category. Normalisation confirms that it is also one of the most significant categories.
<b>FAETP inf.</b>	Plastic waste has a significant impact on water systems: FAETP is one of the most significant normalised categories and was selected to represent aquatic toxicity.
<b>GWP 100 Years</b>	GWP is a significant public concern and political issue. Including GWP is therefore essential for the credibility of the analysis.

ADP (fossil) is a category where the final design of the RT7000 performs well: Table 4 shows that Plaxx<sup>TM</sup> recovery provides a significant reduction in fossil resource depletion. Using Plaxx<sup>TM</sup> as a substitute for LFO gives the greatest improvement in this category, whilst use as wax or naphtha substitute are comparable. The final design of the RT7000 process also shows a significant reduction in FAETP impact across all scenarios compared to both Incineration and Landfill; with the greatest reduction in FAETP obtained by using the Plaxx<sup>TM</sup> as a HFO substitute. The process also performs well in the GWP category, especially when compared to

Incineration. Use of Plaxx<sup>TM</sup> as a substitute for wax is particularly beneficial, with a net environmental benefit.

## 4.2. Analysis of Design Changes

The RT7000 is still under development, with the RT700 pilot plant being used to guide the development and form the basis for the initial RT7000 design. Possible process modifications with potential to improve performance are summarised in Table 6 and shown in Figure 1. LCA impacts from the initial and final designs for the RT7000 designs are given in Table 2.

*Table 6: List of design modifications proposed for incorporation in the RT7000 initial design to form the final design*

ID	Description
<b>Initial RT700</b>	Direct scale up of the RT700 flow scheme without modification, the initial RT7000 design.
<b>1</b>	Heat integration in the drier, replacing LPG as the energy source
<b>2</b>	Heat integration on the thermal cracker, to use fluidisation gases to replace the electric heater
<b>3</b>	Use of by-product light hydrocarbon gas product instead of LPG in the regenerator preheat burner
<b>4</b>	Use of by-product light hydrocarbon gas product instead of LPG in the regenerator
<b>1+2</b>	Full heat integration: combination of options 1 and 2
<b>3+4</b>	Full use of light hydrocarbon gas product: combination of options 3 and 4
<b>Final RT7000</b>	Proposed final design for RT7000 commercial plant (1+2+3+4)

The LCA results for these modifications and savings compared to the initial design for the RT7000 are shown in Table 7 with the key categories, identified in section 4.1.2, shown in bold. The modifications investigated at this stage in the design do not affect the yield or composition of the product, so the analysis has been conducted on a gate-to-gate basis without system expansion; for any modifications that may affect the products or inputs or later life cycle stages, the evaluation would have to be on a full life cycle basis.



Table 7: Reductions in LC impacts resulting from modifications to the initial RT7000 design to the final design iteration (not including system expansion)

	Initial RT700	1	2	3	4	1+2	3+4	Final RT7000
ADP elements [%]	0.0	0.4	2.3	0.9	0.2	2.7	1.1	3.8
<b>ADP fossil [%]</b>	<b>0.0</b>	<b>13.7</b>	<b>41.3</b>	<b>7.0</b>	<b>3.9</b>	<b>54.9</b>	<b>10.9</b>	<b>65.8</b>
AP [%]	0.0	0.3	29.4	8.3	14.3	29.7	22.6	52.2
EP [%]	0.0	0.9	30.3	5.9	11.6	31.2	17.6	48.8
<b>FAETP inf. [%]</b>	<b>0.0</b>	<b>0.2</b>	<b>39.3</b>	<b>1.7</b>	<b>3.7</b>	<b>39.5</b>	<b>5.3</b>	<b>44.8</b>
<b>GWP 100 years [%]</b>	<b>0.0</b>	<b>7.7</b>	<b>19.1</b>	<b>3.6</b>	<b>13.8</b>	<b>26.8</b>	<b>17.5</b>	<b>44.3</b>
HTP inf. [%]	0.0	0.2	37.6	2.6	4.5	37.8	7.1	44.9
MAETP inf. [%]	0.0	0.1	46.4	1.6	4.3	46.5	5.9	52.5
ODP steady state [%]	0.0	14.9	28.3	25.7	2.6	43.2	28.3	71.5
POCP [%]	0.0	1.1	29.6	10.3	15.6	30.7	25.9	56.6
TETP inf. [%]	0.0	0.1	5.5	0.8	0.5	5.6	1.3	6.9

Modification 2 gives the largest reductions across all impact categories, so it is clear that this option is the first to be recommended for incorporation into design of the RT7000. In order of priority:

- Modification 2: Replace the electrical heater on the reactor fluidisation gases with a heat exchanger heated by the flue gases. This saves electrical power and increases energy recovery and efficiency.
- Modification 3: Switch the preheat burner from LPG to light hydrocarbon gas product. This saves LPG and reduces the overall direct emissions from the plant by reducing light hydrocarbon gas product wastage.
- Modification 4: Switch the regenerator fuel gas from LPG to light hydrocarbon gas product. This saves LPG and reduces the overall direct emissions from the plant by reducing light hydrocarbon gas product wastage.
- Modification 1: Utilise flue gases to heat the drier instead of LPG. This saves LPG and eliminates direct emissions from combustion in this unit.

#### 4.2.1. Hotspot Analysis & Key Process Units

Following implementation of these changes, there is likely to be scope for further improvements. As shown in Figure 1, hotspot analysis is used following identification of the key impact categories to give a breakdown of where the majority of impacts arise in the process, enabling areas for further possible improvements to be identified. Figure 3 shows a breakdown of the environmental impacts arising from different components of the final RT7000 (Figure 2).

Figure 3: Environmental impact contributions associated with the RT7000

The hotspot analysis reveals four areas of concern: the regenerator, the preheater, product purification and the sand transfer system. The regenerator and preheater were expected to make a significant contribution to energy consumption as they represent the main energy demand to sustain the thermal cracking reaction. However, the latter two were less obvious; the significance

of sand transfer in particular was unexpected. More detailed analysis revealed that the impacts arise primarily from consumption of nitrogen gas used for cleaning and of bicarbonate for neutralisation of any acid gases created. The main source of impacts for the sand transfer system is also nitrogen consumption in the L-valve to control the rate of transfer. This leads to a recommendation to the designers of the RT7000 that use of nitrogen should be reviewed and replaced by another gas with less environmental impact if possible.

#### 4.2.2. Decision Analysis

Decisions which require trade-offs between different impacts require assessment of their relative significance. In the toolkit introduced in this paper, this decision analysis is applied following the identification of the principal design changes which do not involve trade-offs (see Figure 1). In the specific case of the Recycling Technologies process, trade-offs between different impacts must be considered in deciding the best use of the Plaxx™ product and in comparing the process with conventional approaches to managing plastic waste.

Normalisation expresses the impact estimates in dimensionless form, so that their relative importance can be expressed by assigning weights to the different impacts. This is a standard approach in multi-criterion decision analysis, which attempts to avoid subjectivity in assigning the weights by ensuring that they emerge from a structured process involving a range of stakeholders (see e.g. Elghali et al., 2008; Seppälä et al., 2001). However, it is impracticable to hold a structured decision conference for every process design. Instead, the toolkit deploys an approach proposed by Hofstetter et al. (2000) that enables graphical representation across the entire range of weighting possibilities provided that the number of performance parameters (in this case, normalised impacts) to be traded-off is as small as three (Figure 1). All weighting choices are represented on a ternary diagram where a total weighting of 1.0 is allocated between the three different normalised LCA categories. The ternary diagram is used to show “lines of equivalence” or “indifference lines” where the weightings are such that the overall weighted scores are identical for two options so that neither is preferred over the other. This gives a clear display of the ranges of weights over which one of the three options emerges as preferred.

The line of equivalence for each pair of scenarios is calculated according to the method set out by Hofstetter et al. (2000). The three chosen performance criteria are denoted by subscripts  $A$ ,  $B$  and  $C$  and the two options by subscripts 1 and 2. The normalised scores and weighting factors are denoted by  $N$  and  $W$  respectively. The total of the weights assigned to the three impacts is unity; i.e.

$$W_A + W_B + W_C = 1 \quad (2)$$

The total performance score for a given option is:

$$LCA\ Score = W_A N_A + W_B N_B + W_C N_C \quad (3)$$

A line of equivalence intercepts a side of the triangular diagram when the weighting factor attached to the criterion represented by the opposite apex is set to zero. The resultant equations for the intercepts are as follows:

$$\text{Intercept on the AB side: } W_A = (N_{B1} - N_{B2}) / (N_{B1} - N_{B2} + N_{A2} - N_{A1}) \quad (4)$$

$$\text{Intercept on the BC side: } W_B = (N_{C1} - N_{C2}) / (N_{C1} - N_{C2} + N_{B2} - N_{B1}) \quad (5)$$

$$\text{Intercept on the AC side: } W_C = (N_{A1} - N_{A2}) / (N_{A1} - N_{A2} + N_{C2} - N_{C1}) \quad (6)$$

This set of equations applies to every pair of options selected for presentation on the ternary diagrams. The equivalence lines are formed by joining the points where they intersect adjacent sides; if a value for  $W$  is negative or greater than unity, the equivalence line does not intersect with that side within the triangle. The areas bounded by the equivalence lines show the range of weights where a particular scenario is preferred. In this way, it becomes clear if any option is preferred over a wide range of relative weights.

Figures 4a and 4b show the resulting plots of data from Table 4 to reveal the best and worst options assessed against the three impact categories in Table 5. Three options are chosen for analysis in each diagram. Figure 4a presents the three options for the use of Plaxx™ with the lowest impacts in the three dominant categories, i.e. wax, HFO and LFO. Figure 4b presents the two options - Incineration and Landfill - scoring worst (i.e. highest) in each category, plus the Recycling Technologies option scoring worst - Gas - to provide the third scenario.

From Figure 4a, unless very high weight is attached to ADP (fossil) or FAETP with GWP given little significance, using the Plaxx™ to substitute for wax is preferred on the grounds of overall environmental impact. Use as LFO is only preferred if ADP is regarded as the impact of overriding importance. Similarly, use to substitute for HFO is only preferred if only the impact FAETP is considered overriding. From Figure 4b, landfill is generally the worst treatment for the plastic waste, although incineration is worst if GWP is considered to be the impact of overriding concern.

*Figure 4: Ternary diagrams based on the three selected impact categories: (a) best options (b) worst options*

Figure 5 shows the outcome of an alternative selection of impact categories, basing the decision on Acidification Potential (AP) in place of FAETP. From Figure 5a, giving equal weighting to all three impact categories leads to the conclusion that using Plaxx™ to substitute HFO is the best overall option whilst, from Figure 5b, landfilling the waste plastic remains the worst environmental option over a wide range of relative weights.

*Figure 5: Ternary diagrams based on the alternate selection of key impact categories: (a) best options (b) worst options*

Because these diagrams represent the three most important impact categories, the option that is favoured over the greatest area of the diagram has the greatest likelihood of being declared as 'best' on a random weighting of these categories. From Figure 5a, using Plaxx™ to replace wax has the greatest coverage and thus is most likely to emerge as the best option for a recycling application, this is reinforced by results introduced in section 4.2.3. Over a range of weightings for the four most important categories (Figures 5a and 5b), the worst options are clearly Landfill and Incineration.

### 4.2.3. Environmental Break-even Analysis

Finally, the tool-kit uses a form of break-even analysis to set out the performance targets that the process must meet to be viable (see Figure 1). In the specific case of the Recycling Technologies process, calculating the product yield at which the environmental impacts show improvement over alternative processes narrows down the acceptable operational envelope for the RT7000. The process is designed to achieve high yield and maximise product yield. However, if the yields identified by the environmental analysis cannot be achieved, then the whole project should be reviewed as it would represent an improvement over incineration.

The LCA analysis was repeated in the GaBi simulation using a number of potential product yields with the results analysed to identify the yields at which the LCA impacts of the RT7000 and Incineration were equal. For each of the key impact categories, the difference between the LCA impacts from the various use/disposal phase scenarios and that of incineration were plotted against the product yield. An example of such a plot, for GWP, is shown in Figure 6. For this case study, all these relationships were found to be linear. The environmental break-even points were identified as the yields at which thermal cracking in the RT7000 showed the same impact as incineration. The results are given in Table 8.

Figure 6: Example of Break-even point plot for some of the use/disposal phase scenarios in the case study

Table 8: Break-even compared to Incineration (to nearest percentage point)

	Wax	Naphtha	Crude	HFO	LFO	Gas
<b>ADP elements</b>	*	*	*	*	*	*
<b>ADP fossil</b>	42	43	47	43	42	45
<b>AP</b>	86	*	*	57	*	*
<b>EP</b>	*	*	*	*	*	*
<b>FAETP inf.</b>	**	**	**	**	**	**
<b>GWP 100 years</b>	40	46	49	45	45	59
<b>HTP inf.</b>	**	**	**	**	**	**
<b>MAETP inf.</b>	48	49	50	40	55	62
<b>ODP, steady state</b>	*	*	*	*	*	*
<b>POCP</b>	48	77	*	54	87	*
<b>TETP inf.</b>	41	*	*	59	*	*

\* – RT7000 performs worse across all yields

\*\* – RT7000 performs better across all yields

The yields required to break even in the three significant categories, ADP (Fossil), FAETP and GWP are relatively low, the highest being 59%. The lowest required yields are for Plaxx™ use as a wax substitute. These are rather modest values, confirming the potential environmental benefits of the Recycling Technologies process.

#### 4.2.4. Feedback to the RT7000 design process

The LCA results from the toolkit enabled the key environmental impacts arising from the Recycling Technologies process to be identified. This in turn enabled identification of design changes to improve the environmental performance of the process, and prioritisation of further improvements to be explored when the plant is operational. Furthermore, the results enable comparison against incineration to define targets for the performance of the process.

Identification of high impact process areas using hotspot analysis proved to be very useful, particularly where the results were unexpected. Nitrogen consumption is an example: it has been identified as a high priority whereas it was previously treated as a routine decision. As a result, alternative designs for the sand transfer system that eliminate reliance on nitrogen are now under development.

As a multifunctional product, Plaxx™ is capable of finding a number of applications. The powerful combination of the initial LCA, the selection of the key impact categories and decision analysis using ternary diagrams enabled the application with the highest benefits to be identified. This analysis informed the next iteration in the process design of the separation train of the RT7000, to optimise the recovery of the most beneficial product. It reinforced the decision to focus further design work upon production of heavier hydrocarbon products such as wax and HFO.

The yield of product from the RT7000 is expected to vary with the composition of waste plastic in the feed, as are the LCA impacts. The information provided from the toolkit showing the yields at which the process offers a net benefit over incineration demonstrates that the yields required to realise a net benefit are relatively low compared to those expected. The process may therefore be expected to be widely applicable to many existing mixed plastic streams. This information is of great interest to investors in Recycling Technologies

## 5. Application of the Toolkit to Other New Processes

The general procedures for design followed in the development of the Recycling Technologies process is common to all processes under development. Thus the general approach embodied in the toolkit should be applicable in the development of any new process, particularly a process producing multiple products. Therefore, benefits similar to those obtained in the case study can realistically be expected when the toolkit is applied to any other new process.

The benefits of a systematic approach to incorporating environmental considerations include the resultant change in design culture. Our experience in developing the Recycling Technologies process is that once the design team is aware of environmental issues and their possible quantification, they are motivated towards innovation to address them. However, if, for whatever reason, environmental issues cannot be addressed at the design stage, process operations identified by hotspot analysis as leading to high impacts become targets for optimisation during operation of the plant.

## 6. Conclusions

Consideration of environmental impacts early in design will allow cheaper and more sustainable processes to be designed. LCA is a powerful tool for evaluation of environmental impacts, but current approaches to data analysis are not well adapted for integration with the design process. Consequently, a quick and simple approach is needed that can produce useful feedback to designers without requiring high quality data or significant expertise.

The simple LCA toolkit presented in this paper was developed to overcome these challenges. The toolkit was designed for use in the design process and was successfully applied during the development of the Recycling Technologies RT7000 process for recovery of hydrocarbons from plastic waste. The use of the toolkit enabled early consideration of environmental concerns so that changes could be incorporated to improve the design of the RT7000. Comparing design changes using LCA enabled the most environmentally beneficial design changes to be identified. Application of the toolkit has resulted in an overall decrease in the expected emissions from the process. For example, GWP is reduced by 44% between the initial and final designs. The hotspot analysis tool was particularly useful because this analysis often highlights unexpected sources of emissions (nitrogen use in the specific case on the Recycling Technologies process). Awareness of such issues within the design team motivates them towards innovation.

If a design change that reduces environmental impact is not found, hotspots become areas where multivariable optimization that includes environmental performance is likely to be important. When such a design decision is needed, normalisation and representation using a ternary diagram can enable the most and least environmentally beneficial technologies to be identified across the entire range of possible weighting.

The results generated by these tools were found to give a clear picture of the likely environmental performance of the plant being designed (RT7000) and thereby enabled intervention in the early decision making processes of the design. The analysis also provided justification to continue with the development by confirming that the RT7000 thermal cracking process is a better environmental option than landfill or incineration across a range of relative weights.

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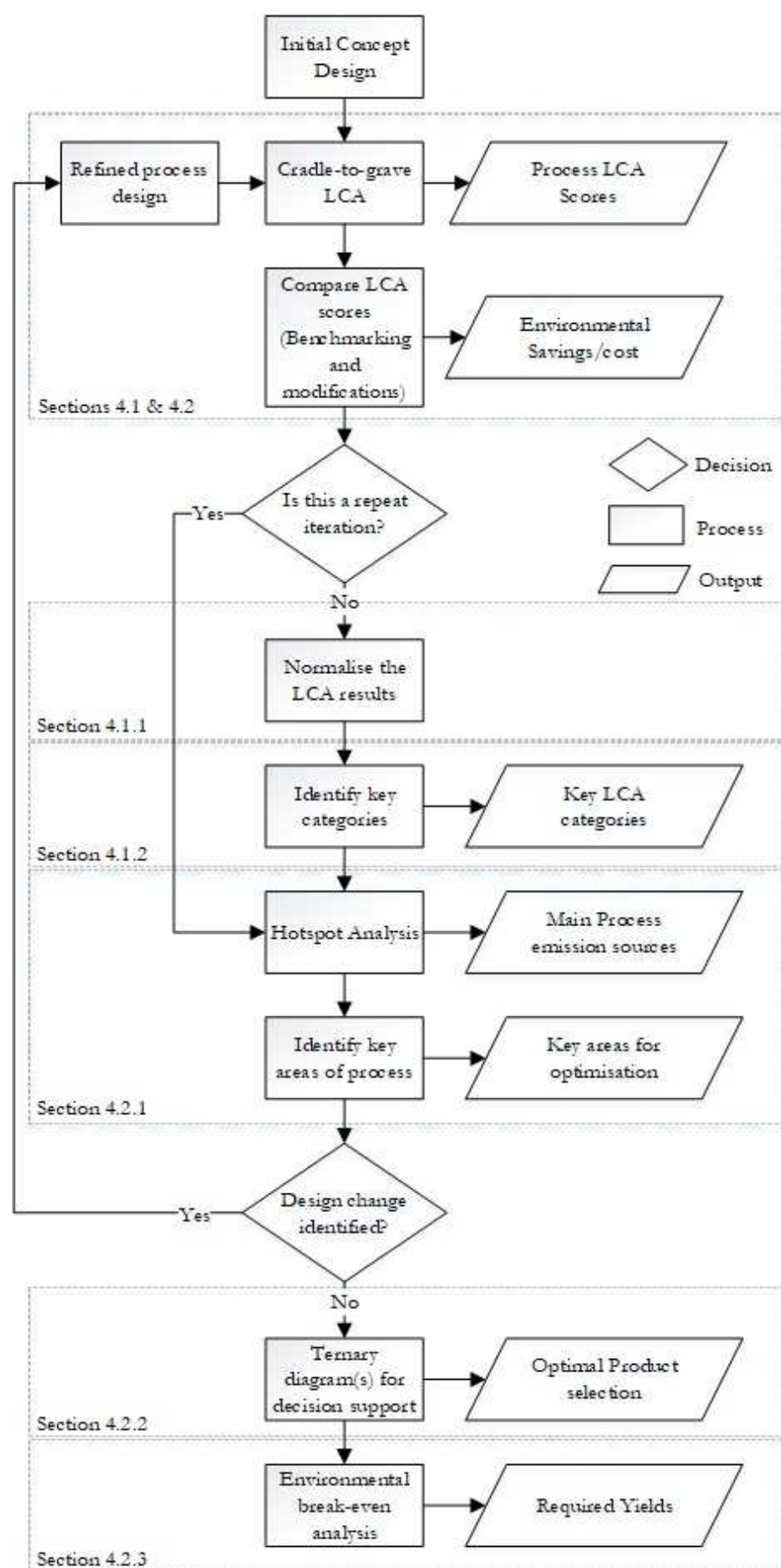


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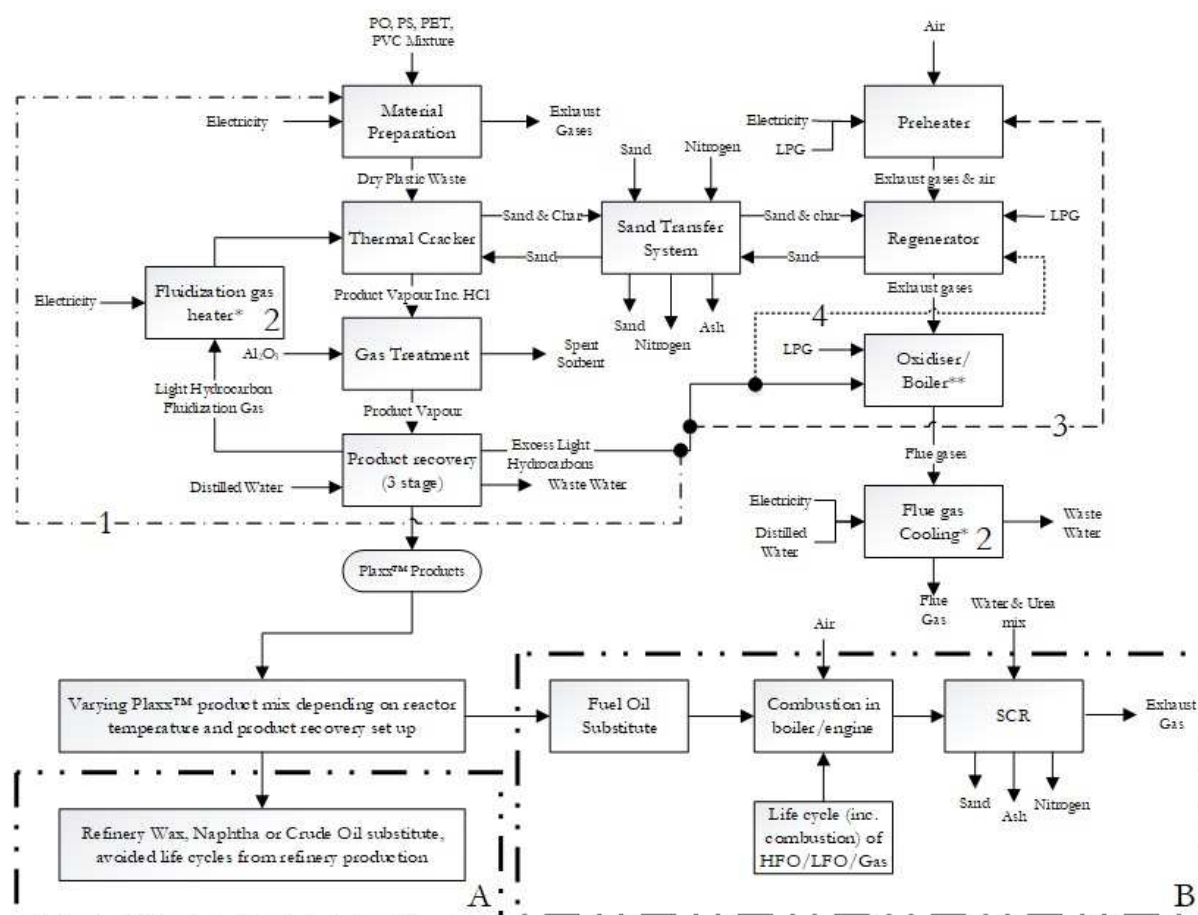
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\*\* Future Design iterations may export the excess light hydrocarbon gas instead of oxidising it, and the oxidiser may be removed from design.



