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Carbon footprint analysis in plastics manufacturing

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ABSTRACT

This paper describes an investigation of the carbon footprint associated with plastic trays, used as packaging for foodstuffs (e.g., mushrooms). In recent years there has been an increase in both consumer and legislative pressure on the packaging sector to reduce the environmental impact of its products, which are often only single use items. Using data from a plastics manufacturer, a cradle-to-grave study was conducted for trays produced from recycled polyethylene terephthalate, calculating their product carbon footprint and analysing how various parameters affect the carbon footprint. A model based on a spreadsheet analysis was developed, which allows the product carbon footprint to be determined using production batch data. It was found that the cradle-to-grave carbon footprint of 1 kg of recycled polyethylene terephthalate trays containing 85% recycled content was 1.538 kg CO_2e. The raw material, manufacturing, secondary packaging, transport and end-of-life stages each contributed 45%, 38%, 5%, 3% and 9% of the total life cycle greenhouse gases respectively. The recycled content of raw material was found to have a significant effect on product carbon footprint: a 24% decrease in tray carbon footprint could be obtained by manufacturing trays from 100% recycled content, compared to the current recycled content level of 85%. A reduction in tray weight was found to give almost an equivalent proportionate reduction in carbon footprint, with 20% and 30% tray weight reductions resulting in product carbon footprint reductions of 18.7% and 28% respectively. Transport was found to only contribute a minor amount of the greenhouse gases (3%) and hence improving transport efficiency had very little effect on the carbon footprint. The effect of end-of-life treatment was also found to be relatively small. The worst case scenario of no recycling taking place in the end-of-life stage results in the carbon footprint of the trays increasing by 2.7%, while increasing the recycling rate from 23.7% to 32% and 50%, results in the carbon footprint decreasing by 1% and 3% respectively. In both the extrusion and thermoforming processes, the specific manufacturing carbon footprints arising from consumption of electricity, chilled water energy and compressed air were found to decrease logarithmically with production speed. The greatest reductions in the carbon footprint of recycled polyethylene terephthalate trays can be achieved in the raw material and manufacturing life cycle stages. The proportion of recycled raw material should be maximised while extrusion and thermoforming process speeds should be optimised as significant manufacturing energy reductions can be attained when the speeds of both processes are increased. Tray light-weighting should be implemented to as great an extent as possible without compromising tray structural integrity while high recycling rates in the end-of-life stage should continue to be targeted.

1. Introduction

Anthropogenic greenhouse gas (GHG) emissions to the atmosphere are regarded as the chief contributor to global warming (Soloman et al., 2007). In 2010, global plastics production totalled 265 million tonnes. Europe produced 57 million tonnes in the same year and 39% of the demand was attributable to the packaging sector (PlasticsEurope, 2011a,b). In 2009, generation of plastic packaging waste was 29 kg per capita in the European Union (Eurostat, 2011). The dominance of plastic in the packaging market,

Abbreviations: CF, carbon footprint; DEFRA, Department for Environment, Food and Rural Affairs; GHG, greenhouse gases; PAS, Publically Available Specification; p-crPET, post-consumer polyethylene terephthalate; PET, polyethylene terephthalate; rPET, recycled polyethylene terephthalate; r-grPET, re-ground polyethylene terephthalate; vPET, virgin polyethylene terephthalate; WRAP, waste & resources action programme.

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and within the resulting waste stream has led to the need to ensure that its production, use and disposal are managed efficiently and sustainably.

The Courtauld Commitment is an agreement between the Waste and Resources Action Programme (WRAP) and major UK grocery organisations that voluntarily sign up to the commitment, which supports the target of the UK Climate Change Act 2008 to reduce GHG emissions by 34% by 2020 and by 80% by 2050 (Great Britain, 2008). Phase 1 of the Courtauld Commitment aimed to reduce the total amount of packaging waste in the UK (2.9 million tonnes in 2006) and resulted in an estimated 340,000 tonnes of packaging waste being avoided between 2006 and 2009 (WRAP, 2010). Phase 2 of the Courtauld Commitment has since been published (WRAP, 2012). Following the results of phase 1, it moves away from solely weight-based packaging waste targets to achieve a more sustainable use of resources over the entire life cycle of products, throughout the whole supply chain. The packaging targets of phase 2 aim to achieve by 2013: (i) 10% reduction in the carbon footprint (CF) of grocery packaging through a number of measures including: weight reduction, increased recycling rates and an increased material recycled content, and (ii) a 5% reduction in grocery packaging waste tonnage (WRAP, 2012).

Many high street food retailers have signed up to the Courtauld Commitment and must therefore meet packaging CF reduction targets regarding the food products they sell. Signatories therefore place increased demands on their packaging suppliers to aid them in meeting these targets. In competition for contracts with food retailers, some packaging manufacturers are now striving to measure, develop and implement techniques to reduce the CF of their products, and thus out-perform their competitors. Given the widespread use of plastic within the packaging market (over half of all goods produced in Europe are packaged in plastic (Perugini et al., 2005)), CF analysis was chosen to examine its manufacture and subsequent life cycle stages.

Within the plastic packaging sector, CFs have already been calculated for various food plastic packaging products: Madival et al. (2009) compared polyethylene terephthalate (PET) clamshell strawberry containers to those manufactured from polylactic acid (PLA), and polystyrene (PS) while Pasqualino et al. (2011) examined the CF effects of bottling water in both PET and glass bottles of various sizes. Humbert et al. (2009) compared glass and polypropylene (PP) plastic as packaging materials for baby food cups while Keoleian et al. (2004) examined the CF of PP yogurt cups.

Both Humbert et al. (2009) and Pasqualino et al. (2011) found plastic to have a lower CF than glass as a packaging material (e.g., depending on the country of production, baby food cups manufactured from PP were found to have a CF of between 28% and 31% lower than those manufactured from glass (Humbert et al., 2009)). The inclusion of recycled content in plastic packaging products has been found to significantly reduce their carbon emissions; increasing the recycled PET content of drinks bottles from a zero baseline to 50% and 100%, resulted in their total CO_2 emissions dropping by 13% and 27% respectively (Best Foot Forward Ltd, 2008). The contribution of transportation to the CF has been found to be relatively large when the CF associated with the food produce (filling) transportation is included in the study. Transport associated with filled packaging made up 79% of the total CF for packaged strawberries (Madival et al., 2009) and 28% for bottled water (Pasqualino et al., 2011). The high contribution of transport in the case of packaged strawberries was due to US-wide transportation of the filled product taking place. These studies did not include the CF associated with the filling production. A significant increase in CF would have resulted had production of the tray filling been included, as was the case when strawberry production was found to contribute 41% (0.364 kg CO_2e/kg_{trays}) of the total CF for punnets of strawberries (Denstedt et al., 2010). When transport of the filling is omitted, the CF of a packaged food product is found to decrease significantly; the total CF decreased by almost a factor of four in the case of packaged strawberries when transport of the strawberries themselves was excluded from calculations (Madival et al., 2009). Investigations into the impact of end-of-life management on the CF of plastic waste have found recycling to result in the least amount of GHGs, followed by landfill, and then incineration, in the cases of both PET strawberry containers and water bottles (Madival et al., 2009; Pasqualino et al., 2011). Furthermore, a literature review of available European Life Cycle Analysis (LCA) studies which evaluated plastic waste treatment found that, regarding studies which compared mechanical recycling and incineration, approximately 80% of the studies found mechanical recycling to be better than incineration from a global warming potential (GWP) point of view (Lazarevic et al., 2010). The primary source of post-consumer recycled PET (p-crPET) is beverage bottles and following the approval of the inclusion of recycled PET in food contact applications (EU, 2008) by means of a superclean process which employs a high temperature vacuum to remove contaminants, demand for recycled PET is increasing and actually a shortage of food-grade recycled PET has recently been experienced in Europe (Barton, 2010). The collection rate for post-consumer bottles in Europe was 48.4% in 2009 (Petcore, 2011) however when the appropriate infrastructure and collection system is in place very high collection rates can be achieved; Germany collected 93.5% of its post-consumer bottles in 2009 (Petcore, 2011). The sorting of the collected bottle waste stream is either carried out manually or by automatic machines. The waste stream must also sort any non-transparent colours accordingly (Welle, 2011). Of the post-consumer recycled PET collected in 2009, 49% was used for packaging (Welle, 2011).

The objective of the current paper is to describe a product CF analysis carried out for a commercial plastics manufacturer located in Ireland. The goals of the research were to calculate the CF of recycled PET trays and then analyse how the CF is affected by varying the raw material recycled content, transport efficiency, end-of-life scenario, tray weight and its manufacturing speed. In this analysis, a process map for a recycled PET tray produced by Holfeld Plastics Ltd. was developed. The process map describes the production of the product, showing all inputs to its life cycle. Metering was installed on-site which recorded electricity, chilled water energy and compressed air consumption of both extrusion and thermoforming machines, and the uncertainty associated with the metering process was also quantified. An EXCEL model was developed which, when data for a production batch is entered, calculates the product CF, taking account of raw material, production energy, secondary packaging, transport and the end-of-life stage. The model was developed in accordance with Publically Available Specification (PAS) 2050, the product carbon footprinting standard (BSI, 2011). When the CF quantification forms part of an entire LCA, studies often only use secondary data to calculate the impacts associated with the entire life cycle of the packaging. This study however, in accordance with PAS 2050, uses primary data to analyse the impacts of the primary packaging production process.

2. Scope

2.1. Functional unit

In accordance with PAS 2050, where a product (in this case, recycled PET tray) is manufactured in different unit sizes (e.g., 15 g, 18 g or 20 g tray), a common functional unit must be specified and in this study the functional unit chosen was weight of recycled PET trays required to deliver 14 kg mushrooms (BSI, 2011). This functional unit equates to 1 kg recycled PET trays in the case of conventional trays, and due to its simplicity and conciseness, this version of the functional unit shall be referred to in the text.

2.2. System boundaries

The system boundary on which the CF was analysed is detailed in the following paragraphs. In accordance with PAS 2050 and BSI EN 14040, the basis for any decisions regarding exclusions or assumptions is detailed (BSI, 2011; BSI, 2006). The process map for a recycled PET packaging tray produced by Holfeld Plastics Ltd. is shown in Fig. 1. Processes that lie outside the system boundary on the process map are not accounted for in the study.

Considering the manufacturing stage, three inputs of raw material to the process can be identified as follows:

1. Virgin PET (vPET) pellets
2. Post-consumer recycled PET flake (p-crPET) (recycled from bottles)
3. Re-ground recycled PET (r-grPET) derived from industrial recycling of sheet edge trimmings, defective trays and skeletal waste from the production processes which is operated on an in-house closed loop basis.

This study firstly accounted for GHGs arising from the raw material arriving at the manufacturer's premises, which extends back to the point of crude oil extraction in the case of the vPET pellets and accounts for all processes using production site data; the most recent PlasticsEurope CF for the production of European vPET is 2.15 kg CO_2e/kg (PlasticsEurope, 2011a,b). For the CF of the p-crPET flake input, the material has already undergone the production processes in its previous use (beverage bottles) and only requires GHGs to be calculated for its collection, sorting, prewashing (for label removal etc.), grinding, cleaning, washing and drying (Perugini et al., 2005). The original production of the material is therefore excluded from CF calculations as this would result in double counting (BSI, 2011). Energy consumption data was gathered from the primary p-crPET supplier to calculate the emission factor for the p-crPET raw material. In the case of both the vPET and p-crPET, the transport stages for the raw material up to the point of arrival at the manufacturing plant are also included in the raw material CFs. As r-grPET arises from closed loop recycling of waste, its CF is calculated according to Annex D.1 in PAS 2050 (BSI, 2011). The recycling energy associated with the r-grPET material was calculated by measuring the granulation electricity consumed over an extended period of time and dividing by the mass of material granulated to give an energy consumption figure per kg product ($kWh/kg_{material\ granulated}$).

A mixture of the three inputs is then extruded into PET sheets. The standard sheet structure is made up of 15% vPET, 50% p-crPET and 35% r-grPET and unless otherwise stated, this is the sheet structure used for analysis in this study. Sheets are typically extruded with a layer of vPET on either side which is necessary for trays which require gaseous sealing (e.g., for air sensitive foodstuffs) as recycled PET does not offer sealing capabilities as good as vPET.

As the sheet is extruded, its side edges are trimmed off due to their variations in thickness, yielding sheet edge trimmings. The rolled sheets are then placed on the thermoforming machines where the final products are made. The thermoforming stage yields good trays and defective trays, as well as skeletal waste (the parts of the sheet that are not thermoformed into a tray). The skeletal waste and defective trays from the thermoforming stage, along with the edge trimmings from the extrusion stage, are re-ground in granulators thus giving r-grPET which is used in extruding new sheets. Electricity, chilled water and compressed air are inputs to both the extrusion and thermoforming processes and for each of these, the associated CFs are calculated using primary data and this is described further in Section 3.1.

After the thermoforming stage, the trays are packed in secondary packaging which consists of: cardboard (boxes), low density polyethylene (LDPE) bags, LDPE stretch wrap, cardboard roll cores and wooden pallets. The calculation method used to determine the amounts of secondary packaging attributable to the functional unit (on a mass basis) was based on the total mass of the secondary packaging (e.g., pallets) purchased by the manufacturer per annum, and then normalising with respect to the proportion of the total annual product that the functional unit contributes.

The packaged tray products are shipped from the manufacturer's premises for produce filling, before being transported to the retailers. Because the filling process is considered to relate to the food production (e.g., mushroom production) aspect of the CF and

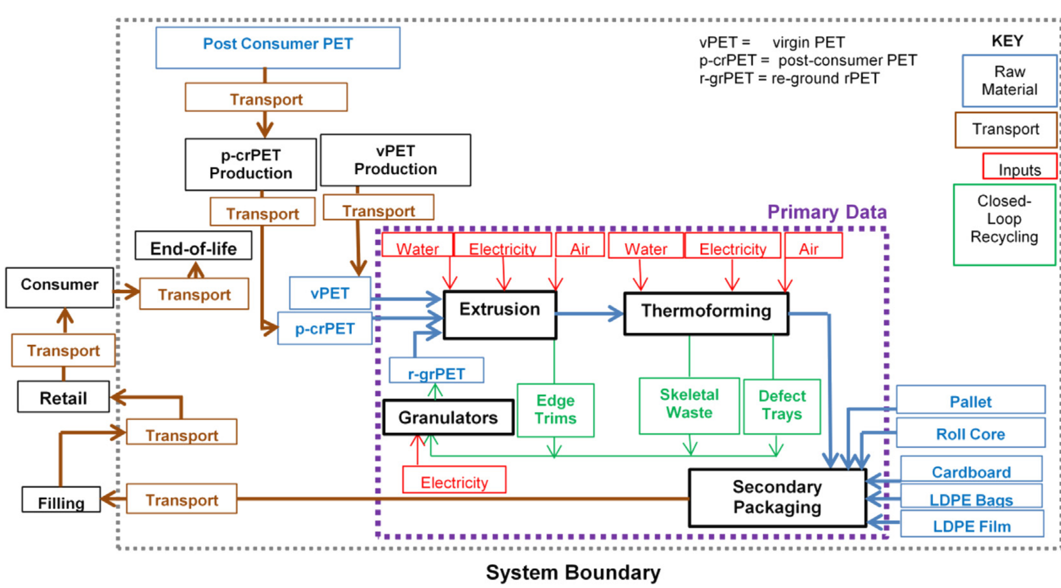

Fig. 1. Recycled PET tray manufacturing process map.

not the packaging, it is not included in this study. Transport of the trays (excluding the weight of the filling) to the filling process site and thence to the UK retail facility is however included and is assumed to take place in a 32 tonne diesel truck which is utilised for another transport assignment on its return. The averaged representative distance from the manufacturing site to the UK retail facility (via the food filling facility) consists of a 640 km road journey and a 113 km sea journey. A container unit with 27,500 kg payload capacity, utilised on return, is used to transport the trays by ship from Ireland to the UK. The emissions associated with refrigeration during transportation are again attributable to the life cycle of the food and not the packaging and hence are excluded. Transport of consumers to and from retail outlets is excluded under PAS 2050. The end-of-life stage of the trays can be affected by their manufacture (e.g., colour/material choices) and is hence included in the study, along with transportation to the end-of-life stage which is assumed to take place in a 28 tonne truck which is returned empty. A generic distance of 50 km is assumed for transportation to the end-of-life stage.

3. Methodology

3.1. Data collection

According to PAS 2050, the GHGs arising from processes operated by the footprinting organization (Holfeld Plastics Ltd.) must be determined using measured primary data, whereas secondary data may be used to calculate the GHGs arising from processes upstream and downstream of the product manufacturing stage. In this work, on-site manufacturing processes which used measured primary data are indicated by the inner boundary shown in Fig. 1. Table 1 also shows, by means of inverse shaded cells, the processes where primary data was collected by on-site metering for subsequent CF analysis. To achieve this, electricity, chilled water energy and compressed air meters were installed on both the extrusion and thermoforming production lines, where specific production machines were measured over an eight month period. The specific volumetric energy (kWh/m^3) in the case of the compressed air, and the coefficient of performance (COP) in the case of the chilled water energy, which were obtained from manufacturer's data sheets, were used to convert metered values into their equivalent electrical energy consumptions. The outputs from the meters were connected to the plant's production management software system, allowing tabular data for each batch run to be produced, showing consumption of electricity, chilled water energy and compressed air inputs as well as the production batch data (tray description, good and defect quantities, production speed etc). The electricity is Irish grid electricity while the chilled water supply is a closed system within the factory premises. Under PAS 2050, the GHGs arising from operation of production premises must also be taken into account and these included: consumption of diesel, kerosene and gearbox oil (which were allocated on the basis of a proportion of the functional unit of the total annual product) and premises lighting (which was allocated on the basis of floor space and residence time of the product).

Table 1
Contributors to various life cycle stages.

Raw material	Manufacturing	Secondary packaging	Transport	End-of-life
vPET & p-crPET production & transport to Holfeld	**Extrusion process energy**	Materials production	Holfeld to Fill site	Incineration
On-site r-grPET production	**Thermoforming process energy**	Transport to Holfeld	Fill site to retail (tray only)	Landfill
	Premises operation	Packaging electricity input	Consumer to end-of-life site	

Bold font indicates processes that were analysed using primary data.

3.2. Model

A model was developed using EXCEL which, using primary data for in-house production processes, calculates the CF for any PET plastic packaging tray produced by Holfeld Plastics Ltd. The raw material type is specified as an input to the model by the user. The emission factors for both the recycled and virgin plastic inputs as they arrive at the factory had been previously calculated using Ecoinvent data (Swiss Centre for Life Cycle Inventories, 2010). Values for electricity, compressed air and chilled water energy consumption, along with other parameters (batch run times, sheet and tray weights and quantities produced) are also entered into the model. Premises operation, standard usage of secondary packaging and transport, as well as the assumed end-of-life treatment are included by default (but are modifiable) in the model.

In the model, Gabi software (PE International, 2008) was used to calculate emissions arising from both road and sea transport. The emission factor for the Irish grid was based on medium voltage electricity generation in the Ecoinvent database (Swiss Centre for Life Cycle Inventories, 2010). The emission factor for LDPE bags was sourced from DEFRA (2008), while the emission factors for cardboard, LDPE stretch wrap and pallets were based on data from Ecoinvent. Diesel consumption in forklift operation and kerosene consumption for the heating boiler were also modelled using Ecoinvent, while the emission factor for gearbox oil usage was taken from Gabi.

For the end-of-life stage, landfill was modelled using the Ecoinvent process "disposal, polyethylene terephthalate, 0.2% water to sanitary landfill". Incinerated trays are assumed to be incinerated with energy recovery in the UK and an emission factor ("incineration – plastics, PET/PMMA/PC (with energy credit)" (ELCD, 2006)) - which accounted for energy recovery – was used. Under PAS 2050, product recycling in the end-of-life stage is not accounted for in the life cycle of the product under study, but in that of the product that uses the recycled material as a raw material input (BSI, 2011). End-of-life modelling was based on the most recent UK plastic packaging waste treatment statistics (as the majority of Holfeld trays undergo the end-of-life process in the UK) which were 68.53% landfill, 7.82% incineration with energy recovery and 23.65% recycling, as of 2008 (Eurostat, 2011).

3.3. CF calculation

The CF of an activity is calculated by multiplying the activity data (e.g., kWh electricity consumed) by the emission factor for that activity (e.g., kg CO_2e per kWh electricity) (BSI, 2011). The total CF is calculated by then summing the individual CFs for all activities within the specified life cycle as outlined in Equation (1):

$$\text{Carbon Footprint} = \sum \text{Activity data} \times \text{Activity emission factor} \quad (1)$$

4. Carbon footprint results and discussion

4.1. Carbon footprint result

Using the model described in Section 3.2, the cradle-to-grave CF of 1 kg of 85% recycled content PET trays was found to be 1.538 kg

CO_2e. The contribution of the various life cycle stages to the total CF is shown in Fig. 2. Table 1 gives a breakdown of the processes which contributed to the various life cycle stages of the product.

Despite containing 85% recycled content (50% p-crPET and 35% r-grPET), the raw material inputs still contributed 45% of the total product CF. It should be noted that the GHGs associated with transport of both the raw materials and the secondary packaging to the factory were accounted for in the respective raw material and secondary packaging CFs, and not in the transport stage CF. The in-house manufacturing processes contributed 38% of the GHGs, which when combined with the impact of the raw materials, together contributed 83% of the total product CF. Of the 38% of the total CF contributed by the manufacturing stage, 21% was contributed by the extrusion process, 16% was contributed by the thermoforming process and 1% was contributed by premises operation. The in-house secondary packaging of trays accounted for only 5% of the total CF while the transport stage was found to make a minor contribution of only 3%. The end-of-life stage was found to contribute 9% of the total CF.

4.2. Effect of raw material recycled content on carbon footprint

Given that raw material was responsible for 45% of the total CF, the impact of varying the raw material composition mix on the CF was investigated. Results thus far have assumed that the 85% recycled content of the trays has been composed of 50% p-crPET and 35% r-grPET. Because r-grPET arises from in-house recycling of production waste (sheet edge trimmings, skeletal waste and defective trays), the quantities available for reuse are limited to the waste generated within the production process. Using 35% as the upper limit of the r-grPET input, the effect of varying the total recycled PET content (i.e., p-crPET + r-grPET) of trays was examined and the results are shown in Fig. 3.

It can be seen that had the tray been manufactured using no recycled content (100% vPET), the CF would have been 3.64 kg CO_2e/kg. By currently manufacturing the trays with 85% recycled PET, the CF is reduced by 58% (2.102 kg CO_2e/kg) to 1.538 kg CO_2e/kg, compared to the case where no recycled content is used.

If the tray was manufactured using 100% recycled content, its CF would decrease by 24% (0.363 kg CO_2e/kg) further from the current 85% recycled content scenario. Current manufacturing practice is to extrude sheet rolls with the 85% recycled PET content in the middle and the 15% vPET layered on the top and bottom of the sheet to allow tray sealing where sealable trays are required (e.g., cheese slices). Trays that do not require sealing however (e.g., mushroom trays) do not require a vPET layer on the surface and could therefore, if sufficient p-crPET raw material stocks were available, be manufactured from sheets made from 100% recycled content, achieving the 24% reduction in tray CF. Furthermore, trays that require sealing only require a layer of vPET on the sealing side, not on both sides of the tray (the bottom side of the tray does not require a layer of vPET). It would therefore be feasible to extrude these sheets with only one layer of vPET, resulting in trays containing 93% recycled content, as opposed to 85%. This would result in a further 12.6% decrease in the total CF for sealable trays, with the CF reducing from 1.538 kg CO_2e/kg to 1.344 kg CO_2e/kg. Considering the raw materials in more detail, 96% of the CF associated with the vPET raw material input (2.696 kg CO_2e/kg) was contributed by the production stage associated with the vPET material (off-site) while the remaining 4% (0.102 kg CO_2e/kg) arose from transportation of the material to the factory. For the p-crPET raw material input, 72% (0.273 kg CO_2e/kg) of the CF was contributed by the plastic recycling stage while 28% (0.108 kg CO_2e/kg) was contributed by transportation of the material to the factory.

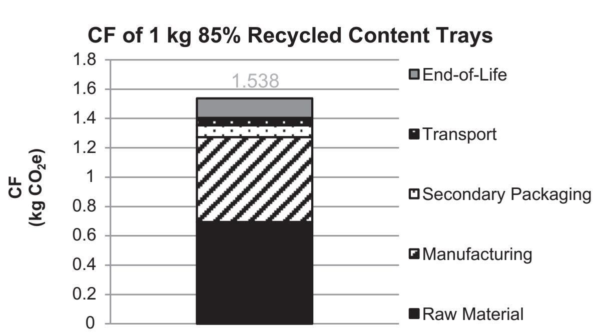

Fig. 2. Contribution of life cycle stages to total CF.

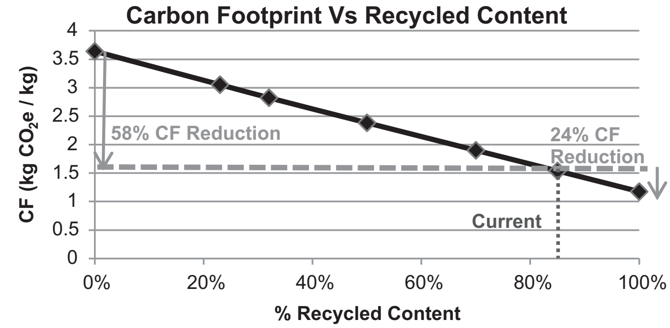

Fig. 3. Effect of recycled content on CF.

4.3. Effect of transport on CF

Transport was found to make a minor contribution of only 3% to the product CF, or 0.051 kg CO_2e/kg. This is notable given that this study assumes the transportation of trays to Great Britain for their eventual use, as opposed to confining the life cycle of the trays to within the island of Ireland. It should be noted that this figure does not include the transportation of raw materials or secondary packaging to the factory (see Section 4.1). If transportation of secondary packaging and raw materials were included in the transport CF, as opposed to their individual respective CFs, the transport CF would increase by 35% from 0.051 kg CO_2e/kg to 0.069 kg CO_2e/kg, however the contribution of the transport stage to the total CF would only increase from 3% to 4%. A 10% improvement in truck fuel economy was deemed feasible through incremental changes such as reducing driving speeds and idling time as well as improving aerodynamics and reducing rolling resistance of trucks by Keoleian et al. (2004). Considering such an improvement, it would reduce the total CF by only 0.3%. It should also be remembered that this study only accounted for transportation of trays; a full CF study of a packaged food product reveals a considerably higher contribution from the transport stage when the weight of food (e.g., mushrooms) is accounted for, as was found in the case of strawberries by Madival et al. (2009). If the weight of the tray filling (14 kg of mushrooms) was included in this case, the transport CF would increase by a factor of 8.2 (from 0.051 kg CO_2e/kg to 0.42 kg CO_2e/kg), and the total product CF would increase by 24% from 1.538 kg CO_2e/kg to 1.908 kg CO_2e/kg, resulting in transport then contributing 22% of the total product CF.

4.4. Effect of end-of-life on carbon footprint

Given the various options available for the end-of-life treatment of plastic trays, the CF results of three different end-of-life scenarios were examined. The most recently available UK plastic packaging waste treatment statistics (68.53% landfill (68.5_L), 7.82% incineration with energy recovery (7.8_I) and 23.65% recycling (23.7_R) (Eurostat, 2011)) were used as a baseline to examine the effect of varying the end-of-life treatment of the trays and the results are shown in Fig. 4.

4.4.1. No recycling

The first scenario examined is where recycling is eliminated. This results in only landfill and incineration (adjusted pro rata to 89.8_L and 10.2_I) taking place in the end-of-life stage, which is compared to the baseline case. Due to the lack of detailed data availability for post-consumer plastic trays, this study used data for the entire plastic packaging waste stream. Some products (e.g., post-consumer PET bottles) have a very high recycling rate of about 40% (PlasticsEurope, 2009) while other products (e.g., post-consumer plastic trays) have a lower recycling rate (soiled trays are very unlikely to be recycled (PlasticsEurope, 2010)). The situation where no recycling takes place showed a 2.7% increase in the total CF from 1.538 kg CO_2e/kg to 1.579 kg CO_2e/kg.

4.4.2. Recycling rate increased to 32%

The UK plastic packaging recycling rate target for 2012 is 32% (32_R) and this scenario was compared to that of the current 23.7_R situation. Increasing the end-of-life recycling rate of trays from the current rate of 23.65–32% in line with the UK 2012 plastic packaging recycling target resulted in the CF decreasing by 0.9% from 1.538 kg CO_2e/kg to 1.524 kg CO_2e/kg.

4.4.3. Recycling rate increased to 50%

Finally, it is likely that at some stage in the future a 50% plastic packaging recycling rate (50_R) will be achieved and this scenario is also analysed. Increasing the end-of-life recycling rate of plastic trays to 50% would result in the total CF being reduced by 3% compared to the current 23.7_R scenario, reducing from 1.538 kg CO_2e/kg to 1.492 kg CO_2e/kg.

The end-of-life stage only contributes 9% of the total CF, hence making any significant improvements in that life cycle stage does not necessarily result in very large reductions in the total product CF. As landfill of plastic waste effectively keeps the carbon "locked up", preventing it from being released to the atmosphere, landfill of plastic waste has a lower GWP than its incineration with energy recovery. Although landfill is found to be a favourable disposal option for plastic waste when only the CF is being analysed, a full LCA, which analyses other environmental categories such as natural resource depletion, finds that landfill of plastic waste is then a less preferable end-of-life treatment option (Perugini et al., 2005). Of the 29 landfills operating in Ireland, 16 will be full by 2013 (IE EPA, 2011) and landfills in the UK are predicted to reach maximum capacity by 2018 (The Independent, 2010). The current pressure on landfill capacity alone eliminates it as a long term disposal option for plastic waste. Further, the EU Landfill Directive dictates that waste sent to landfill must be reduced to 50% of 1995 levels by 2013 (The Council of The European Union Legislation 182, 1999).

4.5. Effect of tray light-weighting on carbon footprint

The weight of a tray affects the quantities of raw material and production energy required and therefore the carbon footprint effect of making lighter trays was investigated. Tray weight can be initially reduced by using better tray designs (e.g., ridges to give strength) and eliminating all excess/unnecessary material from trays; an average reduction of 4% in grocery packaging weight was obtained between 2005 and 2009 in the UK on a per product basis (WRAP, 2010). Beyond these basic steps to reduce packaging weight, there exists potential to further reduce tray weight. One possibility is the manufacture of foamed trays – where an inert gas is introduced into the extrusion process creating small gas pockets in the sheet – thereby reducing material density while maintaining strength and other design requirements. The volume of the sheet remains unchanged, but the overall sheet density is reduced. Foamed trays have proved to be an extremely effective weight reduction technique, being 20–30% lighter than conventional trays of the same dimensions and capacity. The mechanical properties of the tray are affected as a result of foaming and hence the amount of foam lightweighting that can be implemented is limited by the level at which it begins to hinder tray performance resulting in food spoilage. The effects of making trays 10%, 20% and 30% lighter were investigated. A 10% reduction in packaging weight is more indicative of a tray minimal material design approach, while the 20% and 30% light-weighted trays show the carbon footprint effect of producing foamed trays. Furthermore, it should be noted that the 20% and 30% light-weighted cases do not take account of the CF arising from the inert gas (Nitrogen) input itself, however this should not make a significant contribution, as the suggested likely dosage rates are only in the region of 0.09 L N_2/kg_{PET}. On a per kg basis, this would represent approximately 0.1% of the raw material inputs to the sheet. The results of different light-weighting ratios are shown in Fig. 5.

It can be seen that by reducing tray weight by 10%, the CF is reduced by 9.3% from 1.538 kg CO_2e to 1.394 kg CO_2e. Almost all of the CF of the tray is a function of the tray weight; reducing tray weight by 10% – thereby reducing the raw material and manufacturing energy requirements – there is almost an equivalent CF reduction of 10%. Processes that are not a function of tray weight are premises operation (diesel, kerosene and gearbox oil usage, lighting and operation of metal detectors) and secondary packaging. All other model inputs/parameters are deemed a

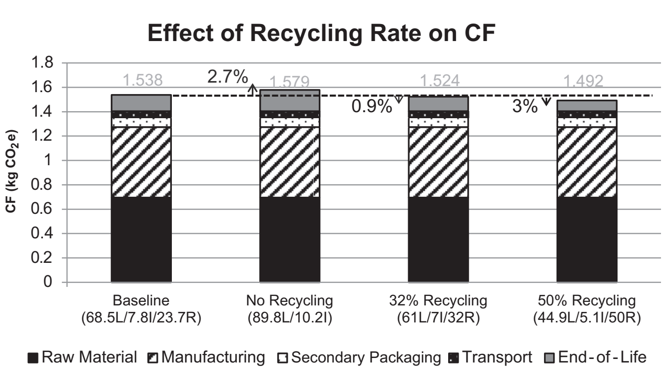

Fig. 4. Effect of end-of-life waste treatment scenario on CF.

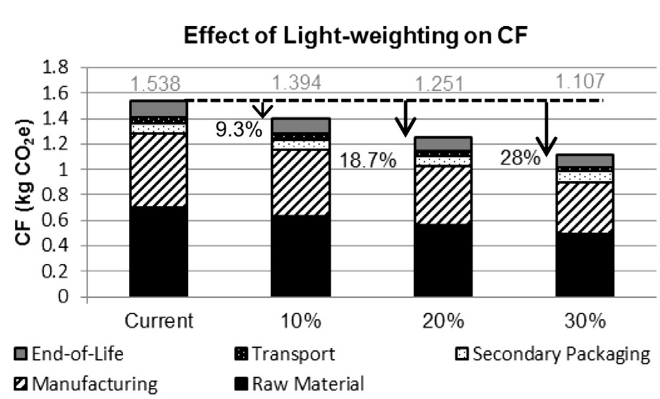

Fig. 5. Effect of 10%, 20% and 30% tray weight reductions on CF.

function of tray weight (raw materials, sheet extrusion, tray thermoforming, transport and end-of-life processes) and hence the CF reduction resulting from tray light-weighting can be calculated by reducing them in proportion with the weight reduction being investigated. Analysing the effect on the CF of manufacturing foamed trays, it was clear that potentially very large CF savings can be obtained: a 20% foam-light-weighted tray results in the CF decreasing by 18.7% from 1.538 kg CO_2e to 1.25 kg CO_2e while a 30% foam-light-weighted tray results in the CF decreasing by 28% from 1.538 kg CO_2e to 1.107 kg CO_2e.

4.6. Effect of production speed

From analysis of metered thermoforming batch runs conducted over an eight month period, it was clear that as the thermoforming production speed (kg/min) increased, the specific energy consumption (kWh/kg) of the three energy inputs (electricity, chilled water and compressed air) decreased, as did the total product CF. It was observed that certain trays (e.g., shallow trays) could be formed at faster production speeds than others and this resulted in lower energy inputs on a unit kg basis. It was found that a logarithmic relationship could be established between the thermoforming production speed and the three energy inputs, which is illustrated in Fig. 6 for the case of the chilled water energy input. By varying the thermoforming speed alone (keeping extrusion speed and all other parameters fixed), it was found that the total product CF could range from a minimum of 1.447 kg CO_2e/kg to a maximum of 2.205 kg CO_2e/kg, equating to a 6% decrease and a 43% increase respectively, relative to the 1.538 kg CO_2e/kg baseline CF in this study. Trays that are, for example, very deep, and are hence manufactured at a very low production rate ($\approx$1.5 kg/min) are seen to be responsible for very significant increases in the total product CF, as well as in the thermoforming specific energy consumption, while the reducing effect of production speed on CF is significantly less pronounced for products formed at speeds greater than 3 kg/min. A similar logarithmic relationship was observed between specific energy consumption of electricity, chilled water energy and compressed air, and production speed in the extrusion process. Fig. 7 shows the relationship between extrusion production speed and specific electricity consumption. By varying the extrusion speed alone, the total CF can range from 1.378 kg CO_2e/kg to 2.347 kg CO_2e/kg, about the 1.538 kg CO_2e/kg baseline in this study. This results in a 53% increase in product CF in the case of the minimum production speed, and a 10% decrease in product CF in the case of the maximum production speed, about the average baseline. Sheets for example, that are very narrow or very thick and are hence extruded at very low rates (5–10 kg/min), result in significant increases in the product CF. Fig. 8 examines the scenarios where the extrusion and thermoforming processes both operate at their maximum and minimum production speeds simultaneously. Arising from the logarithmic trends that were found to be present between specific energy consumption and production speed, the CF could be reduced by 14% from the baseline case to 1.321 kg CO_2e/kg when both processes operate at their fastest production speeds, while a 64% increase in total CF would result when processes operate at their slowest production speeds (increasing to 2.529 kg CO_2e/kg).

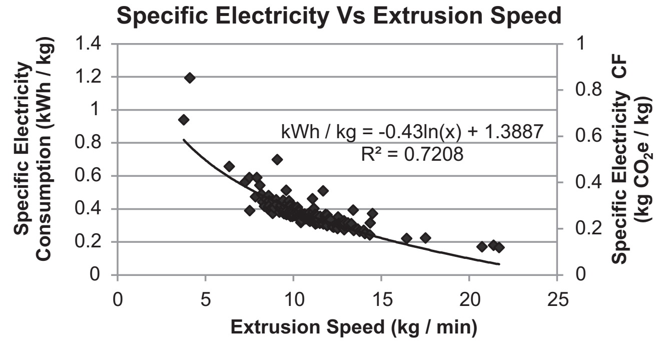

Fig. 7. Effect of extrusion speed on specific electricity consumption.

4.7. Uncertainty

The uncertainty associated with metering the inputs to both the extrusion and thermoforming processes was calculated by combining the errors of the electricity, chilled water energy and compressed air meters using the propagation of error formula provided by NIST (2012):

$$S_Y = \sqrt{\left((\partial Y/\partial X)^2 S_X^2 + (\partial Y/\partial Z)^2 S_Z^2 + \ldots + (\partial Y/\partial X)(\partial Y/\partial Z) S_{XZ}^2 + \ldots\right)} \quad (2)$$

Where:

S_x = standard deviation of the X measurements
S_Z = standard deviation of Z measurements
S_Y = standard deviation of Y measurements
$\partial Y/\partial X$ = partial derivative of the function Y with respect to X, etc
S_{xZ} = estimated covariance between the X, Z measurements.

The uncertainty totalled $\pm$0.008 kWh/kg for the extrusion process and $\pm$0.007 kWh/kg for the thermoforming process, or 0.006 kg CO_2e/kg for both processes. This uncertainty equated to $\pm$1.88% and $\pm$2.47% for extrusion and thermoforming processes

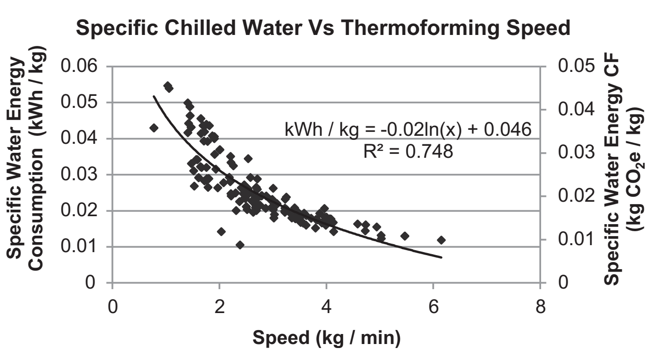

Fig. 6. Effect of Thermoforming speed on specific chilled water energy consumption.

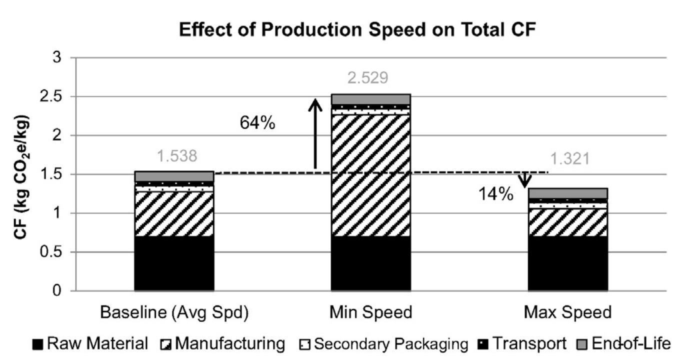

Fig. 8. Effect of combined extrusion and Thermoforming maximum and minimum production speeds on CF.

respectively which corresponded to an uncertainty of ±0.77% for the total product CF measurement (0.012 kg CO_2e/kg). There is further un-measured uncertainty associated with the CF result arising from the raw material, transport, end-of-life and secondary packaging life cycle stages however it was not possible to assess these in the context of the current project.

5. Conclusions

The conclusions associated with this investigation are both specific and generic. Considering the specific findings first, using the PAS 2050 CF standard, the cradle-to-grave CF of 1 kg of 85% recycled PET content trays was found to be 1.538 kg CO_2e. Further investigation revealed that the CF associated with the raw material inputs and manufacturing processes contributed most to the CF (45% and 38% respectively). The end-of-life stage was found to contribute 9% of the total CF while the secondary packaging and transport stages contributed 5% and 3% of the GHGs respectively. The proportion of recycled content in raw material was found to significantly affect CF; by currently manufacturing the trays with 85% recycled content, the CF is reduced by 58% (2.102 kg CO_2e/kg), compared to if no recycled content was used. Trays that do not require sealing should be thermoformed from sheets manufactured from 100% recycled PET, thus achieving a further 24% (0.363 kg CO_2e/kg) reduction in total product CF. Further, in the case of trays that are to be sealed, by only extruding the sheet with a layer of vPET on the sealing surface (as opposed to both surfaces), these trays could be manufactured from sheets extruded with 93% recycled PET content, yielding a 12.6% (0.194 kg CO_2e/kg) decrease in product CF. Tray light-weighting was found to yield significant CF reductions; a 10% tray weight reduction would result in the CF being reduced by 9% (0.143 kg CO_2e/kg) while producing foam-light-weighted trays 20% and 30% lighter than conventional trays would result in the product CF being reduced by 18.7% (0.288 kg CO_2e/kg) and 28% (0.431 kg CO_2e/kg) respectively. Because the tray filling was not accounted for in this study, transport was found to make only a minor contribution of 3% to the CF and hence a 10% improvement in truck fuel efficiency resulted in only a 0.3% reduction in product CF. The effect of varying the end-of-life waste treatment of the trays was found to have only a small effect on their CF. It was found that for the scenario of no recycling taking place in the end-of-life stage, a 2.7% (0.041 kg CO_2e/kg) increase in CF resulted, compared to the baseline case which used the most recent UK plastic packaging waste treatment statistics. The scenario where the 2012 UK plastic packaging recycling target of 32% is satisfied was found to result in a 1% (0.014 kg CO_2e/kg) decrease in product CF from the baseline case, while a 50% plastic packaging recycling rate would result in a 3% (0.046 kg CO_2e/kg) decrease in product CF. The CF advantages of operating production lines as quickly as possible were clear in the manufacturing stage, where logarithmic relationships were found to exist between all three energy inputs (electricity, chilled water energy and compressed air) and the production speed (kg/min) of both the extrusion and thermoforming processes. Thermoforming trays at their slowest production rate results in up to a 43% (0.667 kg CO_2e/kg) increase in total product CF, while their thermoforming at the fastest production rate results in a potential 6% (0.091 kg CO_2e/kg) decrease in product CF, in comparison with the average baseline. Extruding sheets at their slowest production rate results in a potential 53% (0.809 kg CO_2e/kg) increase in total product CF, while their extrusion at the fastest production rate results in a potential 10% (0.16 kg CO_2e/kg) decrease in total product CF, with respect to the average baseline. Considering extrusion and thermoforming together, the CF could be reduced by 14% from the baseline case to 1.321 kg CO_2e/kg when both processes operate at their fastest production speeds simultaneously, while a 64% increase in total CF would result when processes operate at their slowest production speeds (increasing to 2.529 kg CO_2e/kg).

Considering the more generic conclusions, with regard to PET food trays, the raw material and manufacturing life cycle stages provide the greatest scope for CF reduction as they contribute the majority of the life cycle GHGs while the end-of-life, secondary packaging and transport stages are only minor contributors. Given that the CF of all sources of recycled PET consumed was lower than that of vPET, the proportion of recycled material should always be maximised when producing PET trays. Extrusion and thermoforming process speeds should be optimised as significant CF and energy reductions can be attained when the speeds of both processes are increased. Tray light-weighting should be implemented to as great an extent as possible without compromising tray structural integrity as significant CF reductions can be achieved by reducing the amount of raw material used to produce a tray. Looking to the future, a potential challenge for environmental management systems is the integration of CF analysis. The plastics industry will likely experience it being a legal requirement to quantify CFs for their products in the future. Standards such as PAS 2050 will become more widely used and independent verification will continue to be employed to check the accuracy of analyses.

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