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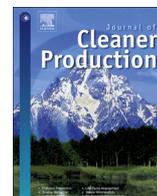
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Incorporating lean thinking and life cycle assessment to reduce environmental impacts of plastic injection moulded products



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ABSTRACT

In the last decades, environmental footprint of the product manufacture has emerged as an important public concern, causing manufacturers to re-assess their product's environmental impacts. Responding to global outcry on global warming, world leaders have agreed to limit global temperature rise to less than 2 °C above the temperature in pre-industrial times. As a result, governments and industrial leaders around the world have proposed a roadmap for 80% emissions reduction by 2050. The aim of this work develops a novel approach of linking Life Cycle Assessment (LCA) and Lean manufacturing to reduce the negative environmental impacts of a plastic injection moulded product. Products that use plastic as their primary source of raw materials are mainly produced by plastic injection processes. Although plastic injection moulding has many benefits such as 'high production rates', there is a lack of through investigation on the effects of this process has on the environment such as climate change, ozone depletion etc. This paper proposes a novel cross-functional mapping approach of linking lean-thinking and LCA. The implementation case study has been presented with the view to re-assess carbon footprint of an existing plastic product. The reported implementation work demonstrates that the adaptation of lean thinking and LCA could significantly minimise negative environmental impacts of a plastic injection product. A case study indicates that the overall environmental impact has been reduced by approximately 40% in climate change, human toxicity, photochemical oxidant formation, acidification and ecotoxicity.

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1. Introduction

Manufacturing is a process of providing products and services to societies and supporting the quality of life. This industry contributes a large proportion of wealth to the world's economy (Haapala et al., 2013). Yet, manufacturers are increasingly under extreme pressure to produce their products with less environmental impacts in order to meet government's environmental legislations (Fargani et al., 2017). In the manufacturing industry, carbon emissions are mostly produced by production processes due to their usage of energy such as electricity and fossil fuels (Upadhyayula et al., 2012). Recent studies by various authors indicate the importance of carbon emissions reduction and environmentally friendly products, for example: (i) Zeng et al. (2016) forecasted the

efficiency of carbon emissions and financial incentive on non-fossil energy based products; (ii) Aso and Cheung. (2015) developed a software to aid designers to design wind turbines with minimum carbon emissions and cost impacts. Manufactures will need to consider not just their products' technical performance and cost impacts of technology and materials but also the environmental burdens (Ribeiro et al., 2016). Companies are suggested to implement more 'environmental-friendly' initiative in order to stay competitive and economically sustainable. Manufacturers will need to change their traditional production techniques with a more sustainable approach to minimise the number of manufacturing steps using advanced and alternative methods (Gupta et al., 2016).

There is a great concern for the amount of waste generated by manufacturers as a result of accountability required in total resources (material, energy etc) consumed until product's end-of-life phase (Cheung et al., 2015). Today, linear nature of the product life cycle is replaced with closed loop recycling/re-use to reduce extent of material wastage streams (Anthony and Cheung., 2017). As the

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Abbreviations

5S	Sort, Set in order, Shine, Standardise, and Sustain	LCA	Life Cycle Assessment
CS	Current State	LCI	Life Cycle Inventory
DEA	Data Envelopment Analysis	MRP	Material Requirements Planning
FIFO	First In-First Out	NVA	Non-Value-Added
FS	Future State	NVAMC	Non-Value-Added Material Consumption
GWP	Global Warming Potential on climate change	POFP	Photochemical Oxidant Formation Potential
HTP	Human Toxicity Potential	SMED	Single-Minute Exchange of Die
I/O	Input/Output	TAP	Terrestrial Acidification Potential
ISO	International Organisation for Standardisation	TETP	Terrestrial Eco-Toxicity Potential
JIT	Just In Time	TPM	Total Productive Maintenance
		VSM	Value Stream Mapping

world's population grows, these material wastage streams cause great concern given their impact on the environment. These impacts can be improved by adopting a more effective production method and design approach (e.g. design for environment) using less materials which in turn will generate less waste (Shahbazi et al., 2016). While addressing requirements for reducing carbon footprint of the product manufacture and to minimise waste in manufacturing, a number of methods can be found. For instance, the approach of material flow cost accounting by Kokubu and Kitada (2015), modelling of material, energy and waste flows by Smith and Ball (2012), eco-efficiency by Ehrenfeld (2005) and in cleaner production: Dhingra et al. (2014) investigated the synergy of lean and green manufacturing; Cheung and Pachasia. (2015) developed a cost estimation approach in recycling and repurposing of waste paper. This work has identified that there is lack of research on linking lean manufacturing practices and life cycle assessment technique to address environmental impact reduction of a product. The closet work are summarised as follows.

Kur dve et al. (2014) focus on integrating production system and lean tool and they suggest that lean methods can be used to improve plant layout and to make their production process greener. Chiarini (2014) and Faulkner and Badurdeen (2014) also concluded that lean tools such as Value Stream Mapping, 5S, cellular manufacturing etc can help to reduce environmental impacts of a manufacturer. Pampanelli et al. (2014) proposed an integrated lean and green model using Kaizen approach which resulted in reduction of both production waste and environmental impact. Verrier et al. (2014) developed a framework for lean and green management for a manufacturing enterprise. The approach can be used to balance a manufacturer's lean and green practices by taking consideration of economic earnings. Dües et al. (2013) explored the synergy between lean and green practices. Their research findings indicate that the integration of lean thinking and green practice will bring benefits to companies. Yang et al. (2011) investigated the relationship between manufacturing practices and environmental management. They suggest that lean manufacturing alone is not enough to improve environmental performance due to conflicts between environmental performance objectives and lean manufacturing principles. This conclusive remark is also supported by a recent state-of-the-art-review performed by Cherrafi et al. (2016). For this reason, there is a distinct need to explore an alternative approach by incorporating lean thinking and LCA to facilitate environmental performance of a manufactured product.

Plastic is one of the most versatile materials and is widely used in many products. It comes with a huge environmental levy due to its extremely low degradability and dramatic production rate (Gallimore and Cheung., 2016). Products that use plastic as their primary source of raw materials are mainly produced by plastic

injection moulding processes. This process has many benefits such as 'high production rates'. Nevertheless, there is lack of studying on the effects of this process has on the environment such as climate change, ozone depletion etc. This paper aims to examine the environmental impact of a plastic injection moulding product and presents a novel approach to use cross-functional mapping to integrate lean thinking and LCA techniques.

Lean manufacturing aims to eliminate waste and non-value-added (NVA) activities and its main goal is to improve every process within an organisation (Shingo., 1989; Bortolini et al., 2016). Lean manufacturing can be used to improve resource requirements of making products such as the demand in both materials and energy (Moreira et al., 2010). Lean can be used to achieve these requirements by using a set of techniques and tools such as Heijunka, Six Sigma, Kanbans, First In-First Out (FIFO), Value Stream Mapping (VSM), Takt time, Just In Time (JIT), Single-Minute Exchange of Die (SMED), and 5 S principles (Aghajani et al., 2012).

VSM is a method to visualise the time for production processes and shorten the time needed in between processes (Brown et al., 2014). VSM is used to determine where waste could occur within the manufacturing process and to establish plans for future improvement (Abdulmalek and. Rajgopal, 2007). Roosen and Pons (2013) pointed out that VSM is a very useful technique as it can be used to identify the opportunity for reducing environmental impact. In terms of resources, Cellular manufacturing, 5S and Kanban signalling systems can reduce consumption usage such as electricity, materials and labour availability, whereas Total Productive Maintenance (TPM) can help to reduce several impacts of the machines in a production process (Chiarini, 2014).

Curran (2012) states that "LCA is a systematic method for evaluating the environmental burdens associated with the product, process or activity, by identifying and quantifying energy and materials consumed and wastes released to the environment". According to Curran (2012), a full LCA investigation involves four stages: (i) goal and scope definition; (ii) data gathering LCA inventory; (iii) environmental impact assessment and, (iv) interpretation of results and future recommendations. Over the years, there have been numerous LCA investigations reported in the literature, however research on LCA in the past has focused on methodological issues, for example: Tan and Khoo (2005) explored the LCA method to improve the environmental life cycle of aluminium from mining to its final production. Rex and Baumann. (2007) investigated the fundamental differences in LCA practice between two similar companies. Wang et al. (2014) proposed an approach of integrating LCA, fuzzy logic and analytical network process to support the selection of environmental sustainable product designs. Huang et al. (2015) conducted a first of its kind LCA on the environmental impact of drill and blast in tunnelling. Tait and

Cheung. (2016) developed a cradle-to-gate LCA to improve carbon emissions of concrete mix design. Coelho and McLaren (2013) concluded that very few researchers investigate whether the use of LCA can improve a production system of manufacturing a product.

Evaluation of these discrete approaches and corresponding literature for reducing through life cycle waste indicates few research gaps: i) Collective implementation of these lean approaches has not been investigated ii) Although polymers are highlighted as environmentally taxing materials, lack of case studies reporting life cycle assessments and corrective measures for reducing environmental impacts plastic products. Overall contribution of the research reported in this paper is to develop a cross-functional mapping approach of integrating lean and LCA to reduce negative environmental impacts of a plastic injection product. Cross-functional mapping approach is used because a number of functional areas such as Lean manufacturing, LCA and product development process are involved. The remainder of this paper is organised as follows: Section 2 describes the proposed methodology and implementation; Section 3 presents relevant case studies; Section 4 discusses the overall result and finally the conclusion and future work.

2. Method of linking lean manufacturing and life cycle assessment for environmental impact reduction

The proposed framework for reassessing environmental impacts of existing product lines is illustrated in Fig. 1. The lean approach can help an organisation to improve the management of their products throughout their lifecycle from material requirements, scheduling to waste generation etc. VSM can be used to identify the NVA such as the time wasted in individual stage of the production process. VSM can also map the material flow and to identify the amount of materials used throughout the whole production process in conjunction with other lean techniques such as Cellular manufacturing, 5S and Kanban signalling systems etc (Gupta and Jain., 2013).

LCA system will perform the evaluation of the environmental impacts based on data input from manufacturing processes such as energy requirements, time intervals and materials of a product.

- Setting the goal of evaluating the potential environmental impacts of a plastic casing product.
- Gathering and collecting inventory inputs data of the injection moulded process and the plastic casing.
- Evaluating the potential environmental impacts associated with those input and output (I/O) data.
- Interpreting the results of the impacts phases in relation to injection moulding and the plastic product.

Fig. 1 illustrates a cross-functional representation of product mapping in lean manufacturing and LCA. The method is functioned as follows:

- Current-State (CS) in this context is referred to a product's specification stage. Based on the product specification a set of relevant manufacturing data such as processes, materials requirement and time intervals can be modelled visually using lean's VSM technique.
- Based on the VSM layout, a set of input and output data such as material type, requirements, total weight of materials and process energy requirements can be identified. These data type will act as the input values for LCA evaluations. The system boundary of the assessed injection moulding process is shown in Fig. 2. The LCA is focused on cradle-to-gate including raw materials supply, the injection moulding process and delivery to customers.
- If improvement of CS is requested, a feasibility study using lean manufacturing techniques will require and this can be determined through the CS's VSM. By creating a second set of VSM for the future state (FS), this allows key processes to be identified so that unnecessary waste can be eliminated.
- Based on the FS's VSM layout, a new set of input and output data will be formulated and a subsequent LCA evaluation can be performed.
- The final stage of the method is to compare LCA results of CS and FS.

The lean techniques are incorporated into a visual stream mapping process for the CS and FS stages. The future state analyses the improvement of the current process cycle to recommend

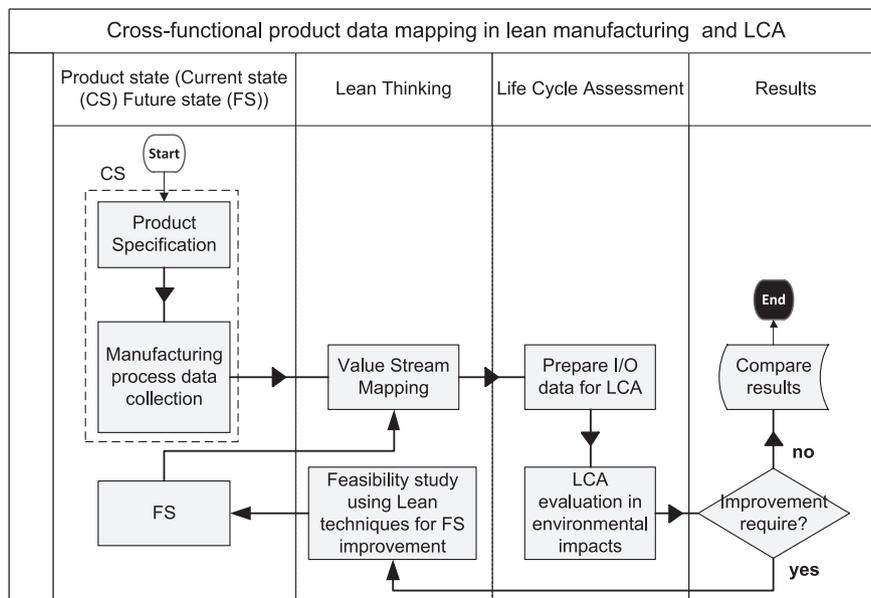


Fig. 1. The proposed method of incorporating lean thinking and Life Cycle Assessment in manufacturing environmental impact analysis.

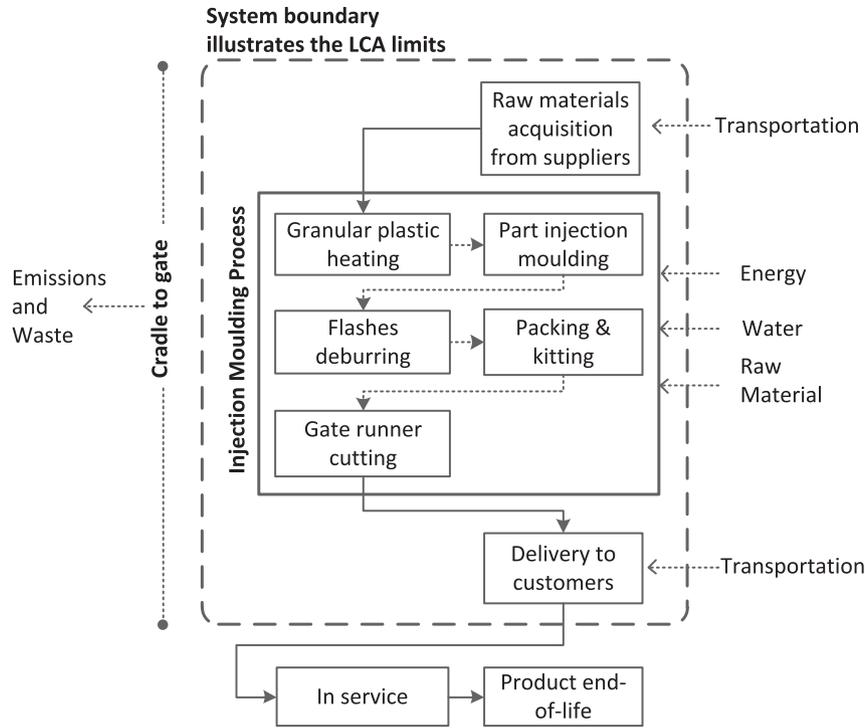


Fig. 2. The LCA system boundary of the injection moulding process.

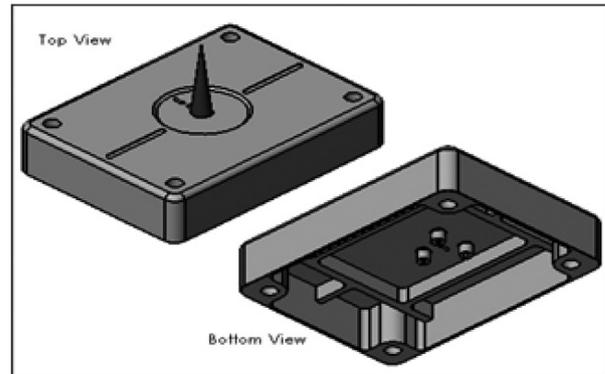
changes which should make the product more sustainable. Modelling of a plastic injection moulding product has been created for the study to focus upon improving the product and the life cycle analysis of this process based on the literature review. The software Simapro V8 was used to carry out the data analysis for the “current state” and “future state” of a product specification. The main focus categories are the climate change (global warming potential), human toxicity, photochemical oxidant formation, terrestrial acidification and terrestrial ecotoxicity. Both set of results are compared to show where improvements can be made in the manufacturing process in order to make it more environmentally friendly.

3. The case study: Re-assessment of plastic injection moulded products

Paramit is a turnkey plastic injection moulding specialist providing both design and manufacturing of plastic injection moulded products to customers around the globe. Environmental directives in Malaysia have taken major initiative to monitor carbon footprint for consumer electronic products manufactured there. In response, Paramit started re-assessment of their existing product lines to estimate carbon footprint. The implementation work reported in this paper has been carried out using Paramit's data with the view to apply LCA technique and revise existing manufacturing flow with Lean tools. This work was carried out at Northumbria University in collaboration with the University of the West of Scotland, UK and the referenced cradle-to-gate LCA model is based on European databases.

3.1. Product specifications

The case study is a plastic casing and its specification is shown in Fig. 3. The monthly forecast arranged on the material requirement planning system is 4000 pieces. The finished product will be placed into a returnable tray which carries 5 pieces per tray and 12 trays on



Specification	Description	Unit
Product ID	Top housing	-
Size (L x W x H)	425 x 315 x 95	mm
Material	Polycarbonate (PC)	-
Part weight	1.1	kg
Gate runner weight	20	g
Colour	Pantone Black 2C	-
Surface Finishing	Commercial Smooth (320 GRIT)	-

Fig. 3. The plastic casing and its specification.

a pallet. The products will be shipped to customers every Tuesday and Friday by a lorry truck with a size no greater than 7 t. The manufacturer's normal working day is 8 h, with 2 working shifts/d. The planned production for the day is to produce 360 pieces and this is equivalent to 180 pieces per shift. In order to produce 4000 pieces monthly the amount of time required is 12 working day with

23 shifts. Each shift will require 198 kg of material and this is based on the quantity of products multiplied by the part weight, $1.10 \text{ kg} \times 180 = 198 \text{ kg}$. The total waste during the plastic injection moulding process is calculated as follow:

- The hopper dryer machine's (part of the granular plastic pre-heating process) material waste rate (failure rate) is 0.15%, the dryer hopper would contribute $198 \times 0.15\% = 0.3 \text{ kg}$ per shift,
- The machine set-up/test runs waste rate is 0.25% and this will contribute $198 \times 0.25\% = 0.5 \text{ kg}$
- The part moulding defects flashes waste rate is 0.0125%, the part moulding defects contributes $198 \times 0.0125\% = 0.025 \text{ kg}$, per part weight.
- The total amount of waste materials is 0.825 kg.

For the required 4000 pieces per month, the total material required per shift is calculated as: total number of shifts multiplied by the total required materials, i.e, $22.22 \times 198.825 \text{ kg} = 4417.9 \text{ kg}$.

3.2. Manufacturing process data collection

The manufacturing process of the top housing and the process requirements data are summarised in [Table 1](#).

- Raw material is ordered by a MRP system planned in 6 week forecasts with 5 t of granular plastic polycarbonate to be delivered to the manufacturing site on monthly basis by a lorry truck. The truck travels 150 km and this is equivalent to $150 \times 5 = 750 \text{ tkm}$.
- The next step is granular plastic pre-heating, the process takes 40 min and there is no inventory at this stage. The equipment requires a 200 kg plastic hopper dryer with a power rating of 9.25 kWh. In order to complete a monthly demand of 4000 pieces, the total required overall energy is equivalent to 144.43 kWh. There is an overall 6.63 kg of materials is added as NVA items in the hopper dryer machine due to potential machine failure allowance of 0.15%.
- For part injection moulding the design requirements must be followed to achieve the desired dimensions. The injecting moulding process requires a cycle time of 70 s. The inventory volume is set at 1500 pieces, the daily requirement of 200 pieces, lead time needed is 7.5 d. A 650 t hydraulic injection machine with a motor pump power rating of 95 kWh is used in the manufacturing process. In order to complete the 4000 pieces monthly demand, the total overall energy is equivalent to 7388.15 kWh. There is an overall 11.04 kg of materials is added

as NVA items due to machine setup/sample test run machine allowance of 0.25%.

- For the flashes deburring process the cycle time takes 5 s. The inventory is set at 950 pieces in the process and the lead time as per the daily requirement is equivalent to 4.75 d. The flashes deburring has a failure allowance of 0.0125% which is equivalent to 0.53 kg as NVA waste in the process.
- Gate runner cutting requires a 10 s cycle time. The inventory is set at 1300 pieces and the lead time as per the daily requirement is 6.5 d. The machine power rating is 0.7 kWh, in order to complete 4000 pieces, the production power energy consumption is equal to 7.78 kWh. The removal gate runner considered as the NVA item, with a total waste materials of 80 kg.
- The cycle time for the packing and kitting process is 10 s. The inventory is set at 1100 pieces and lead time needed as per the daily requirement is 5.5 d. No electric equipment was used.
- The last stage of the process is transporting the products to customers which has been arranged on every Tuesday and Friday and it's travelled by a truck with size less than 7 t and travels 50 km. Overall for 4000 pieces monthly order, total 4319.7 kg has been carried and a total of 215.98 tkm was required.

3.3. Value Stream Mapping of the product's current state

From the manufacturing data in [Table 1](#), a VSM to represent the product's 'current-state' (CS) has been created and this is shown in [Fig. 4](#). Based on CS's VSM, the overall amount of material and energy consumptions for the CS is summarised in [Table 2](#). These are the CS input data into the LCA software.

3.4. LCA analysis of current state

3.4.1. I/O setup for LCA evaluation

[Fig. 5](#) illustrates the LCA's system boundary of the product CS. The system boundary includes all necessary inputs which represent the overall amount of materials and energy requirements in the production of 4000 pieces of the plastic house casings.

This LCA analysis adopts the ISO 14044:2006 standard ([International Organisation for Standardisation, 2006](#)). In this research work the injection moulding process is studied and analysed. Environmental impact results are calculated using the ReCiPe midpoint (E) method ([Goedkoop et al., 2010](#)). This midpoint approach is especially useful in injection moulding process which will allow engineers to compare different alternatives ([Elduque](#)

Table 1
Top Housing process requirement summarised list.

Process #	Process Requirements									
	Op.	Inv.	Time			Material/Transportation			Machine/Equipment	
			L/T d	C/T s	C/O s	Item#	Usg '+'	Usg '-'	Item#	Usg '+'
Material acquisition (Receiving)	N/A	N/A	5	N/A	N/A	Polycarbonate (PC) >7 t Lorry truck	5 t 750 tkm			
Granular plastic pre-heating	2	0	N/A	2400	0	Raw material granular plastic (PC)	4417.9 kg	6.63 kg	200 kg plastic hopper dryer machine	144.43 kWh
Part Injection Moulding	2	1500	7.5	70	5	Pre-heated Polycarbonate (PC)	–	11.04 kg	650 t Hydraulic injection moulding machine	7388.2 kWh
Flashes deburring	1	950	4.75	5	5	Mould part	–	0.53 kg		
Gate runner cutting	1	1300	6.5	10	5	Deburr part	–	80.00 kg	Bench drill machine	7.78 kWh
Packing & Kitting	1	1100	5.5	10	0	Completed Part	–			
Shipping Customer	N/A	N/A	N/A	N/A	N/A	Packed Finish Good >7 t Lorry truck	215.98 tkm			

* Op- operator, Inv- Inventory, L/T- Lead time, C/T: Cycle time, C/O: Changeover time.
Usg "+" = value added, Usg "-" = non value added.

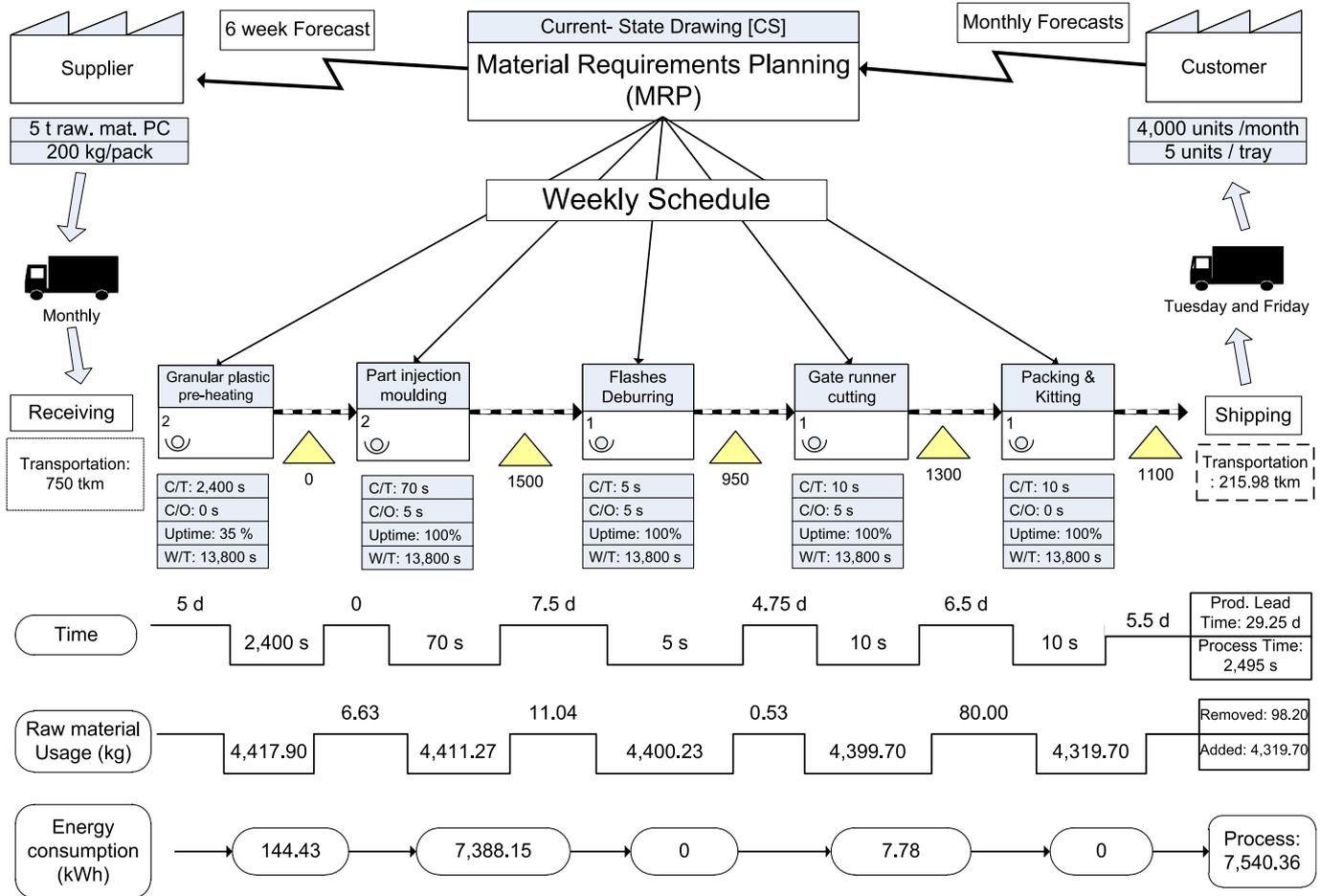


Fig. 4. VSM diagram of the product's current state [CS].

Table 2
VSM current state (CS) overall process requirement summarised list.

Details	Total	Unit
Production Lead Time	29.25	d
Process Time	2495	s
Operator	7	–
Material (value added)	4319.70	kg
Material (non-value added)	98.20	kg
Energy Consumption	7540.36	kWh
Transportation (from supplier)	750.00	tkm
Transportation (to customer)	215.98	tkm

et al., 2015). This method is used when a final result is needed and the method such as ReCiPe is strongly recommended by Elduque et al. (2015) and Dong and Thomas, 2014.

In the ReCiPe midpoint (E) method, there are eighteen environmental impact indicators. However, in accordance with Huang et al., (2015)'s finding, the most influential environmental impact indicators in an energy intensive production process are “climate change’s global warming potential (GWP)”, “human toxicity (HTP)”, “photochemical oxidant formation (POFP)”, “terrestrial acidification (TAP), and “terrestrial eco-toxicity (TETP)”. As a result this study is focused on these five indicators.

3.4.2. Current-state environmental impact results

The full LCI results of CS are shown in the supplementary data file (Product’s Current State LCI results). The environmental

impacts of CS are shown in the Appendix. Figs A1 and A2 represent the characterisation and normalisation of the product current state environmental impacts. The environmental impacts inventory is shown in Table A1. To present the results more clearly the LCA of the product CS’s selected environmental impact factors are shown in Fig. 6.

- Fig. 6(a) illustrates the impact of Climate Change (GWP). It shows that the material usage contributed 73.40% with 28,470.04 kgCO2eq. The injection moulding process produced 14.20% with 5488.73 kgCO2eq and electricity consumption added further 11.30% with 4292.88 kgCO2eq and transportation provided the minimum impact of 1.10%, 440.32 kgCO2eq.
- Fig. 6(b) illustrates the impact of Human Toxicity (HTP). It shows that injection moulding produced the largest impact of 58% with 98,082.73 kg 1,4-DB eq. Next was electricity consumption which has produced 24% with 39,969.3 kg 1,4-DB eq. Material usage was 16.60% with 28,010.74 kg1,4-DBeq and the lowest impact was produced in transportation with an impact factor of 1.48% and 2539.97 kg1,4-DBeq.
- Fig. 6(c) illustrates the impact of Photochemical Oxidant Formation (POFP). The material usage has produced the highest score of 76.70% with 80.729 kg NMVOC. The second highest impact in this category was the injection moulding process with, 12.30%, 12.97 kgNMVOC. Electricity produced 8.66% with 8.937 kgNMVOC. The lowest impact in this category was transportation with 2.35% and 3.46 kgNMVOC.

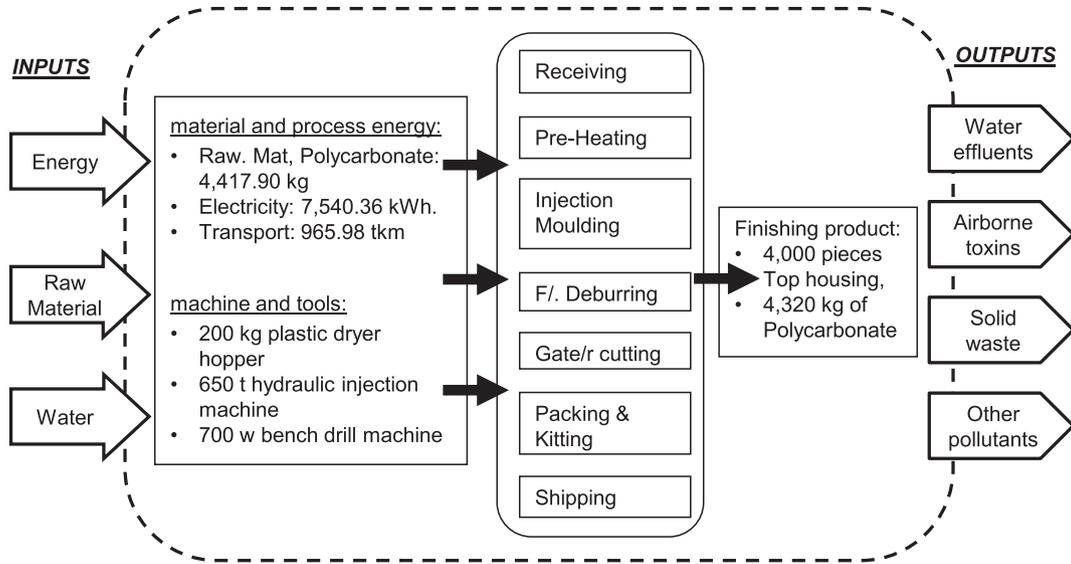


Fig. 5. System boundary for I/O LCA data for CS.

Fig. 6(d) illustrates the impact of Terrestrial Acidification (TAP). The highest impact was the material usage at 73.30% with 104.89 kgSO₂eq. Next was the injection moulding process with

14.60% and 20.89 kgSO₂eq. Electricity produced an impact of 10.70% with 15.03 kgSO₂eq. Transportation has the lowest impact with 1.35% and 2.54 kgSO₂eq.

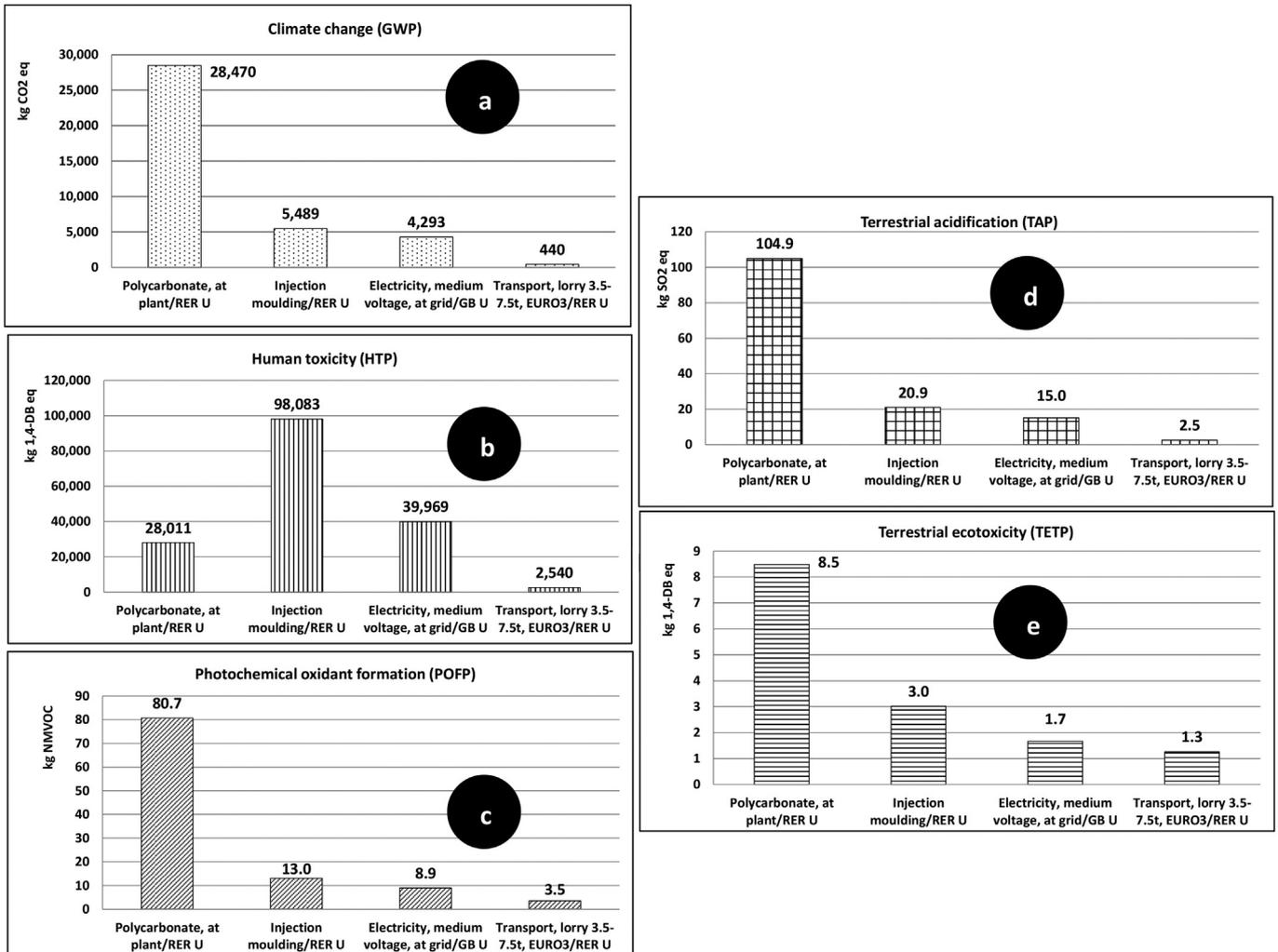


Fig. 6. Environmental impacts of CS.

Table 3
Lean manufacturing improvement feasibility study of the injection moulding process.

Task No.	Defects and findings	Causes	Effects by the causes	Lean techniques and tools for improvements
1	<ul style="list-style-type: none"> Production and process lead time can be reduced Number of operators can be minimised 	Order demand requirement Inventory arrangement Raw material order requirement Production operation efficiency, machine and equipment failure	<ul style="list-style-type: none"> Material usage Higher energy consumption Land and space occupancy Transportation produced higher CO ₂ emission <ul style="list-style-type: none"> Energy consumption Worker capabilities under fully utilises 	Kanban pull system – a method to control the demand order requirement for both suppliers and customers Using cellular manufacturing and TAKT time methods to fully utilise the capability of the worker and machine capabilities
2	Material usage is high and non-value-added material waste can be improved	<ul style="list-style-type: none"> Production requirement, monthly order planning. Machine efficiency, additional failure, set-up, parts defect allowance 	<ul style="list-style-type: none"> Material usage Higher energy consumption 	Using 5S and TPM methods to reduce material usage and to improve wastes
3	Material usage causes high emission output	Higher climate change	Global warming potential	Tasks 3 and 4 can be improved using the same lean techniques and tools as identified in solutions 1 and 2
4	Concern of the injection moulding process produces high human toxicity	Environmental persistence	Accumulation in the human food chain (exposure) and toxicity (effect) of a chemical	

- Fig. 6(e) illustrates the impact of Terrestrial Eco-Toxicity (TETP). Material usage contributed the largest impact with 58.70% and 8.48 kg1,4-DBeq. The injection moulding process contributed the second highest impact with, 20.90% and 3.026 kg1,4-DBeq. Next was electricity with 11.60% and 1.674 kg1,4-DBeq. Transportation has the lowest impact with 8.74% and 1.270 kg 1,4-DB eq.

As seen from the results, usage of material contributes to the largest impact among all the categories, reducing which will improve these negative environmental impacts. The second factor to be considered will be the manufacturing process and its associated energy consumptions reduction.

3.5. Product improvement for environmental impact reduction

3.5.1. Improvement using lean production tools

A feasibility study has been conducted using 'lean manufacturing' techniques to perform the improvements on injection moulding process lead times, machine failure, set-up time, NVA material waste, and most significantly material usage in the product. The areas of improvement were identified using the principle of seven forms of waste in lean manufacturing (Ohno, 1988). Table 3 summaries the activities undertaken during the feasibility study. In order to carry out an improvement of the injection moulding process, there are four main tasks to follow and each of the tasks is associated with findings where defects can be disclosed. Once a defect is identified, further investigation is focused on the causes. Once causes are diagnosed, suitable lean tools and techniques will be used to rectify the defects. Fig. 7 illustrates where improvements can be made by using different lean manufacturing techniques.

3.5.2. Improvements applied to the current state of the top housing product

Changing the data will allow a much more improved product for its FS and also provide the product with less negative environmental impacts. The main improvements are: (i) revised the

customer order strategy and change the delivery pattern; (ii) rearranged the production plan and (iii) updated the materials requirement planning:

- To revise the customer order strategy by changing the delivery days from Tuesday and Friday to a daily delivery basis. The packing methods remained 5 units in returnable tray and up to 12 trays per pallet. New order quantity can be arranged into 150/100/50 pieces. Assuming that the customer's new delivery arrangement is 50 pieces/d, the manufacturer will need to run two production d/week in a monthly basis. Overall, 8 d and 16 sessions are required in a month.
- To rearrange the production plan based on a new customer's order method. The lead time remains the same with 27,600 s per working day and with 2 sessions/d. Using the Kanban pull system's method to change the previously planned 360 pieces into 300 pieces/d is required. The time needed for the production will be 1 d in order to complete the arrangement of 150 pieces in 2 sessions/d.
- Materials requirement for each session of the new process is 165 kg and this is based on the quantity of products multiplied by the part weight, $1.10 \times 150 = 165$ kg per session;
- By using the 5s and TPM methods, the following can be reduced as follows:
 - The hopper dryer's failure rate into 0.1%
 - The machine set-up/sample test run at 0.1%
 - Part defect flashes at 0.01%.

The total part weight requires for each session can be determined as follows:

- Part weight is equal to 165 kg
- Hopper dryer failure is equal to 0.165 kg
- Machine set/sample test run is equal to 0.165 kg
- Part defects flashes is equal to 0.0165 kg.

The total required weight per session is 165.35 kg. Overall

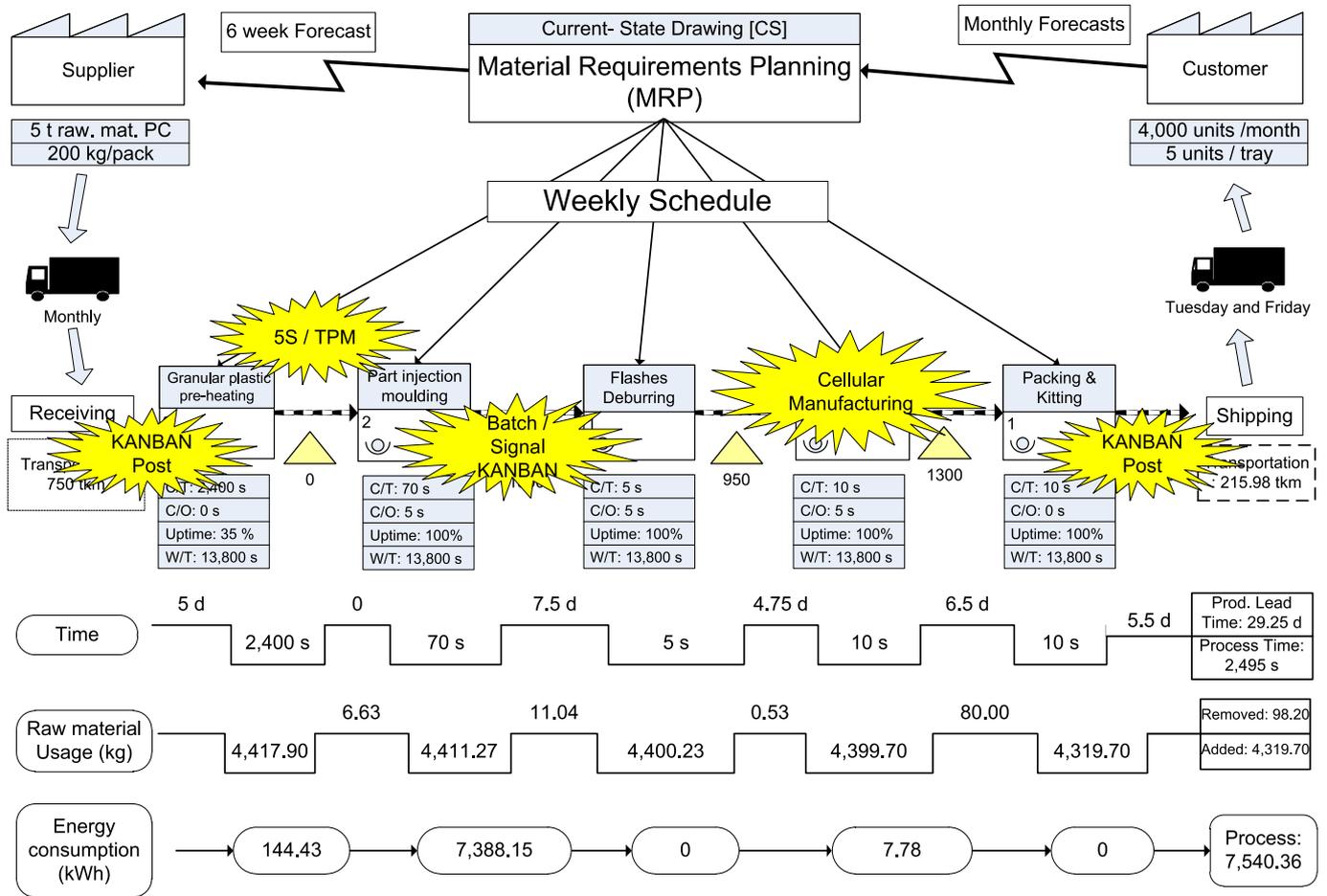


Fig. 7. Continuous improvement “Kaizen” diagram.

weight based on the new arrangement the total material required is $165.35 \times 16 = 2645.60$ kg.

3.5.3. The plastic injection moulding process improvement

Changing of a customer’s order strategy has affected the production plan and material requirements. The production process will require rearranging and the data of this rearrangement are shown in Table 4.

- Raw material acquisition implemented the Kanban pull system technique in order to manage the new method. The previously 6 week forecasts and order of 5 t of materials in monthly basis has changed to daily delivery in a single standard pack size of 200 kg. Order quantity has been reduced, the raw material supplier produced and deliver lead time has been completed in 1.5 d. Transportation remains the same with a truck size no greater than 7 t and the distance taken is 150 tkm from supplier to manufacturer. The new process requires 5 packs to be delivered per week with a total of 600 tkm.

Table 4
New improvement top housing manufacturing process requirement summarised list.

Process #	Process Requirement									
	Op.	Time			Material/Transportation			Machine/Equipment		
		L/T d	C/T s	C/O s	Item#	Usg '+'	Usg '-'	Item#	Usg '+'	
Material acquisition (Receiving)	N/A	1.5	N/A	N/A	Polycarbonate (PC) >7 t Lorry truck	4 t 600 tkm				
Granular plastic pre-heating	2	0	2352	0	Raw material granular plastic (PC)	2645.6 kg	1.32 kg	200 kg plastic hopper dryer machine	101.92 kWh	
Part Injection Moulding	2	1	68.6	2.75	Pre-heated Polycarbonate (PC)	–	1.32 kg	650 t Hydraulic injection moulding machine	4344.64 kWh	
Flashes deburring	1	0.5	23.75	0	Moulded part	–	48.264 kg	Bench drill machine	4.4 kWh	
Gate runner cutting Packing & Kitting Shipping Customer	N/A	N/A	N/A	N/A	Packed Finish Good >7 t Lorry truck	– 54tkm				

* Op- operator, L/T- Lead time, C/T: Cycle time, C/O: Changeover time.
Usg “+” = value added, Usg “-” = non value added.

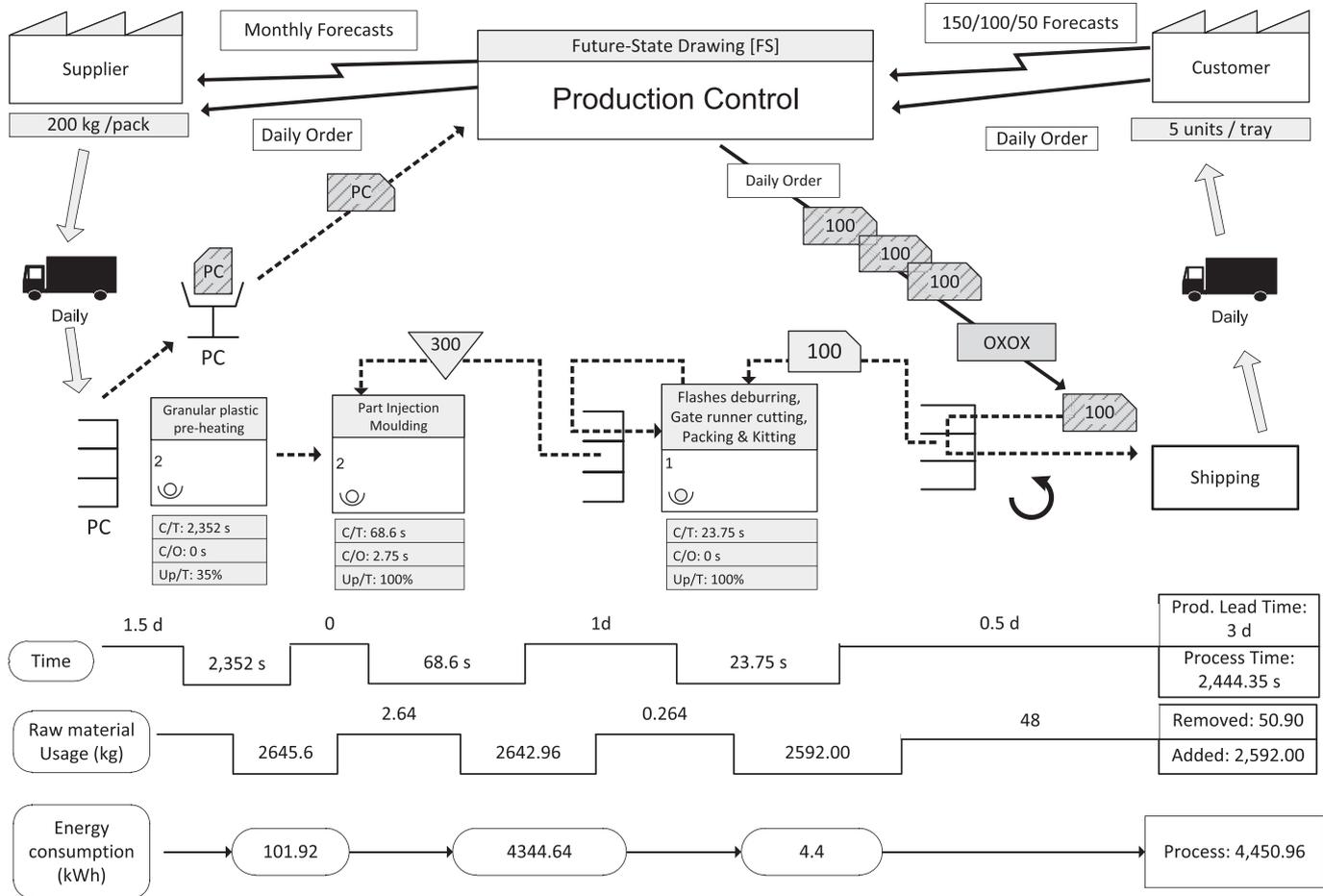


Fig. 8. VSM diagram for the product's future state (FS).

- Granular plastic pre-heating utilising the 5S and TPM techniques which resulted an improvement of 2% on the cycle time and this is equivalent to 39.2 min (2352 s). In order to complete the new process, the total energy consumption used by the plastic hopper dryer is 101.92 kWh. The hopper dryer failure allowance is 0.1% which contributes to 1.32 kg of waste material.
- Part injection moulding process also used the 5S and TPM techniques and resulted an improvement of 2% on the cycle time which has reduced the cycle time to 69.6 s. Total energy consumption for the injection moulding is 43,44.4 kWh. The machine set-up has a failure allowance of 0.1% which contributes to 1.32 kg of non-value-added material consumption (NVAMC).
- By using the cellular manufacturing method, the individual process of flashes deburring, gate runner cutting, packing and kitting have been grouped together at the same work station which requires only one operator. The overall cycle time has been improved by 5% and the total cycle time has been reduced

- to 23.75 s. The total NVAMC of the combined process is determined as follows:
 - A material flash deburring has an allowance rate of 0.01% which is equal to 0.264 kg.
 - The gate runner removal allowance rate is 1.8% which is equal to 48 kg.

Therefore the total NVAMC of this process is 48.3 kg. The energy for the drilling machine for gate runner removal process is 4.4 kWh.

- Shipping and deliveries to customers have changed from every Tuesday and Friday to daily basis. The lorry size is less than 7 t and the distance between manufacture to customer site is 50 km. The new shipping arrangement is equivalent to 54 tkm.

3.5.4. Value Stream Mapping for future state (FS)

Using the data from Table 4 an updated VSM for the improvement of the top-housing product is shown in Fig. 8. A new data set of the improved process requirement, material usage and energy consumptions are summarised in Table 5. This revised data set will be used as the inputs into the LCA for the product FS.

3.5.5. LCA of the product future state (FS)

The system boundary of the LCA I/O is shown in Fig. 9. The full LCI results of FS are shown in the supplementary data file (Product's Future State LCI results). The environmental impacts of FS are shown in the Appendix. Figs A3 and A4 represent the

Table 5
VSM future state (FS) overall process requirement summary list.

Details	Total	Unit
Production Lead Time	3	d
Process Time	2444	s
Operator	5	–
Material (value added)	2592	kg
Material (non -added)	48.26	kg
Energy Consumption	4451	kWh
Transportation (from supplier)	600	tkm
Transportation (to customer)	54	tkm

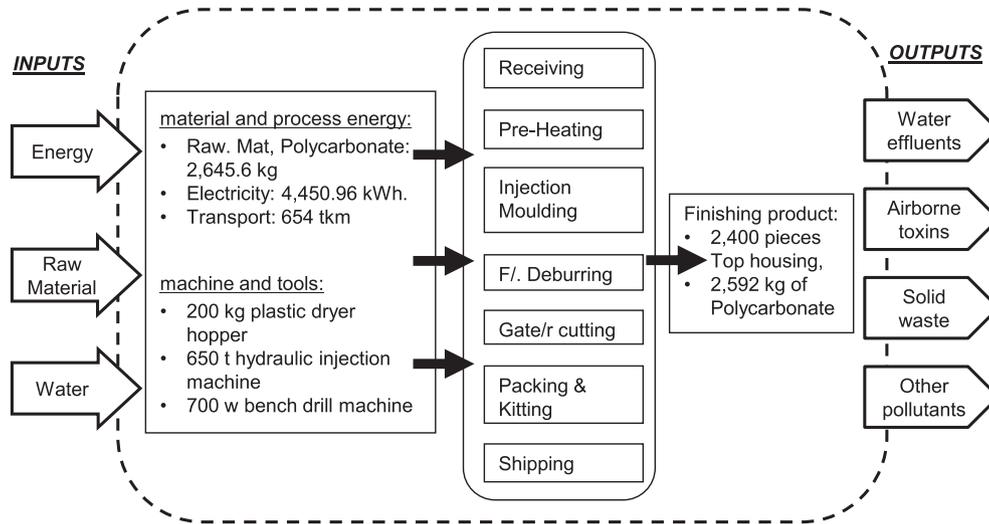


Fig. 9. System boundary for I/O LCA data for FS.

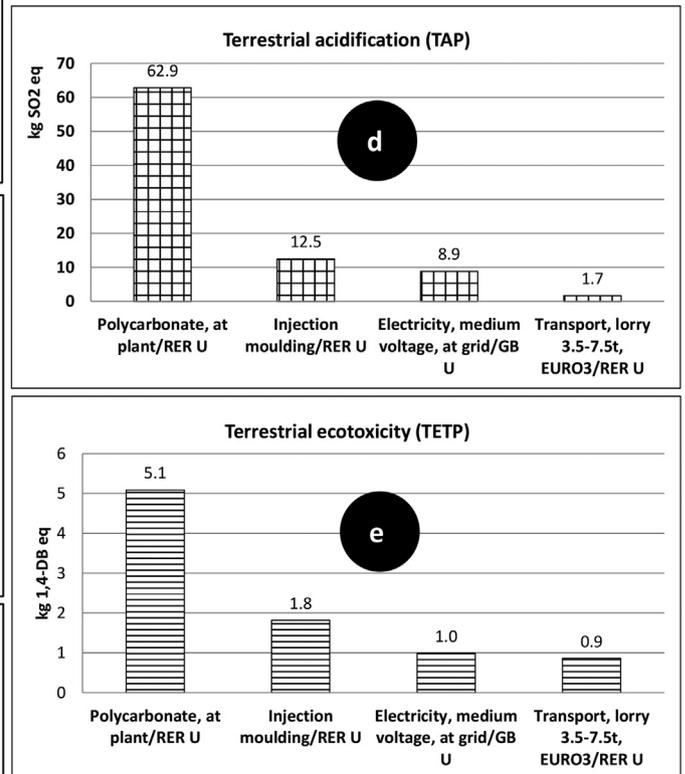
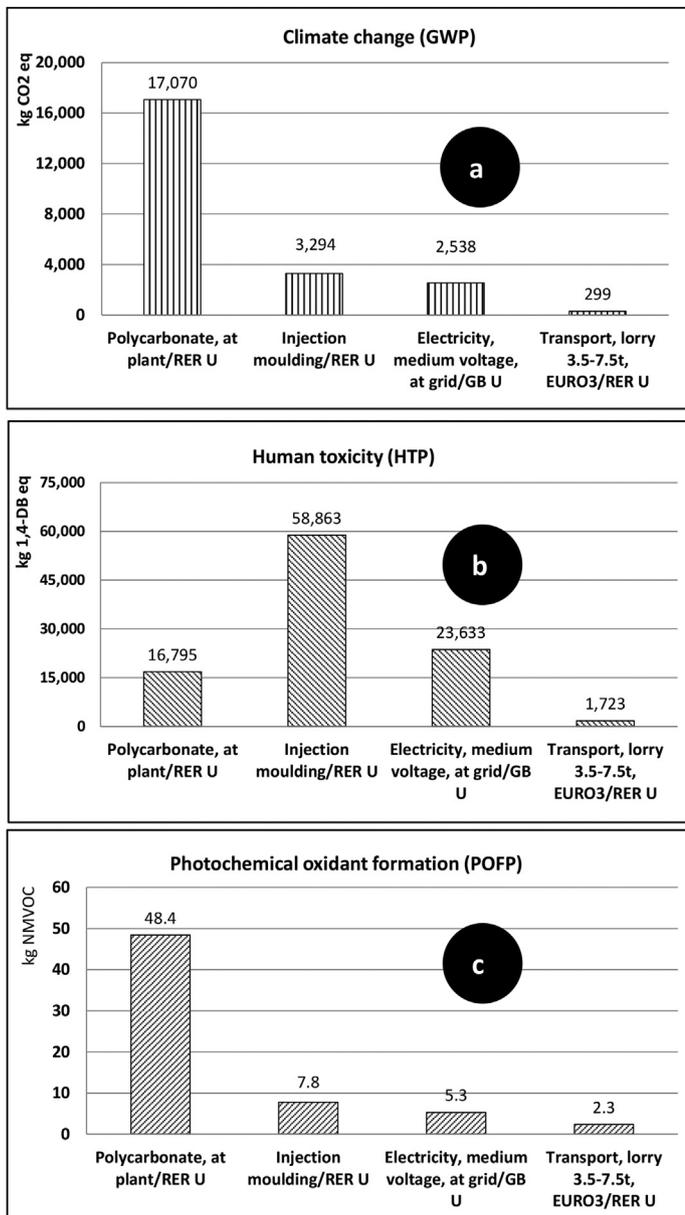


Fig. 10. Environmental impacts of FS.

Table 6
The overall analyse results and the outcomes.

Items #	Unit	Current State (CS)	Future State (FS)	Improved %
Production Lead Time	d	29.25	3	89.74%
Process Time	s	2495.00	2444.35	2.03%
Operators	–	7	5	28.57%
Material usage (value added)	kg	4319.7	2592.00	40.24%
Material usage (non-value added)	kg	98.2	48.26	
Energy Consumption	kWh	7540.36	4450.96	40.97%
Transportation (from supplier)	tkm	750	600	20.00%
Transportation (to customer)	tkm	215.98	54	32.30%
Climate change (GWP)	kgCO ₂ eq	38,691.97	23,201.26	40.04%
Human toxicity (HTP)	kg1,4-DBeq	16,8602.78	10,1013.38	40.09%
Photochemical oxidant formation (POFP)	kgNMVOC	106.10	63.82	39.85%
Terrestrial acidification (TAP)	kgSO ₂ eq	143.35	86.04	39.98%
Terrestrial eco-toxicity (TETP)	kg1,4-DBeq	14.46	8.76	39.44%

characterisation and normalisation of the product future state environmental impacts. The FS environmental impacts inventory is shown in Table A2. Fig. 10 highlights the LCA of the product FS's selected environmental impact factors.

- Fig. 10(a) illustrates the impact of Climate Change (GWP). It shows that material usage contributed 73.43% with 17,070.4 kgCO₂eq. The injection moulding process contributed to 14.17% and 3294 kgCO₂eq. Electricity consumption and transportation added further 11.16%, 2593.6 and 1.24%, 288.8 kgCO₂eq.
- Fig. 10(b) illustrates the impact of Human Toxicity (HTP). It shows that injection moulding produced the largest impact of 58.10% and 58,863.2 kg1,4-DB eq. Next were electricity consumption, material usage and transportation contributed 23.64%, 23,955.4 kg1,4-DBeq; 16.58%, 16795 kg1,4-DBeq and 1.68%, 1703.15 kg 1,40DBeq.
- Fig. 10(c) illustrates the impact of Photochemical Oxidant Formation (POFP). The highest impact was the material usage at 76.53% and 48.4 kgNMVOC. Next were the injection moulding process, electricity consumption and transportation processes with impacts of 12.31%, 7.783; 8.52%, 5.388 and 2.65%, 1.675 kg NMVOC.
- Fig. 10(d) illustrates the impact of Terrestrial Acidification (TAP). The highest impact was the material usage at 73.31%, 62.894 kgSO₂eq. The injection moulding, electricity consumption and transportation contributed the following impacts 14.61%, 12.537; 10.56%, 9.0574 and 1.52%, and 1.3039 kgSO₂eq.
- Fig. 10(e) illustrates the impact of Terrestrial Eco-Toxicity (TETP). Material usage contributed the largest impact with 58.11%, 5.087 kg1,4-DBeq. Injection moulding, electricity consumption and transportation contributed the following impacts 20.74%, 1.816; 11.35%, 0.9936 and 9.80%, 0.8576 kg1,4-DB.

Result shows that material usage contributes to the largest impact, reduction of which has improved the negative environmental impacts among all categories. The next session will analysis the overall result of current state (CS) and future state (FS) of the same product.

4. The overall results and findings

The full environmental impacts comparison of CS and FS is shown in the Appendix's Fig A5. Table 6 presents a comparison of

the overall result of the current state (CS) and the improved future state (FS).

The result shows that the production lead time has been reduced from 29.95 to 3 d contributing a reduction of 89.98%. The production lead time has been reduced significantly because of the difference of order arrangements (see Section 3.1's current state and Section 3.5.4's future state). The process time had a slight reduction of 2.03%. The number of operators was also reduced from 7 to 5 which would mean savings from salary. Material used was also reduced from 4319.7 kg to 2592 kg which led to a reduction of 40%. Energy consumption was also reduced due to less production time and total required sessions. This ratio of reduction is 40.97% and the energy usage is reduced from 7540.36 to 4450.96 kWh. The transportation is not a major contributor to the environmental impacts but the total distance driven was reduced from 965.98 tkm to 654.00 tkm and this represents an improvement of 32.3%.

- *Climate change (GWP)*: From environment impacts point of view, polycarbonate (material) presents the largest contributor on both current and future states. The current state contributes to 28,470.05 kgCO₂eq whereas the future state has been reduced to 17,070.40 kgCO₂eq. This is a massive improvement for the process as the raw material costs would significantly decrease. The overall improvement was around 40%.
- *Human toxicity (HTP)*: The injection moulding process is the largest contributor to both states; with the current state contributing to 98,082.73 kg 1,4-DBeq, comparing this to the future state which has been reduced to 58,863.18 kg 1,4-DBeq, contributing to a reduction of approximately 40%. The future state has resulted in a much more improved in Human toxicity with the current state overall total 168602.78, compared to the future states 101,316.73 kg 1,40 DBeq.
- *Photochemical oxidant formation (POFP)*: In terms of POFP, the largest contributor is the materials process. The process has been lowered from the current state's 80.73 to the future state's 48.4 kg NMVOC, this account to a reduction of 60%. The overall total for the current state was 106.098 compared to the future states total 63.25 kg NMVOC, improving the current state by 59%.
- *Terrestrial acidification (TAP)*: The largest contributor to terrestrial acidification was the material usage totalling 104.89 kgSO₂ for the current state. This figure was reduced for the future state cycle to 62.89 kgSO₂. The overall process was decreased from 143.35 to 85.79 kgSO₂, this represented an improvement of 59% for terrestrial acidification.
- *Terrestrial eco-toxicity (TETP)*: The largest contributor for both cycles was the material usage, representing the current states total of 8.486 kg 1,4-DBeq compared to the future states of 5.088 kg 1,4-DBeq, the process for the material usage was improved by 59%. The overall contribution for the current state was 14.45 kg 1,40-DBeq, the future states total was 8.75 kg 1,40-DBeq, making the overall process improved by 61%. This process has been greatly improved.

The largest contributor to terrestrial acidification was the material usage totalling 104.89 kgSO₂ for the current state. This figure was reduced for the future state cycle to 62.89 kgSO₂. The overall process was decreased from 143.35 to 85.79 kgSO₂, this represented an improvement of 59% for terrestrial acidification.

5. Conclusions and further work

The results and finding show that significant improvements on environmental impacts have been achieved by using lean manufacturing techniques. By implementing the Kanban's pull

system to control customer and supplier order arrangement, the total operations time has been shortened significantly by 90%. Due to the change of delivery requirements, the total material usage has been reduced and this has a direct influence in terms of reducing carbon emissions in manufacturing by 40%. The implementation of TPM, 5S and Cellular Manufacturing methods have contributed a significant saving of 41% in energy and electricity consumptions to the production process and this represents a sizeable reduction of human toxicity. Based on the study described in this work, the following conclusive remarks can be made:

- Lean and LCA techniques are insufficient in isolation to make the required progress to minimise environmental impacts of a product. This research has demonstrated that the integration of lean production tools and LCA is imperative in quantifying and reducing environmental impact in manufacturing.
- This research has the potential to provide a major impact on redesigning and reassessing existing plastic products for reducing environmental impacts. For example, in future application, a component in the case study can be replaced with any plastic component, thus contributing a blue print for making plastic product more environmental friendly.
- The proposed methodology can have profound impact on current LCA methods adopted in the industry, as means of producing a revised design can be assessed using Lean techniques reported in the paper.

Finally, economic aspect is an important part of sustainability (Simons and Cheung, 2016), quantifying environmental impact reduction as a cost is recommended for the future work. Another

potential research area that could be investigated is a three-stage data envelopment analysis (DEA) (Li and Lin, 2016) with the current approach. For example, deploying the three stage DEA to explore the effect of environmental factors (Su et al., 2016) in an energy intensive injection moulding process.

Conflicts of interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jclepro.2017.08.208>.

Appendix. Environmental impacts results

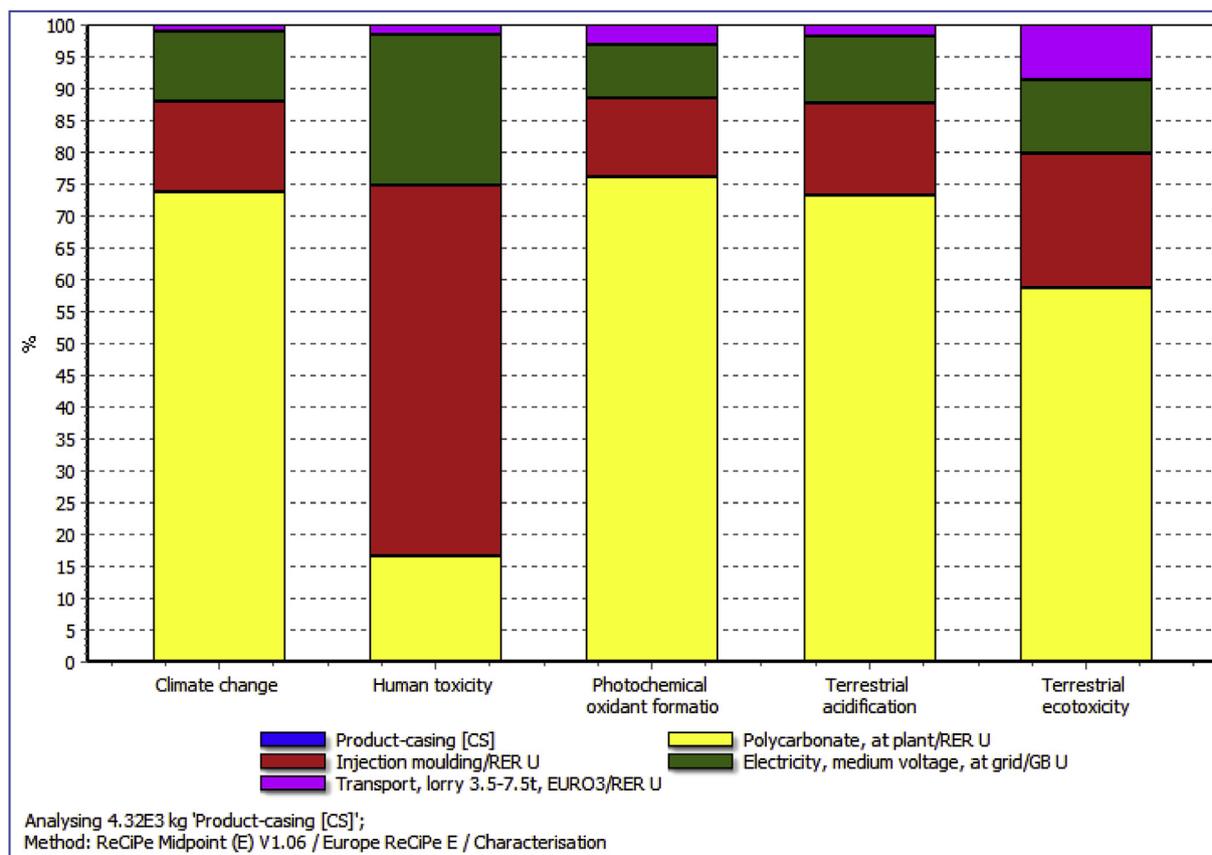


Fig. A1. Product's Current State (CS) Environmental Impacts Characterisation.

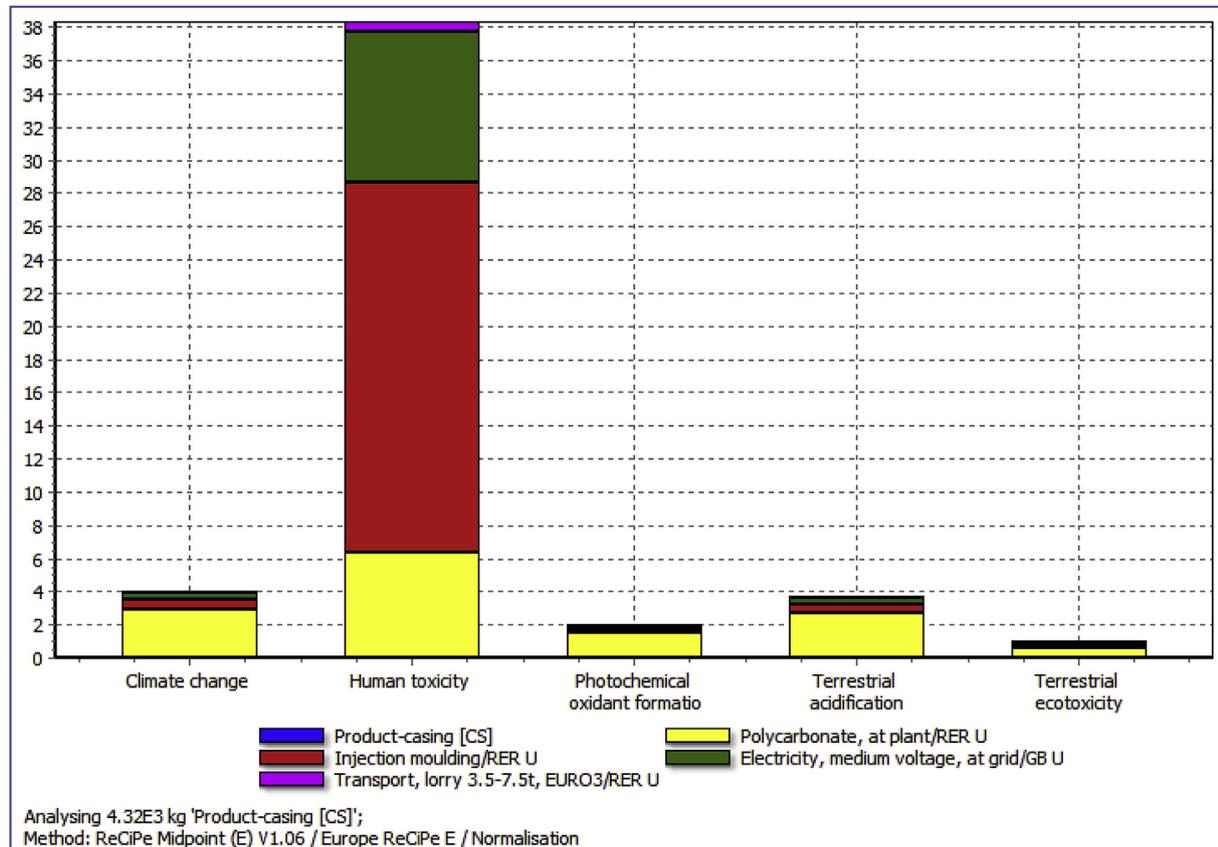


Fig. A2. Product's Current State (CS) Environmental Impacts Normalisation.

Table A1 Product's Current State (CS) Environmental Impacts Inventory.

Sel	Impact category	Unit	Total	Product-casing [CS]	Polycarbonate at plant/RER	Injection moulding/RER	Electricity, medium	Transport, lorry
<input checked="" type="checkbox"/>	Climate change	kg CO2 eq	3.87E4	x	2.85E4	5.49E3	4.29E3	440
<input type="checkbox"/>	Ozone depletion	kg CFC-11 eq	0.015	x	0.0112	0.00368	0.000111	6.94E-5
<input checked="" type="checkbox"/>	Human toxicity	kg 1,4-DB eq	1.69E5	x	2.8E4	9.81E4	4E4	2.54E3
<input checked="" type="checkbox"/>	Photochemical oxidant formation	kg NMVOC	106	x	80.7	13	8.94	3.46
<input type="checkbox"/>	Particulate matter formation	kg PM10 eq	60.9	x	49	6.42	4.48	0.983
<input type="checkbox"/>	Ionising radiation	kg U235 eq	4.89E3	x	16.5	2.78E3	2.02E3	67.7
<input checked="" type="checkbox"/>	Terrestrial acidification	kg SO2 eq	143	x	105	20.9	15	2.54
<input type="checkbox"/>	Freshwater eutrophication	kg P eq	5.76	x	0.913	3.51	1.28	0.0501
<input type="checkbox"/>	Marine eutrophication	kg N eq	3.99	x	2.11	1.16	0.601	0.123
<input checked="" type="checkbox"/>	Terrestrial ecotoxicity	kg 1,4-DB eq	14.5	x	8.49	3.03	1.67	1.27
<input type="checkbox"/>	Freshwater ecotoxicity	kg 1,4-DB eq	139	x	65.2	52.6	19.8	1.44
<input type="checkbox"/>	Marine ecotoxicity	kg 1,4-DB eq	1.33E5	x	1.83E4	8.09E4	3.22E4	1.9E3
<input type="checkbox"/>	Agricultural land occupation	m2a	650	x	0.899	564	82.3	2.26
<input type="checkbox"/>	Urban land occupation	m2a	58.5	x	2.15	26.9	19.4	10.1
<input type="checkbox"/>	Natural land transformation	m2	1.96	x	-0.00444	0.925	0.875	0.164
<input type="checkbox"/>	Water depletion	m3	117	x	57.7	33	24.6	1.84
<input type="checkbox"/>	Metal depletion	kg Fe eq	195	x	13.1	118	40	23.7
<input type="checkbox"/>	Fossil depletion	kg oil eq	1.39E4	x	1.03E4	2.07E3	1.37E3	165

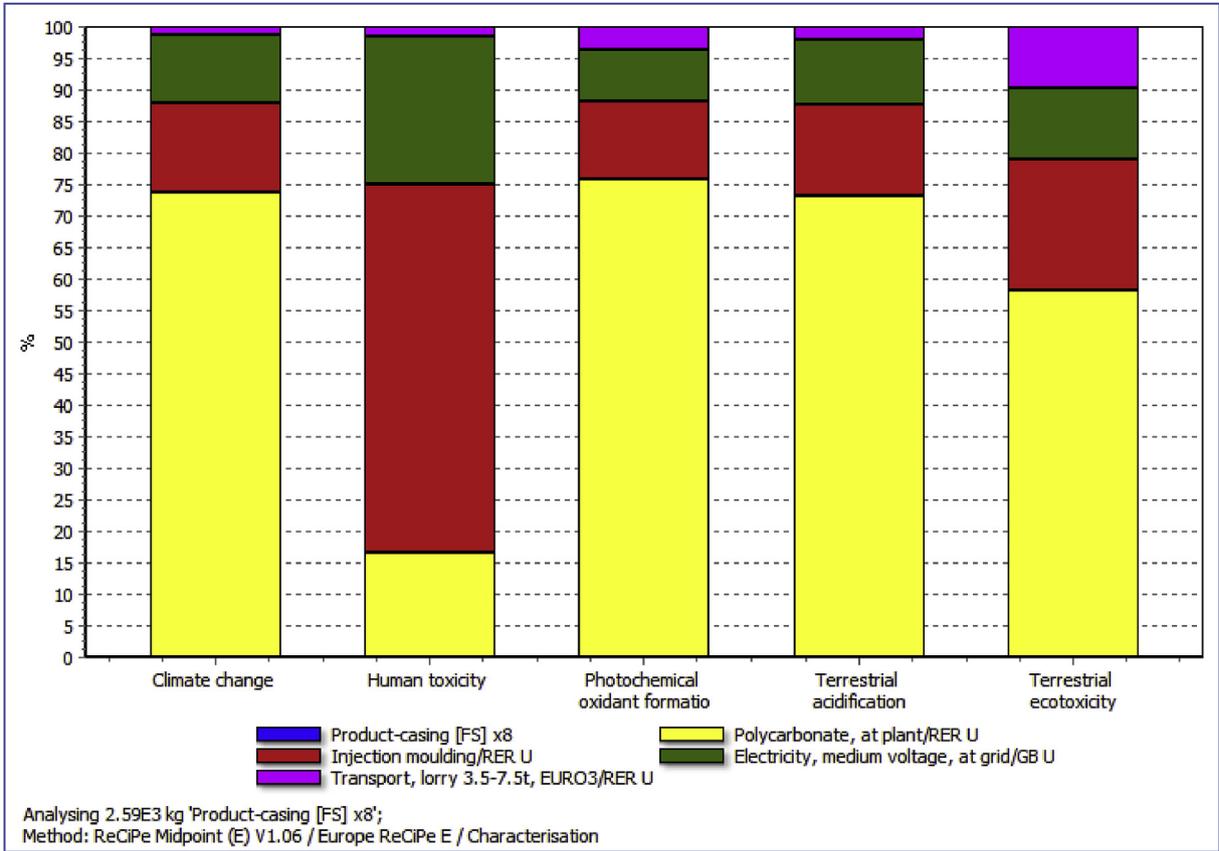


Fig. A3. Product's Future State (FS) Environmental Impacts Characterisation.

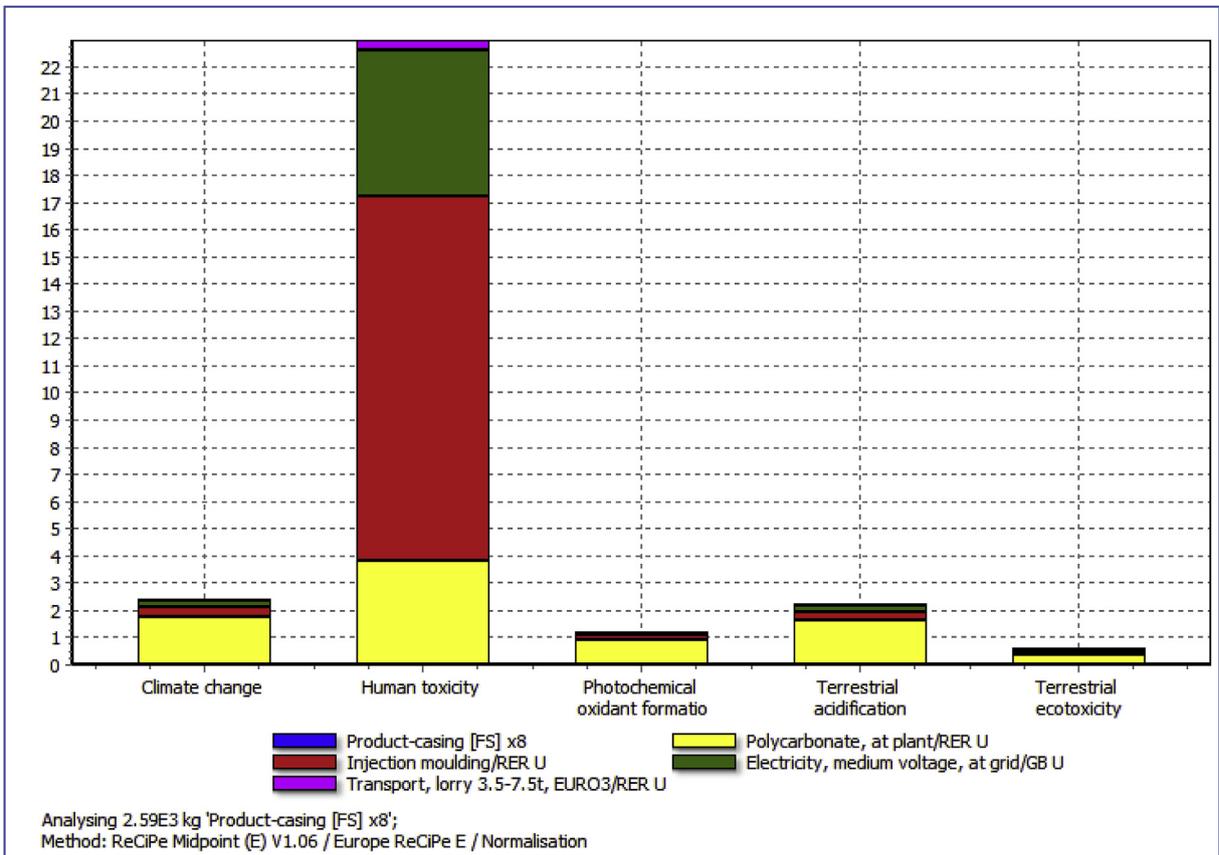


Fig. A4. Product's Future State (CS) Environmental Impacts Normalisation.

Table A2 Product's Future State (FS) Environmental Impacts Inventory.

Sel	Impact category	Unit	Total	Product-casing [FS] x8	Polycarbonate, at plant/RER U	Injection moulding/RER U	Electricity, medium voltage, at grid/GB	Transport, lorry 3.5-7.5t, EURO3/RER U
<input checked="" type="checkbox"/>	Climate change	kg CO2 eq	2.32E4	x	1.71E4	3.29E3	2.54E3	299
<input type="checkbox"/>	Ozone depletion	kg CFC-11 eq	0.00901	x	0.00669	0.00221	6.58E-5	4.71E-5
<input checked="" type="checkbox"/>	Human toxicity	kg 1,4-DB eq	1.01E5	x	1.68E4	5.89E4	2.36E4	1.72E3
<input checked="" type="checkbox"/>	Photochemical oxidant formation	kg NMVOC	63.8	x	48.4	7.78	5.28	2.35
<input type="checkbox"/>	Particulate matter formation	kg PM10 eq	36.6	x	29.4	3.85	2.65	0.667
<input type="checkbox"/>	Ionising radiation	kg U235 eq	2.92E3	x	9.91	1.67E3	1.2E3	45.9
<input checked="" type="checkbox"/>	Terrestrial acidification	kg SO2 eq	86	x	62.9	12.5	8.89	1.72
<input type="checkbox"/>	Freshwater eutrophication	kg P eq	3.45	x	0.547	2.11	0.758	0.034
<input type="checkbox"/>	Marine eutrophication	kg N eq	2.4	x	1.26	0.694	0.355	0.0835
<input checked="" type="checkbox"/>	Terrestrial ecotoxicity	kg 1,4-DB eq	8.76	x	5.09	1.82	0.99	0.861
<input type="checkbox"/>	Freshwater ecotoxicity	kg 1,4-DB eq	83.4	x	39.1	31.5	11.7	0.975
<input type="checkbox"/>	Marine ecotoxicity	kg 1,4-DB eq	7.99E4	x	1.1E4	4.86E4	1.91E4	1.29E3
<input type="checkbox"/>	Agricultural land occupation	m2a	389	x	0.539	339	48.7	1.53
<input type="checkbox"/>	Urban land occupation	m2a	35.7	x	1.29	16.1	11.5	6.84
<input type="checkbox"/>	Natural land transformation	m2	1.18	x	-0.00266	0.555	0.518	0.111
<input type="checkbox"/>	Water depletion	m3	70.2	x	34.6	19.8	14.6	1.25
<input type="checkbox"/>	Metal depletion	kg Fe eq	119	x	7.83	71	23.7	16
<input type="checkbox"/>	Fossil depletion	kg oil eq	8.33E3	x	6.16E3	1.24E3	812	112

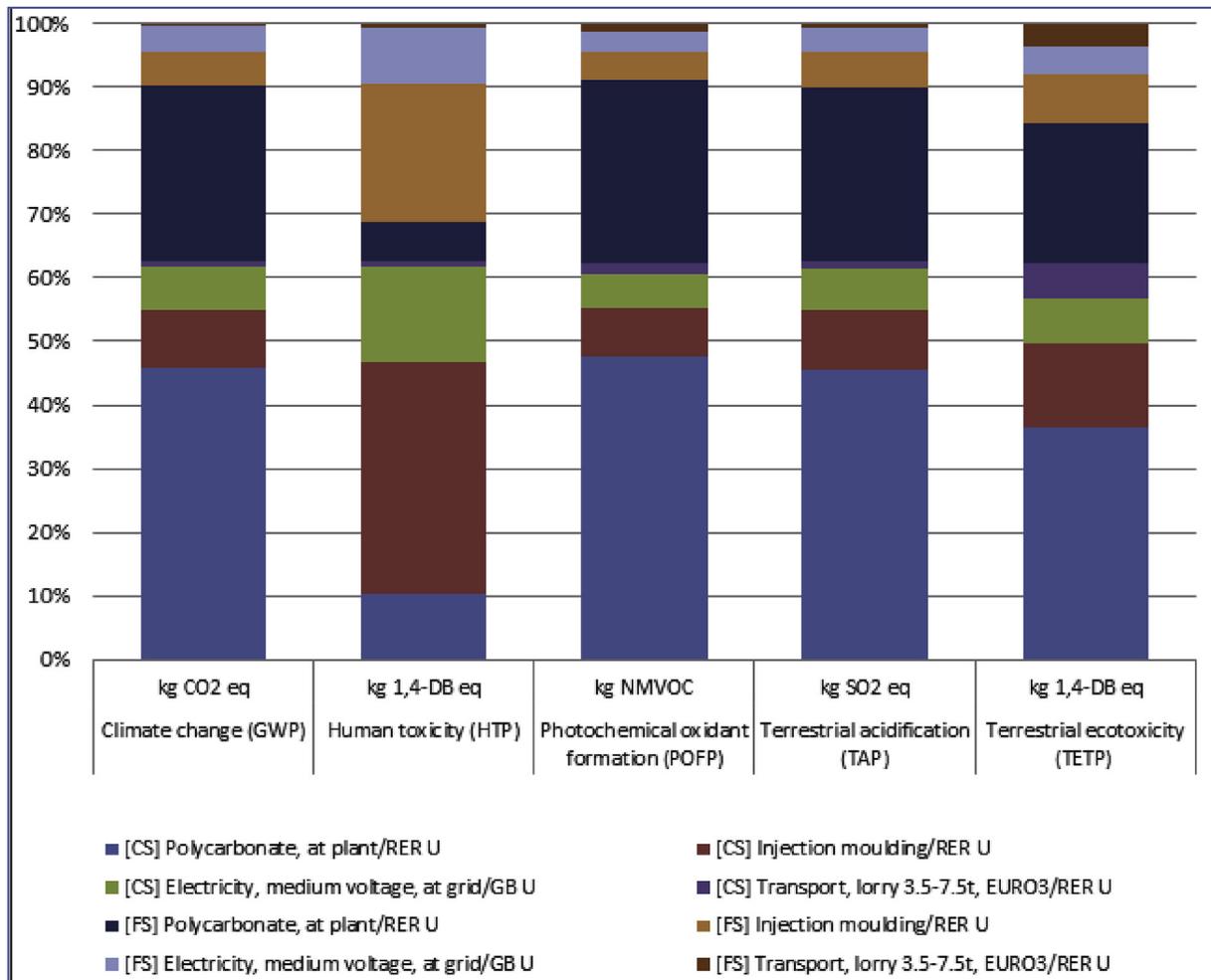


Fig. A5. CS and FS Environmental Impact Comparison.

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