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Understanding the sustainability potential of part consolidation design supported by additive manufacturing

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Abstract

The environmental performance of additive manufacturing (AM) processes and the produced parts has gained increasing interest. Various assessment models have been developed based on the general life cycle assessment (LCA) framework, although different in goals and boundaries, the inputs for these models are always a single part (or a batch of same parts). In contrast, the present research provides a new perspective towards the selection of a more sustainable assembly design. A comparative LCA model is built to investigate the environmental performance difference of two design approaches: assembly design (AD) made via conventional manufacturing (CM) plus assembly operations and part consolidation (PC) made via AM plus machining. The effects of weight reduction, prolonged life expectancy, and improved functional performance (e.g. fuel efficiency) attainable in the PC routine and the advantages of replaceable subcomponents in the AD routine are studied in a throttle pedal assembly example throughout the lifespan of the vehicle. The results reveal that the PC routine can be more environmental friendly than the AD counterpart when the lifespan can be improved by over 200% or the weight savings are more than 30%. The role of functional performance improvement on affecting sustainability may depend on the part/vehicle ratio and vehicle types. This article extends the literature on sustainable assembly design and the proposed LCA model provides a way of identifying the profitable margins of PC in the early design stage.

Keywords: part consolidation, environmental impact, lifecycle analysis, design for additive manufacturing, assembly

1. Introduction

Additive manufacturing (AM) has drawn increasing attention in industry because it is one of the possible manufacturing method parallel with mass conserving (i.e., forming) and subtractive (i.e., machining) processes (Thompson et al., 2016; Yang and Zhao, 2015). Compared to these conventional manufacturing (CM) processes, AM has been proven to be advantageous in the following aspects. First, AM works in a layer-by-layer or even voxel-by-voxel fashion, which largely frees designers from restrictions imposed by CM processes, such as freeform shapes and complex internal structures (Gibson et al., 2010). Second, AM provides a different method of joining materials, by which material waste (e.g. chips in CNC milling) and CO₂ emissions generated during the manufacturing process can be dramatically avoided (Huang et al., 2015; Huang et al., 2013). Third, AM techniques requires a much shorter process route and less assisted tooling. This effectively facilitates localized manufacturing and less demand of spare parts and transportation (Ford and Despeisse, 2016). All these features distinguish AM from CM processes, making it intuitively considered to be a “clean” or “green” process (Le Bourhis et al., 2014).

Given that the manufacturing sector takes responsibility for over 30% global greenhouse gas emissions (Pachauri et al., 2014) and many other environmental impacts, reducing energy consumption and other

resource depletion is important for facilitating much wider applications of AM. With publicly available data, Ford and Despeisse (2016) summarized the impacts of AM on social, environmental, and economic sustainability across the product and material cycle including product and process redesign, material input processing, make-to-order component and product manufacturing, and closing the loop (retirement treatment). As discussed by the authors, the coexistence of beneficial and negative impacts of AM towards sustainability highlights the need of more research to understand the sustainability potentials of AM process, which is evolving rapidly. To quantitatively measure the environmental performance of AM processes, manufacturing systems, or additively manufactured parts, various environmental impact assessment models have been built upon the general framework of life cycle assessment (LCA) (Rebitzer et al., 2004). The progress of published researches on the environmental analysis of AM has been comprehensively reviewed in papers (Jin et al., 2017; Kellens et al., 2017a; Peng et al., 2018). Existing quantitative studies on the environmental dimensions of AM can be roughly redistributed into the following streams:

- (1) **Stream I:** developing analytical models of unit AM processes. For metal-based AM processes, typical works include selective laser melting (SLM) (Faludi et al., 2017; Kellens et al., 2010), electron beam melting (Baumers et al., 2017), direct additive laser manufacturing (Le Bourhis et al., 2014), and binder jetting AM (BJAM) process (Xu et al., 2015). As for polymers, environmental analysis has been reported by Yang and Li (2018) for stereolithography, and Song and Telenko (2017) for fused deposition modelling (FDM). Researches under this theme may differ from types of material and AM machines, environmental indicators (e.g. energy, material, and thereof), and whether material production, embodied energy in machine and auxiliary tools (Faludi et al., 2017), and post processing are included.
- (2) **Stream II:** optimizing process parameters for improving environmental performance of AM systems via minimizing the whole flux consumption of energy, material, and fluids. [Mognol et al. \(2006\) examined the relation between electricity consumption and parameters including orientation, position and height of the part, layer thickness, and support.](#) Kellens et al. (2014) further investigated the variables of operation patterns, nesting efficiency, and powder refresh rate in selected laser sintering process. [Similar works are also reported in literatures \(Al-Meslemini et al., 2018; Griffiths et al., 2016; Ma et al., 2018\).](#)
- (3) **Stream III:** comparing the environmental performance of various manufacturing processes with fixed part design as the input. Researches in this stream emphasizes on the differences of energy and carbon footprint due to the selection of different processes (AM-AM or AM-CM) for fabricating the same part(s), thereby suggesting the proper manufacturing process. Baumers et al. (2011a) compared the electric energy consumption of two major polymeric laser sintering platforms, identifying the time-dependent energy consumption as the main energy drain. Morrow et al. (2007) developed the first comparative analysis qualifying the energy consumption and CO₂ emissions in the scenario of producing molds and dies via CNC milling and laser-based direct metal deposition. The results highlighted the significance of geometry complexity in the selection of more sustainable process. Yoon et al. (2014) expanded the comparative analysis to include FDM, injection molding, and milling as the fabrication methods of a plastic component, which indicates the deterministic role of batch size in specific energy consumption (SEC) characterization. Similar works are reported by Paris et al. (2016) and Le Thao et al. (2017) with different AM processes and material production flow. Watson and Taminger (2015) proposed a computational model in support of choosing the most energy-efficient process for the production of a metallic part. In conclusion, the additive approaches may be more sustainable when the part is in low batch size, with high void-to-solid ratio, and the AM printers have capability of adding features on an existing part compared to conventional routines.

- (4) **Stream IV:** Investigating the sustainability potential of additively manufactured optimized design in contrast with legacy design fabricated by CM (subtractive or formative). Researches in this category also need to build comparative LCA models of AM and CM, but they emphasize on measuring the impacts of AM-enabled design freedoms on sustainability. Representative studies are reported in literatures (Huang et al., 2015; Priarone and Ingarao, 2017; Tang et al., 2016a). Huang et al. (2015) focused on examining the impacts of weight reduction that was derived from design optimization on energy consumption and greenhouse gas emission with five aircraft components throughout the service life of flight. The results have shown that the energy savings primarily come from reductions in resource production due to material savings. Similar results are echoed by Tang et al. (2016a) which emphasized the importance of topology optimization in achieving sustainable design. By considering the effects of lightweight obtainable by AM, literatures (Ingarao et al., 2018; Priarone and Ingarao, 2017) examined the repercussions on the environmental impacts throughout the entire life cycles of an additively fabricated part (with a lightweight factor) and a conventionally made part; then, the choice of the most environmentally friendly processes changes as the lightweight factor varies.

Overview of the existing quantitative studies of the environmental performance of AM process or additively manufactured part(s) has highlighted the importance of considering different design inputs for AM due to its new characteristics, such as lightweight (Huang et al., 2015; Tang et al., 2016a), part complexity (Morrow et al., 2007), batch size (Faludi et al., 2017). However, although some researchers (such as (Kellens et al., 2017a)) mentioned the importance of integrating improved performance (e.g. aerodynamic properties) in use stage to compensate the higher SEC of AM process in production stage, rare studies actually examined this effect. Moreover, almost all of these studies focus on a single part or a batch of the same parts, little attention has been drawn to the sustainability study of assemblies. Part consolidation (PC), as an alternative solution of assembly design, consolidating multiple parts into one piece without assembly operations, although widely recognized as one of the major motivations of utilizing AM technologies (Schmelzle et al., 2015; Yang et al., 2016), the sustainability potential of which remains unknown. Through PC, it can eliminate assembly operations, avoid assembly-related quality issues, shorten supply chain, and improve functionality; meanwhile, it shows disadvantages in replacing failed sub-components as the assembly design (AD) does. The complicated effects of PC towards sustainability requires a comprehensive lifecycle model to support better decisions in terms of AD or PC in the context of environment benign product development.

Reported researches on PC mainly serve as proof of concept (GE Capital, 2013; Schmelzle et al., 2015), establish the conditions or rules under which PC is technically feasible with the aid of AM technologies (Yang et al., 2018a; Yang et al., 2018b; Yang and Zhao, 2018), or investigate the comparative monetary cost of PC in product development and production (Johnson and Kirchain, 2009). For example, the number of parts in the fuel nozzle of GE LEAP jet engine is reduced from 20 to 1 with more intricate internal cooling pathways and the mass becomes 25% lighter while it becomes 500% more durable than its conventionally manufactured counterpart (GE Capital, 2013). However, very few efforts have been aimed at understanding the sustainability potential of PC. The increasing applications of PC in industries such as aerospace and automobile make environment-benign PC design a pressing need. The environmental impacts of PC in the context of CM are examined under the themes of design for manufacturing and assembly (DfMA) and design for environment (DfE). Chowdary et al. (2009) proposed an integrated framework for combining DfMA and DfE in the early design concept selection stage and tested it with a redesign case study of a desk organizer. By reducing the part count from 45 to 11, the new design reduced 22% mass, 62% assembly time, and 82% environmental impacts derived from direct material savings. However, the change of manufacturing process because of PC is not considered in this study. This deficit was overcome in another study of an industrial digital clock conducted by Mesa et

al. (2018) with consideration of different SECs of alternative manufacturing processes. Through choosing more sustainable process, reducing part weight, and integrating multiple parts, the new product reduced 80% welding operations, 10% electricity energy, and 60% carbon footprint in the production stage. Tang et al. (2016b) and Yang et al. (2017) are the first ones to investigate the sustainability of PC in the context of AM. Tang et al. (2016b) combined PC with topology optimization to further reduce material usage while securing satisfaction of engineering requirements. Comparative analysis was conducted for the PC design made by BJAM process and the AD made by CNC milling in the production stage. By using the ReCiPe midpoint method (Heijungs et al., 2003), the results have shown that the PC design outperformed the AD design in almost all categories except human health and ionizing radiation because of the use of bronze in BJAM process to infiltrate the steel part. Yang et al. (2017) extended the work to include gas welding in the assembly stage for a welded assembly comprised of sheet metal components. Their findings revealed that the PC design showed significant reduction in all environmental indicators compared to the AD design, and the environmental burden caused by the assembly stage only accounted for at most 13%. There are several deficits in these preliminary investigations. First, prior studies only compare the environmental impacts caused by the production stage for both design scenarios. Without comprehensive investigation of the entire life cycles of both designs, it may lead to a biased view of PC's sustainability potentials. Second, it is not accurate by assuming that all components in the assembly are fabricated by one single process (e.g. CNC milling). The SECs and yield ratios of different processes may vary drastically. For example, the SECs of CNC milling and turning are 44.83 MJ/kg and 12.9 MJ/kg respectively (Yoon et al., 2014). Third, rare research studied the effects of improved performance or prolonged lifespan of consolidated design in the use stage. As shown in the example of GE fuel nozzle (GE Capital, 2013), the PC design enjoyed 5 times longer service life and a 15% increase in fuel efficiency, which may drastically enlarge the advantageous margin compared to the assembly design. Lastly, the benefits of flexible replacement of failed components in the assembly design are never evaluated. As such, there is a strong need to evaluate the environmental performance of AM-supported PC design with full considerations of reduced weight, improved performance, prolonged lifespan, and failure of subcomponent replacement.

This paper aims at developing a comprehensive decision support tool of selecting a more sustainable assembly design solution in the early product design stage. Two typical design solutions are compared and analyzed: PC design fabricated by the combination of AM and machining and AD design made by the combination of CM and assembly operations. To avoid biased views of prior studies, the factors of lightweight, improved performance, and prolonged lifespan, and part reuse which is unique in the AD approach are fully considered. To account for the factor of part reuse, extended life cycles (i.e. multiple life cycles in contrast with one life cycle) of both design solutions are innovatively investigated in this study. The structure of this paper is organized as follows. First, a comparative lifecycle model of consolidated design (a steel part made by SLM process and CNC milling for post-treatment) and assembly design (made by CM process and assembly operations) is clearly defined with goal, scope, and LCA boundary in Section 2. Second, the lifecycle inventory (LCI) data are calculated based on the LCA models presented in Section 3 to build an analytical way for comparison. Third, an exploratory case study of a throttle pedal of a passenger vehicle is presented in Section 4 with two design scenarios: consolidated design and assembly design. The effects of the three variables are investigated. Fourth, lifecycle impacts analysis is conducted based on the LCI data by using ReCiPe Endpoint method. Results are analyzed to gain a comprehensive view towards the environmental performance of both design scenarios. In the end, it is wrapped up with conclusions and future research.

Nomenclature

AM	Additive manufacturing	<i>Assm</i>	Phase of assembly
BJAM	Binder jetting additive manufacturing	<i>DisA</i>	Phase of disassembly

PC	Part consolidation	x	One or multiple lifecycle
DfAM	Design for additive manufacturing	y	PC or AD routine
DfMA	Design for manufacturing and assembly	z	Resources including water, argon, and oil
DfE	Design for environment	i	Component $Comp_i$
LCA	Lifecycle assessment	j	j represents the object of PC, AD, or $Comp_i$
LENS	Laser Engineered Net Shaping	p	Lifecycle phases such as Mat , SLM , FM , etc.
CNC	Computer numerical control	s	Process s including Mat , SLM , $Impt$, etc.
BTF	Buy-to-fly ratio	U_y^x	Total energy consumption (MJ) of y by using x method
CM	Conventional manufacturing	E_s	SEC of process s
DED	Direct energy deposition	E_p^y	Energy consumption (MJ) of routine y in phase p
FRV	Fuel reduction value	$E_{p_i}^y$	Energy consumption (MJ) of routine y in phase p for fabricating component $Comp_i$
LCIA	Lifecycle impact assessment	$M_z^{y_p}$	Mass (kg) of resource z consumed in phase p of routine y
FDM	Fused deposition modelling	M_z^y	Total mass (kg) of resource z consumed in routine y
FPI	Functional and physical interaction	M_p^y	Mass (kg) of material after the phase p in routine y
SLM	Selective laser melting	$M_{p_i}^y$	Mass (kg) of material of component $Comp_i$ after the phase p in the routine y
SEC	Specific energy consumption	Occ_j	Occurrence of object j
Mat	Phase of material exaction	LS_j	Lifespan (km) of object j
Atm	Phase of atomization	PF_j	Performance of object j
SLM	Phase of AM	$LS_{vehicle}$	Lifespan of vehicle measured by driving distance
$Post$	Phase of post-processing	C_z^p	Usage rate of resource z in phase p
Use	Phase of use	N_{AD}	Number of (dis)assembly operations in routine AD
$Recyl$	Phase of recycle	R_{gas}	Rate of 1 kg gasoline and joule conversion
Sub	Phase of subtractive process	γ_k	$K=1,2$, or 3 , which represents lightweight ratio, lifespan ratio or performance ratio
FM	Phase of formative process	α	Yield ratio of each process

2. Comparative lifecycle modeling of consolidated design and assembly design

Two distinctive lifecycle models are established for different production routines of consolidated design (fabricated by AM process plus post-processing) and assembly design (produced by CM plus assembly process). For notation purpose, the previous routine is marked as PC routine while the other one is noted as AD routine. Both routines are evaluated throughout the stages of cradle to grave and grave to cradle and thereafter. As such, the advantages of both routines can be embraced to form a more comprehensive view towards the sustainability potential of AM-supported PC.

2.1 Proposed LCA model

The LCA boundaries of both designs are shown in Figures 1 and 2 respectively. The function unit of each routine is one repetitive artifact (i.e. **one AD with n subcomponents or one functionally-equivalent PC part in each installation**) over the lifespan of the installed transportation system (e.g. a vehicle or an aircraft). Some basic assumptions are made as follows:

- (1) SLM process is selected as the default manufacturing process of the PC routine because of its wide adoption in aerospace and automobile industry.
- (2) Additively manufactured part needs finishing process (i.e. CNC milling) to guarantee tolerance requirements and remove support structures.
- (3) Failed consolidated part is directly recycled without possibility of reuse or remanufacture in this paper, although some AM processes (e.g. Laser Engineered Net Shaping (LENS) (Mudge and Wald, 2007)) can help to repair worn-out area.
- (4) Both the consolidated part and the subcomponents of the assembly are made of the same material.
- (5) The components of the assembly are only joined by fasteners to enable non-destructive disassembly.

- (6) Process route of components in the assembly is generalized as two steps: forming and subtractive. If multiple subtractive or formative processes are involved, primary resource consumption is calculated based on the dominant one that removes the most materials.
- (7) Failed components in the assembly design are directly recycled to produce secondary material (e.g. ingots) while the good one is reused until it fails.
- (8) Volume or batch effect is not considered in this study although it has been demonstrated to have an effect on environmental impacts (Baumers et al., 2011b; Faludi et al., 2017).
- (9) All impacts of machine production, auxiliary equipment and tools, and transportation are neglected. Prior studies (Hanssen, 1998) have revealed that environmental impacts of transportation phase accounts for only a few of their total lifecycle impacts, and difference in material transportation is neglectable (Priarone and Ingarao, 2017).

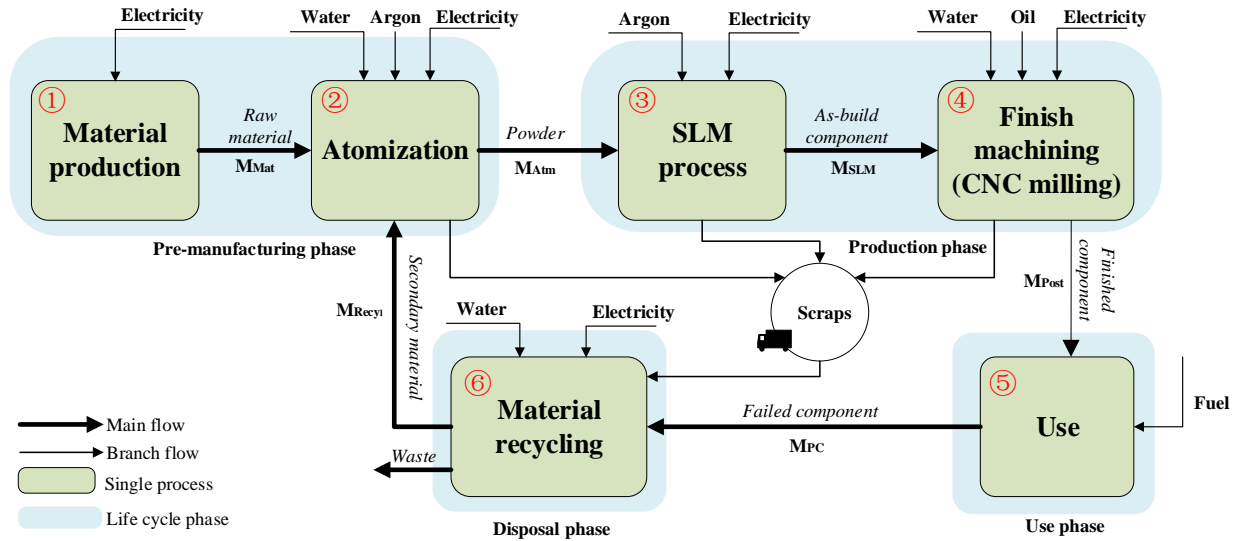


Figure 1 LCA boundary definition of the PC routine. The first life cycle of the PC routine covers sequential processes 1-6, and the second (and onwards) life cycle uses secondary materials recycled from process 6 and partial raw materials from process 1.

As presented in Figure 1, the cradle-to-grave flow of the PC routine starts with material production to get the primary raw material (i.e. ingots). Then, the raw material is atomized into powder by using direct atomization method (Morrow et al., 2007). This powder is melted and joined by the laser-based SLM process layer after layer to create a 3D object. The majority of unused powder is reused in the subsequent prints and can be reused many times (e.g. 8 times for stainless steel powder when properly sieved) as revealed by research (Slotwinski et al., 2014). Post-treatment is required to separate the printed part from the substrate, remove attached powder and support structure, and more importantly, improve surface quality. In this study, CNC milling process is adopted for deburring and good surface finish. Afterwards, the finish part is installed in a vehicle until the part fails. The effects of reduced weight, longer service life, and improved performance (e.g. fuel efficiency) are credited to the consolidated part. By the end of the primary lifecycle, the failed part as well as the scraps produced from the upstream activities including atomization process, SLM process, and the finishing process are recycled through remelting process to produce secondary material (e.g. ingots). Certain amount (12%) of materials will be lost in the recycling process because the thermal effects and contamination in the SLM process and finishing process may cause physical and chemical changes to the recycled scraps (Seyda et al., 2012). As such, complementary virgin materials are supplied to compensate the material losses in the secondary lifecycle and onwards. The processes 1-6 repeat until the vehicle retires.

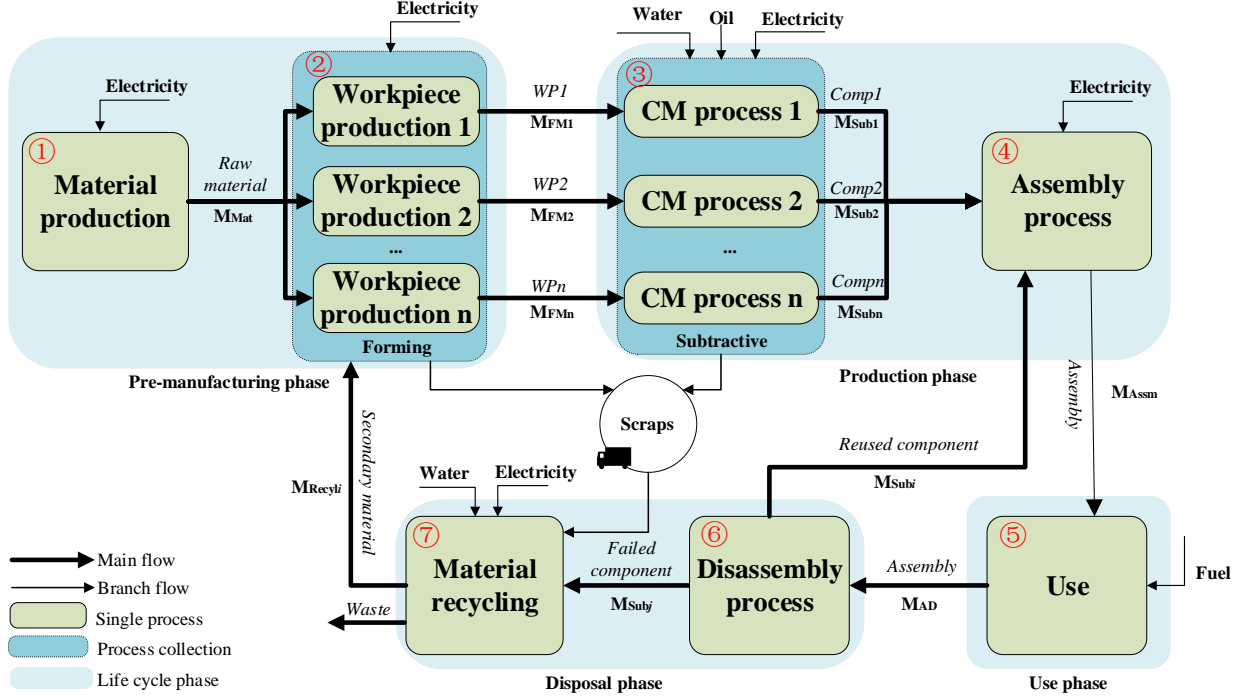


Figure 2 LCA boundary definition of the AD routine. The first life cycle of the AD routine covers sequential processes 1-7, and the second (and onwards) life cycle uses secondary materials recycled from process 7 and partial raw materials from process 1.

In contrast with the PC routine, the AD approach represents drastic different philosophy. These differences are reflected in the following aspects. First, the ingots are formed into desired shapes (e.g. block, slab, or panel) instead of powder by using workpiece production processes (e.g. moulding and casting). Different parts may go through different processes depending on its shapes. Second, subtractive processes are applied to get the final shape as designed. Multiple machining processes may be needed for a specific part, but the process that removes most of the materials or consumes most time is selected as the dominant one. Energy consumption and resource estimation will be calculated on this basis. Third, manual assembly operations are unique to the AD routine to assemble all subcomponents. Fourth, the assembly is disassembled after service, and the good ones are directly reused while the failed one goes for recycling. The recycling efficiency of the scraps is consistent to the PC routine. All these differences signify the strong need of a quantitative method to derive the profitable margins of the PC solution.

2.2 Novel features

In the proposed LCA model, three novel features are proposed compared to prior studies. First, three variables including lightweight ratio (γ_1), lifespan ratio (γ_2), and performance ratio (γ_3) are considered with the AD design being the baseline. The definitions and notations are summarized in Table 1. Lightweight factor of adopting AM has been previously studied in literatures (Ingarao et al., 2018; Priarone and Ingarao, 2017; Tang et al., 2016a), but the effects of the other two variables are rarely investigated. As revealed by the GE nozzle example (GE Capital, 2013), the consolidated design can be 5 times more durable and 15% more fuel efficient. It should be advised that performance improvement should be directly resulted from the design changes of the consolidated part rather than irrelevant parts. Moreover, only improvement in fuel or energy efficiency should be investigated. By varying the possible range of these three variables, the profitable margin of the consolidated design over the legacy design can be captured to support more sound decisions in the early conceptual design stage.

Table 1 variables affecting the decision of consolidation

Variable	Notation	Definition	Description
Lightweight ratio	γ_1	M_{PC}/M_{AD}	Mass ratio of the finished consolidated part over the assembly design
Lifespan ratio	γ_2	LS_{PC}/LS_{AD}	Lifespan ratio of the consolidated part over the assembly as a whole*
Performance ratio	γ_3	PF_{PC}/PF_{AD}	Performance ratio of the consolidated part over the assembly design

* The lifespan of an assembly is equal to that of the weakest subcomponent.

The second novel feature of the LCA model considers the difference of processes for each subcomponent, which is also unique to the assembly design. For example, Parts A and B of an assembly are machined by turning and milling respectively. Due to the difference of each SEC and yield ratio, it is inaccurate to model all parts by using one single process as current single part-related research did. Yield ratio is defined by the input-output mass of a specific process, and the value is dependent on design and process. The third novel feature is the proposal of multiple lifecycles to avoid biased views. This idea is dedicated to the scenario of part reuse in the AD routine; therefore, environmental burden of upstream production can be avoided. Two types of LCA modeling approaches are investigated and compared: one-lifecycle method and multiple-lifecycle method. The logic of these two methods can be differentiated by revisiting Figure 2.

- In one-lifecycle method, no part reuse is involved. As such, each routine covers the primary lifecycle from 1 to 6 (i.e. 7 for the AD routine and same for the following) and secondary lifecycle (and onwards) from process 6 until the vehicle retires. More specifically, all subcomponents in the AD routine are only subject to recycling. Supplementary virgin material is needed to compensate losses in recycling. Recycled materials are stored, and no credits are allocated to the recycling process. This one-lifecycle method was popular in existing literatures (Priarone and Ingarao, 2017; Tang et al., 2016a).
- In multiple-lifecycle method, most of the settings are the same as the one-lifecycle method except that each subcomponent (in the AD routine) can be either reused or recycled after service. For those being reused, processes 4-6 are repeated until the part fails and it is recycled.

3. Life cycle inventory analysis

In this section, the inputs of materials, energy, and main resources for both routines are defined for each lifecycle phases. Since life cycle inventory (LCI) calculation must be associated with specific applicable industries especially in the use phase, parts in a vehicle are selected as the default candidates.

3.1 Pre-manufacturing stage

Similar as the single part-related comparative studies (Ingarao et al., 2018; Priarone and Ingarao, 2017), there is no significant difference in the way of modeling material and energy consumptions in the processes of material production and atomization. However, it is worth highlighting that the forming process (see Figure 2) may be different for each subcomponent. In this paper, material production is the common process to produce primary materials (e.g. ingots) for both routines. The embodied energy (E_{Mat}^y , in MJ) can be obtained by Equation (1), in which E_{Extn} is the unit embodied energy for producing 1kg steel ingots, y represents AD or PC, and it is mass (M_{Mat}^y , in kg) related.

$$E_{Mat}^y = E_{Extn} M_{Mat}^y \quad (1)$$

In the AD routine, ingots undergo a process to turn into desired basic forms such as slabs, tubes, and plates depending on the specific part shapes. Considering the different yield ratio (e.g. $\alpha = 1.33$ of impact extrusion (Yoon et al., 2014) and $\alpha = 1.144$ of pipe drawing 5.2 (Ecoinvent database V3.3)) and SEC of each process, the total energy consumption of the AD routine in the forming process is a

collection of each subcomponent $Comp_i$ as shown in Equation (2), where E_{FM_i} represents the SEC of a specific forming process. Direct powder process (Morrow et al., 2007) is used to produce steel powder from ingots and the material efficiency (i.e. yield ratio of atomization process) can be as high as 97% (Le Bourhis et al., 2014). The energy cost and main resource consumption (e.g. water and argon) can be obtained by equations (3) and (4), in which the rate (C_{Argon}^{Atm} , in kg/kg) of argon usage per kg steel powder can be found in literatures (Kellens et al., 2017b; Paris et al., 2016).

$$E_{FM}^{AD} = \sum E_{FM_i}^{AD} = \sum E_{FM_i} M_{FM_i}^{AD} \quad (2)$$

$$E_{Atm}^{PC} = E_{Atm} M_{Atm}^{PC} \quad (3)$$

$$M_{Argon}^{PCAtm} = C_{Argon}^{Atm} M_{Atm}^{PC} \quad (4)$$

3.2 Production stage

In this stage, the inventory calculation of the two routines are based on SLM process plus CNC milling and subtractive processes plus assembly respectively. It is worth remarking that the “subtractive process” is a collective term of multiple machining processes such as CNC milling (roughing or finishing), turning, and die rolling. Energy demand corresponding to each subtractive method is different. To reduce the complexity of inventory analysis, the full process chain to produce the final shape and allowance is simplified by a dominant process, as widely used in reported literatures (Priarone and Ingarao 2017; Tang et al. 2016a). This simplification also reduces the requirements of process details which may be inaccessible in the early conceptual design stage. In this paper, the dominant process of each part is defined as the one that leads to the most significant environmental impacts of interest. Engineers can customize the option of dominant process according to their industrial sectors or organization’s environmental ethics or simply use aggregated values across impact indicators. Taking energy consumption for example, the dominant process normally either removes most of the materials or consumes most of machining time. Then, the inventory calculation of the full process chain is shifted to the dominant one. Since other non-dominant processes are performed at such a short period, the induced uncertainty of this simplification approach in the production phase is reasonably small, and the resulted error in the full lifecycle assessment is further reduced because the production phase only accounts for a relatively small percentage of total impacts, especially for service-dominant mobility systems. As the preliminary investigation, the accuracy is assumed to be sufficiently satisfactory for rough estimation of environmental performance of the AD and PC routines in the early design stage. As such, the primary energy demand for the assembly can be assessed by Equation (5), in which removed materials ($M_{FM_i}^{AD} - M_{Sub_i}^{AD}$) is multiplied by the SEC of dominant process for each component $Comp_i$. To enable part reuse in the disposal stage, non-destructive joining method is applied to assemble these parts. According to Bookshar’s work (Bookshar, 2001), the SEC (noted as E_{Assm} , MJ/job) of joining operation per fastener is $3.5 \times 10^{-3} MJ$ (in a period of 4 seconds). The total energy demand is shown in Equation (6), and N_{AD} represents number of fasteners.

$$E_{Sub}^{AD} = \sum E_{Sub_i}^{AD} = \sum E_{Comp_i} (M_{FM_i}^{AD} - M_{Sub_i}^{AD}) \quad (5)$$

$$E_{Assm}^{AD} = N_{AD} E_{Assm} \quad (6)$$

In the PC routine, Renishaw AM250® SLM machine is selected as an exemplified machine because of the material processing capabilities and allowable working volume considerations. During the printing process, the building chamber is flooded with protection gas (argon) after initial evacuation. As revealed by literature (Kellens et al., 2017b), the machine does not require continuous argon flow during the process, and the usage was estimated at 208 cubic decimeters (i.e. 0.37kg) per build operation (Faludi et

al., 2017). No argon is recaptured after build completion. The SEC (E_{SLM}) of the SLM process is as high as 365 MJ/kg (Faludi et al., 2017; Kellens et al., 2017b) with no consideration of operation mode, batch size, and embodied impacts of tools. The energy cost can be obtained by Equation (7). Traditional sawing is used to remove the part from the building plate. The separation only incurs a negligible amount of energy consumption of 0.0064 MJ per part separated (Design, 2009). The finish process is implemented by CNC milling to remove the sacrificial support and unmelted powder, and its energy cost is assessed by the amount of chips ($M_{SLM}^{PC} - M_{Post}^{PC}$) by means of Equation (8). As regards the inventory of other resources such as water and oil involved in the wet cutting, it can be estimated by the mass of produced chips. The ratio of one type of resource usage is assumed to be the same for all subtractive processes. For example, the mass of oil consumed in the finish process of PC routine is assessed by the amount of chips multiplied by its ratio ($C_{oil}^{Sub} = 1.01$, kg/kg, Le Thao et al. (2017)).

$$E_{SLM}^{PC} = E_{SLM} M_{SLM}^{PC} \quad (7)$$

$$E_{Post}^{PC} = E_{Mill} (M_{SLM}^{PC} - M_{Post}^{PC}) \quad (8)$$

3.3 Usage

The transportation system of interest is set to be a gasoline-driven vehicle. Although the way of analyzing fuel/energy consumption in service may differ from other types of systems (e.g. powertrain or airplane), the defined variables of lightweight ratio (γ_1), lifespan ratio (γ_2), and performance ratio (γ_3) can be investigated in a similar fashion. The general fuel consumption of a vehicle can be modeled as Equation (12) where fuel attributed to a specific part is a function of its weight (m , kg) and lifespan (LS_m , km) multiplied by fuel reduction value (FRV). Details of FRV can be found in literature (Kim et al., 2015) and USA EPA (Environment Protection Agency) website (EPA, 2017). FRV is vehicle-dependent, and example data can be seen in Table 5. Therefore, the fuel consumption for an assembly can be computed by Equation (13), in which the lifespan LS_{AD} is determined by the shortest lifespan of its subcomponents. However, as prior studies (Frey et al., 2007; GE Capital, 2013) revealed that consolidated parts may have benefits of less weight, improved fuel efficiency, and longer service life (due to avoided contact stress between interfaces), the fuel consumption model for one PC part needs to be revised as Equation (14) with considerations of γ_1 to γ_3 . The total energy costs of the PC and AD parts throughout the lifespan of a vehicle ($LS_{Vehicle}$, in km) can be obtained by Equations (15) and (16) respectively where coefficient R_{gas} represents the conversion rate of 1 liter gasoline and megajoule (Berkely, 2017). The term $LS_{Vehicle}/LS_{AD}$ represents the occurrence of the assembly that will be needed over the service of the vehicle. It should be advised that the effects of prolonged lifespan of consolidated parts on the vehicle can be neglected because the service life of a vehicle needs to fully consider economics, safety, and users' favor.

$$F(m) = FRV \cdot m \cdot LS_m \quad (12)$$

$$F(M_{Assm}^{AD}) = FRV \cdot M_{Assm}^{AD} \cdot LS_{AD} \quad (13)$$

$$F(M_{Post}^{PC}) = FRV^{PC} \cdot M_{Post}^{PC} \cdot LS_{PC} = \frac{\gamma_1 \gamma_2}{\gamma_3} FRV \cdot M_{Assm}^{AD} \cdot LS_{AD} \quad (14)$$

$$E_{Use}^{PC} = \frac{\gamma_1 \gamma_2}{\gamma_3} FRV \cdot M_{Assm}^{AD} \cdot LS_{AD} \cdot \frac{LS_{Vehicle}}{\gamma_2 LS_{AD}} \cdot R_{gas} = \frac{\gamma_1}{\gamma_3} FRV \cdot M_{Assm}^{AD} \cdot LS_{Vehicle} \cdot R_{gas} \quad (15)$$

$$E_{Use}^{AD} = FRV \cdot M_{Assm}^{AD} \cdot LS_{AD} \cdot \frac{LS_{Vehicle}}{LS_{AD}} \cdot R_{gas} = FRV \cdot M_{Assm}^{AD} \cdot LS_{Vehicle} \cdot R_{gas} \quad (16)$$

Table 2 mass-induced fuel consumption of different vehicles (Kim et al., 2015)

Company	Model	Vehicle's Test weight(kg)	Fuel Economy (mpg)	FRV (L/100kg100km)
TOYOTA	Camry	1588	38.2	0.18
FORD	Focus	1474	40.1	0.21

HYUNDAI	Santa Fe	1758	33.6	0.15
DODGE	Charger	1928	29.9	0.20
HONDA	FIT	1304	42.5	0.20

3.4 Disposal

To account for energy consumption in part reuse of the AD routine, electricity cost is credited to the disassembly process as computed by Equation (6). Material recycling is selected as the disposal strategy for both failed parts and recycled scraps in these two routines. The recycling process mainly involves cleaning and remelting steps to produce secondary material (ingots). During this process, certain amount of material is lost due to quality concerns (e.g. oxidization losses because of high surface-to-volume ratios). The recycling efficiency is set at 88% which is consistent for both routines. Recycled content method (Hammond and Jones, 2010; Johnson et al., 2013) is employed in this step. More specifically, the recycling process is exclusively responsible for the energy cost of remelting while receiving no credits of avoided burdens. Hereby, energy demands of recycling can be obtained by multiplying SEC ($E_{Recyl} = 5.45$, MJ/kg) (Morrow et al., 2007) and the mass of recycled content (i.e. failed parts plus scraps/chips from upstream processes). Similarly, water usage in the process is also recycled mass-related, and the average rate has been reported as $C_{Water}^{Recyl} = 800$ (in kg/kg, Le Thao et al. (2017)).

3.5 Comparative lifecycle inventory models

To estimate the profitable margins of the PC routine, a comparative LCI model must be built. The one-lifecycle method and the multiple-lifecycle method are introduced respectively in terms of inventory analysis of material consumption and energy consumption.

3.5.1 One-lifecycle method

As briefed in Section 2.2, no part reuse is considered for this method. The material consumption in each process has the relations as shown in Equation (17) where α_1 to α_4 represent the specific yield ratio of each process. Similar relations can be obtained for each subcomponent in the AD routine with different yield ratios as shown in Equations (18) and (19). These yield ratios are process-dependent.

$$M_{Mat}^{PC} = \alpha_1 M_{Recyl}^{PC} = \alpha_2 M_{Atm}^{PC} = \alpha_2 \alpha_3 M_{SLM}^{PC} = \alpha_2 \alpha_3 \alpha_4 M_{Post}^{PC} \quad (17)$$

$$M_{Mat}^{AD} = \sum \alpha_i M_{FM_i}^{AD} = \sum \alpha_i \alpha_j M_{Sub_i}^{AD} = \sum \alpha_1 M_{Recyl_i}^{AD} \quad (18)$$

$$\sum M_{Sub_i}^{AD} = M_{Assm}^{AD} = \frac{1}{\gamma_1} M_{Post}^{PC} \quad (19)$$

This one-lifecycle method can be seen as the extension of Yang and his colleagues' work (2017) which only investigated the production phase. Since the function unit is defined at the scale of the vehicle's lifespan, it is necessary to calculate the occurrence (OCC_{PC}) of each part in each routine. Taking the energy consumption of the PC routine as an example, we have

$$U_{PC}^{One} = E_{Mat}^{PC} \cdot \left[1 + OCC_{PC} \cdot \left(1 - \frac{1}{\alpha_1} \right) \right] + OCC_{PC} \cdot [E_{Atm}^{PC} + E_{SLM}^{PC} + E_{Recyl}^{PC}] + E_{Use}^{PC} \quad (20)$$

$$OCC_{PC} = [LS_{Vehicle}/LS_{PC}]^+ \quad (21)$$

Where, the operator $[]^+$ represents the smallest integer that is larger than calculated result. In Equation (20), we have three elements. The first element captures the energy demand of primary material production in each lifecycle to compensate material loss in the recycling process. It should be advised that OCC_{PC} must satisfy the condition of $OCC_{PC} \geq 2$. If OCC_{PC} is extremely large, then the very first input of 100% pure primary material can be ignored to simplify the calculation. Similar approach can be taken for

the AD routine with the whole assembly being one unit (or part), and the occurrences of the assembly (OCC_{AD}) is determined by the weakest subcomponent (see Equation (23)).

$$U_{AD}^{One} = E_{Mat}^{AD} \cdot \left[1 + OCC_{AD} \cdot \left(1 - \frac{1}{\alpha_1} \right) \right] + \sum OCC_{AD} \cdot (E_{FM_i}^{AD} + E_{Sub_i}^{AD} + E_{Recyl_i}^{AD}) + OCC_{AD} (E_{Assm}^{AD} + E_{DisA}^{AD}) + E_{Use}^{AD} \quad (22)$$

$$OCC_{AD} = Max(OCC_{Comp_i}) \quad (23)$$

3.5.2 Multiple-lifecycle method

Compare to the one-lifecycle method, the inventory calculation only differs in the AD routine. For the PC routine, the overall energy consumption has a relation of $U_{PC}^{Mult} = U_{PC}^{One}$. To account for the possibility of part reuse, the occurrence (OCC_{Comp_i}) of each subcomponent must be specified in the calculation as shown in Equation (24).

$$U_{AD}^{Mult} = \sum E_{Mat_i}^{AD} \cdot \left[1 + OCC_{Comp_i} \cdot \left(1 - \frac{1}{\alpha_1} \right) \right] + \sum OCC_{Comp_i} \cdot (E_{FM_i}^{AD} + E_{Sub_i}^{AD} + E_{Recyl_i}^{AD}) + OCC_{AD} (E_{Assm}^{AD} + E_{DisA}^{AD}) + E_{Use}^{AD} \quad (24)$$

$$OCC_{Comp_i} = [LS_{Vehicle}/LS_{Comp_i}]^+ \quad (25)$$

4. An exploratory case study

An exploratory case study of a subassembly of a throttle pedal is investigated in this paper. The pedal is used in a Toyota Camry (1588kg) vehicle. It is made of 13 primary components without counting fasteners. All these parts are joined by connectors. The full list of components of the pedal is summarized in Table 3 and a complete physical view of the pedal is depicted in Figure 3 (a). In the following two subsections, the AD and PC routines of the parts of interest are defined, and the parameters of the variables (e.g. lightweight ratio) are tested to study the effect on the profitable margins of PC design. Therefore, a more sustainable routine can be determined in the early design stage.

Table 3 Component list of throttle pedal

	pedal	pins	lever	Right case	Shaft	Bear-ing	Ret. ring	D-pin	Potl. meter	Rot. limit	Spring	Left case	Gasket
#	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Material	steel	steel	steel	steel	steel	steel	steel	steel	plastic	steel	steel	steel	rubber

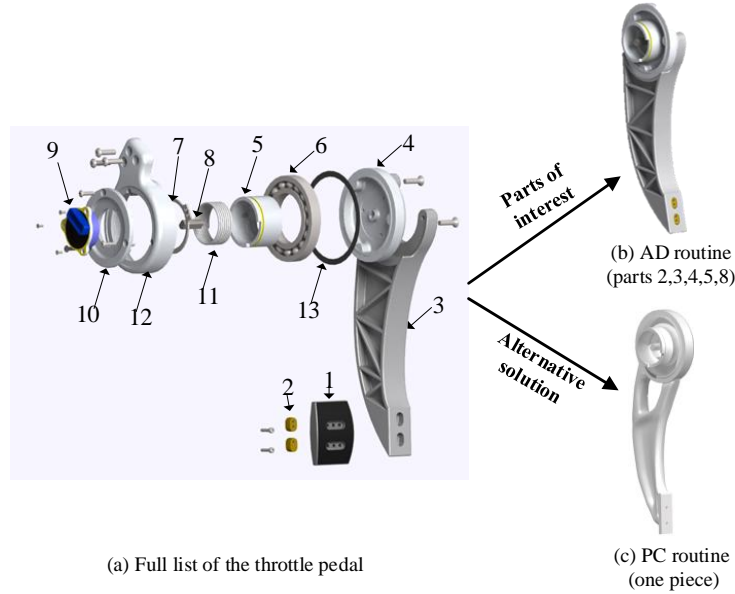


Figure 3 the CAD models of the parts of interest and its alternative solution tested in the two routines.

4.1 AD and PC routines

With a given SLM machine Renishaw 250[®] as the fabrication method, not all components of the gas pedal can be consolidated and printed as one piece because of limitations of volume sizes and materials. According to the candidacy rules previously established by Yang et al. (2018), the subassembly of parts (C2, C3, C4, C5, C8) is identified as the candidacy parts of interest, which serves as design inputs of the AD routine. The detailed view of the assembly design is shown in Figure 3 (b). The functionally-equivalent alternative solution of the subassembly can be derived by using the function surface-based method as proposed by Yang et al. (2015). One possible PC design is presented in Figure 4 (c) with 20% weight reduction subject to a safety factor of 1.5. The comparison of the two design solutions in terms of mass savings and assembly operations is summarized in Table 4 (detailed mass of each part can be found in Table 5). Two points should be advised regarding the inputs of the PC routine. First, the weight savings come from a combination of eliminating fasteners plus assembly interfaces and more importantly topology optimization thereafter. Second, the exemplified PC design is only one of the possible consolidation solutions. As such, a full understanding of the sustainability potential of PC requires to set the lightweight ratio flexible while being conformal to other engineering requirements.

Table 4 comparison between the AD solution and the exemplified PC solution under safety factor of 1.5.

	Mass (kg)	Assembly operations (times)
AD solution	1.031	13
PC solution	0.821	0
Savings	20.37%	100%

With the AD design being the baseline, all the information including manufacturing process, mass, part count per lifecycle, and the occurrences of each part of the AD routine are known and fixed. As shown in Table 5, three types of screws are needed to join the five primary parts. **The dominant processes that remove the most materials of each part or the most time-consuming one are highlighted in bold font.** It is worth remarking that the lifespan data of the subcomponents are inaccessible; therefore, the occurrences are assumed for test purposes. The detailed SEC, yield ratio, and fluid consumption rate that are necessary for the inventory analysis for the AD routine are summarized in Tables 6 and 7. These assumed

values for these data as required in the computation Equations (21) and (24) have been cited from different scientific and technical sources. However, the consolidated design is in its early conceptual design stage; therefore, the values of lifespan ratio (γ_2), and performance ratio (γ_3) of the PC design are inaccessible. Meanwhile, the lightweight ratio (γ_1) is flexible rather than a fixed value. Considering the safety factor, the ratio is subject to a range of 0.7 to 1.0. To investigate the effects of these variables, different scenarios are tested.

Table 5 process, mass, and part count per cycle of the assembly design (AD routine).

#	Component Name	Material	Forming process	Subtractive process	Mass (g)	Part count per lifecycle*	Occurrence	Total
2	Pins	Steel	Casting	N/A	5.44	2	8	16
3	Lever	Steel	Casting	Milling, drilling	707.8	1	2	2
4	Right case	Steel	Casting	Milling, drilling	204.6	1	2	2
5	Shaft	Steel	Pipe drawing	Turning	73.1	1	4	4
8	D-pin	Steel	Casting	N/A	5.1	1	8	8
Fasteners	14 FHS M3	Steel	Impact extrusion	Die rolling	1.9	2	8	16
	15 FHS M4	Steel	Impact extrusion	Die rolling	6.0	3	8	24
	16 BHS M3	Steel	Impact extrusion	Die rolling	2.6	3	8	24

* Occurrence per lifecycle means the number of same parts required in each lifecycle.

Table 6 yield ratio and SEC of each process for steel.

Process	Yield ratio		SEC (MJ/kg)	
	Notation	Value	Notation	Value
Common process				
Material production (primary steel)	N/A	N/A	E_{Extn}	19.3 (Priarone and Ingarao, 2017)
Recycling process (remelting, secondary steel)	α_1	1.136	E_{Recyl}	5.45 (Morrow et al., 2007)
PC routine				
Atomization process	α_2	1.031*	E_{Atm}	15.9 (Morrow et al., 2007)
SLM process	α_3	1.031**	E_{SLM}	365.01 (Kellens et al., 2017b)
CNC milling (finishing)	α_4	2.0	E_{Mill}	44.84 (Morrow et al., 2007)
AD routine				
Casting	α_5	1.33	E_{Cast}	8.2 (Priarone and Ingarao, 2017)
Impact extrusion	α_6	1.33	E_{Impt}	6.1 (Yoon et al., 2014)
Pipe drawing	α_7	1.144	E_{Prw}	5.2 (Ecoinvent database V3.3)
Turning	α_8	2	E_{Trn}	12.9 (Morrow et al., 2007)
CNC milling (roughing)	α_9	4	E_{MillR}	22.8 (Morrow et al., 2007)
Die rolling	α_{10}	1.5	E_{Roll}	28 (Szemmelweis, 2014)
Assembly process	N/A	N/A	E_{Assm}	3.5 e-3 (Bookshar, 2001)
Disassembly process	N/A	N/A	E_{DisA}	3.5 e-3

* Material efficiency in the atomization process can be as high as 97% (Le Bourhis et al., 2014).

** Powder lost in the vacuum or machine gaps is neglectable. To be fair, a 3% loss is considered for SLM process.

Table 7 other resource consumption parameters used in the inventory calculation

Parameters	Symbol	Unit	Reference
Rate of water usage in subtractive process	$C_{Water}^{Sub} = 5.68$	kg/kg	Le Thao et al. (2017)
Rate of water usage in recycling process	$C_{water}^{Recyl} = 800$	kg/kg	Le Thao et al. (2017)
Rate of oil usage in subtractive process	$C_{oil}^{Sub} = 1.01$	kg/kg	Le Thao et al. (2017)
Rate of 1 kg gasoline and joule conversion	$R_{gas} = 39$	MJ/kg	University of California at Berkely (2017)
Rate of water usage in atomization process	$C_{Water}^{Atm} = 155$	L/kg	(Paris et al., 2016)
Rate of argon usage in atomization process	$C_{Argon}^{Atm} = 1.25$	kg/kg	(Paris et al., 2016)
Rate of argon usage in SLM process	$C_{Argon}^{SLM} = 0.37$	kg/job	(Faludi et al., 2017)

Lifespan of the vehicle	$LS_{vehicle} = 200000$	km	
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4.2 Experimental setup

Three cases that have various parameter settings of lightweight ratio (γ_1), lifespan ratio (γ_2), and performance ratio (γ_3) are investigated to understand the profitable margins of the PC routine. The detailed parameters are summarized in Table 8. For simplicity purpose, the settings of variables are noted as ($\gamma_1 \mid \gamma_2 \mid \gamma_3$). The experimental investigation of each case is detailed as follows.

- **Case 1.** Evaluate the environmental performance of both PC and AD routines by using one-lifecycle method and multiple-lifecycle method respectively with the variables being set as (0.8 | 1 | 1). This is consistent with the current PC design of the pedal with 20% weight savings and no improvement for lifespan and performance. The difference of one-lifecycle method and the multiple-lifecycle method will be examined. Moreover, comparative results of the environmental impacts of the PC and AD routines will be analyzed by environmental indicators and lifecycle phases.
- **Case 2.** Investigate the effects of lightweight ratio and lifespan ratio towards the total environmental impacts. In this case, the multiple-lifecycle method is used. The lightweight ratio is set at scales of 70%, 80%, 90%, and 100% while the lifespan ratio is set at scales of 50%, 100%, 200%, 400%, and 800% with γ_3 being fixed as 1. The selection of lightweight ratio is determined by the allowable weight savings with safety considerations for the pedal. The scales of the lifespan extension of the pedal are set by referring to possible gains like the GE fuel nozzle whose life expectancy was 500% prolonged. The scale of 50% is also investigated because concerns of quality issues were shown in some literatures (Ford and Despeisse, 2016) highlighting the uncertainty in additively fabricated part with low maturity of technology. In total, 20 combinations of PC design are investigated in this case.
- **Case 3.** Investigate the effect of performance ratio towards the total environmental impacts. In this case, the multiple-lifecycle method is employed. The performance ratio is set at scales of 100% and 200% while the lifespan ratio is studied at scales of 50%, 100%, 200%, 400%, and 800% with γ_1 being fixed at 0.8. It should be advised that performance improvement of the pedal is not viable with regard to fuel consumption; however, it is interesting to investigate the effects of performance improvement on environmental impacts if applicable for similar parts in other transportation systems like an aircraft.

Table 8 the investigated cases and corresponding variable settings.

#	Experimental purpose	Variables					Scales w.r.t. PC
		γ_1	γ_2	γ_3	Single lifecycle	Multiple lifecycles	
Case 1	Avoid biased views	0.8	1	1	✓	✓	N/A
Case 2	Effect of lightweight ratio	✓*	✓	1		✓	70%, 80%, 90%, 100%
	Effect of lifespan ratio						50%, 100%, 200%, 400%, 800%
Case 3	Effect of performance ratio	0.8		✓			100%, 200%

* the checked parameter is the variable in each test.

5. Results and analysis

In this study, both routines are modeled in Umberto LCA software (Hamburg, 2019) with LCI data presented in Equations (1)-(25) and Tables 6 and 7. It is worth remarking that LCI data of built-in unit process in Umberto is not used. There are two main reasons. First, the built-in process (e.g. turning process) considers embodied environmental impacts of machines and tools while the proposed SLM process does not. This inconsistency may lead to a biased view. Second, the yield ratio of each process must consider the specific design and applied industry while it is a fixed value in the built-in unit process. As such, consistency in modeling is reserved, and the accuracy of the model is assumed to be satisfactory

for the purpose of this paper. Lifecycle impact analysis is conducted by using the ReCiPe Endpoint (H,A) w/o LT method (Heijungs et al., 2003) with Ecoinvent V3.3 database (Weidema et al., 2013). Endpoint indicators are used because it shows environmental impacts on higher aggregated levels with more balanced evaluation of overall impacts. Detailed breakdown of impact categories of damage to human health, damage to ecosystems, and damage to resource availability is also attainable. As the preliminary investigation, the Endpoint method provides designers a straightforward common basis for communication and compare the performance of each routine. However, it should be advised that decision makers can also customize their impact categories that are most closely related to their environmental values or ethics. The results of Case 1 are discussed in Sections 5.1 and 5.2 while the findings of Cases 2 and 3 are presented in Section 5.3.

5.1 Comparison of one-lifecycle and multiple-lifecycle methods

The total environmental impact points are calculated for the one-lifecycle method and multiple-lifecycle method respectively as depicted in Figure 4. Based on the parameter settings in Case 1, the PC design enjoys 20% weight reduction, and this weight saving largely affects the overall performance of the PC routine. In contrast, the multiple-lifecycle method takes part reuse of the assembly into consideration, where significant amount of environmental burden in the upstream production is avoided. The one-lifecycle method which is commonly used in literatures (Ingarao et al., 2018; Tang et al., 2016a) for single part-related research may overestimate the environmental benefits of the PC design. In conclusion, the multiple-lifecycle method is suggested for environmental evaluation of assembly-related design scenarios. However, this test does not prove that the assembly design is a better strategy of reducing environmental burden (i.e. a 2.81Pts drop as shown in Figure 4). It is because the comparison is only based on the condition of 20% weight reduction. Other factors such as lifespan extension, performance improvement, and the percentage of part reuse also determine the profitable margins of PC design.

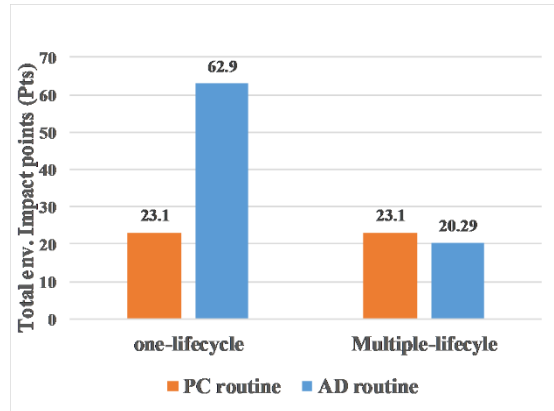


Figure 4 result comparison based on one-lifecycle and multiple-lifecycle methods with 20% weight reduction and no change in lifespan and performance.

5.2 Environmental impact breakdown of PC and AD routines in Case 1

The derived results of the multi-lifecycle method are breakdown to gain a better understanding of the pros and cons of the PC routine in major impact indicators and lifecycle phases compared to the AD routine. As shown in Figure 5 (a), the impacts of both routines are compared in categories of human health, ecosystem quality, and resource depletion. The two routines contribute equally to human health indicators while the environmental burden seems to shift from resource depletion to a more drastic problem of damage to ecosystem for the PC. The underlying reason is the higher material efficiency and extremely increased electricity consumption in the production phase of the PC routine.

To further dig into the detailed performance with respect to more specific environmental impact indicators, 17 subcategories are examined. In human health area, impact indicators including climate change, human toxicity, particulate matter formation, and photochemical oxidant formation are studied. Other indicators such as ionizing radiation and ozone depletion, although affecting human health, are ignored because they contribute to less than 0.004 environmental points. From Figure 5 (b), it is observed that the PC and AD routines contribute equally to all human health-related indicators. When metal and fossil resource depletion are examined, the PC routine performs slightly better than the AD approach in both categories as depicted in Figure 5 (c). This resource savings mainly come from weight reduction in the consolidated part. Freshwater eutrophication and ecotoxicity are not presented due to its low impacts. Amongst indicators in the ecosystem domain, the PC approach leads to almost 6 folds of natural land transformation and 2 folds of agricultural land occupation compared to the AD routine, which significantly affects the overall environmental performance of PC. This drastic increase of negative impacts results from the excessive electricity consumption in the production stage of the PC routine. The installation of water electricity facilities and supplementary resources (e.g. road network and storage) is believed to cause significant land transformation and occupation (Diffendorfer and Compton, 2014; Koellner et al., 2013).

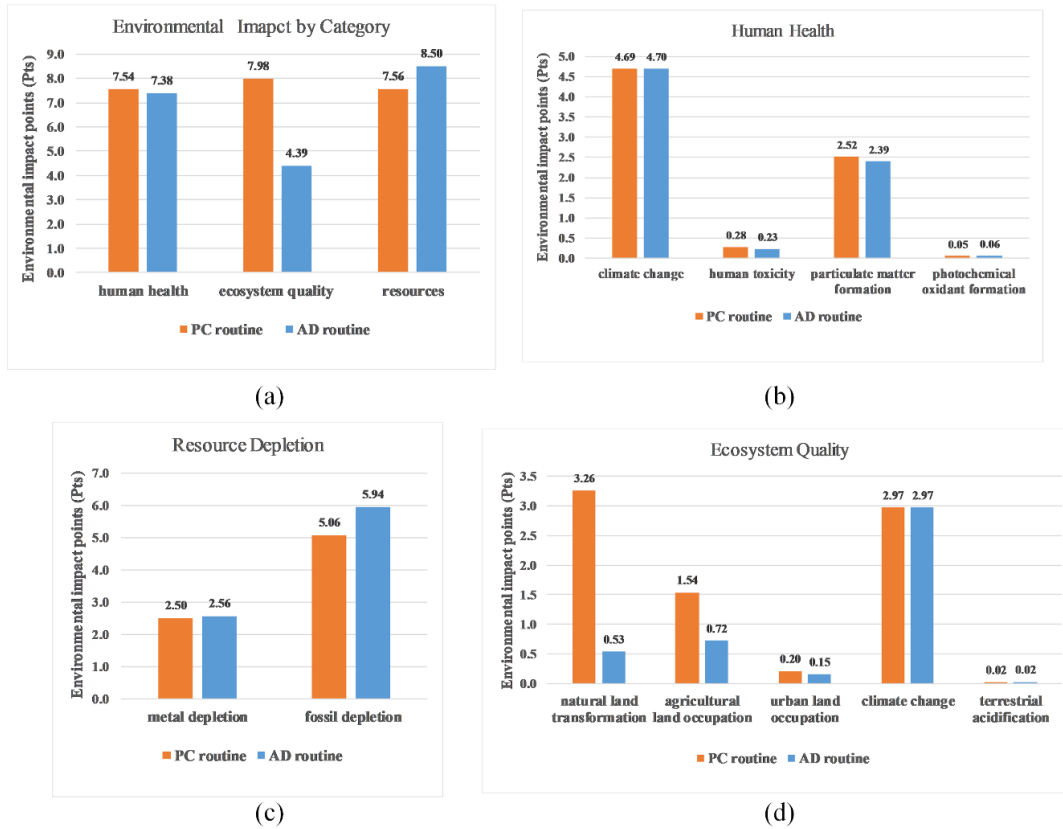


Figure 5 environmental impact breakdown of the two routines by category.

The contribution of activities in the lifecycle of PC and AD routines is further analyzed. As shown in Figure 6 (a), the PC approach performs slightly better in the phases of pre-manufacturing and use; however, it leads to more than 2 times environmental burden in the production and EoL stages. The savings in the pre-manufacturing and use stages are mainly derived from reduced material usage throughout the lifecycles. As summarized in Table 9, the total demand of primary material in the AD routine is almost two times of that in the PC routine while a reverse trend is observed regarding the

supply of recycled materials. It is noted that the high energy consumption in the production stage of the PC routine is significantly environmental burdensome. The energy cost is almost 30 times of that of the AD routine as shown in Figure 6 (c) but the gap between the two routines is much smaller in terms of the total environmental impact points. This is because the source of electricity is set to be local (i.e. water electricity, Quebec) in this model; otherwise, the environmental disadvantage of using SLM process in the production stage is even more significant if other grid is applied (e.g. coal-fired power plant). Another interesting observation in this research is that the pre-manufacturing phase accounts for almost 50% of total environmental impacts for both routines while the use phase only takes up around 17% share (12.9% of PC and 22.8% of AD) of overall impacts. This relatively small portion of savings is not adequate for compensating the drawback of the high SEC of the SLM process. However, this finding is highly case-specific (e.g. heavy part V.S. small part) and transportation system-specific (e.g. aircraft V.S. passenger vehicle). Taking long-haul flight for example, [the use phase may contribute to more than half the environmental impacts for the same part weight \(Huang et al., 2015; Kellens et al., 2017b\)](#), which may significantly enlarge the profitable margin of the PC routine.

Table 9 primary and secondary material consumption at each lifecycle for both routines

No. of life cycles	AD		PC	
	Primary material(kg)	Secondary material(kg)	Primary material(kg)	Secondary material(kg)
1	5.382	0	1.745	0
2	0.010	0.071	0.209	1.536
3	0.030	0.218	0.209	1.536
4	0.010	0.071	0.209	1.536
5	0.030	0.218	0.209	1.536
6	0.612	3.771	0.209	1.536
7	0.010	0.071	0.209	1.536
8	0.030	0.218	0.209	1.536
Total	6.112	4.638	3.208	10.752

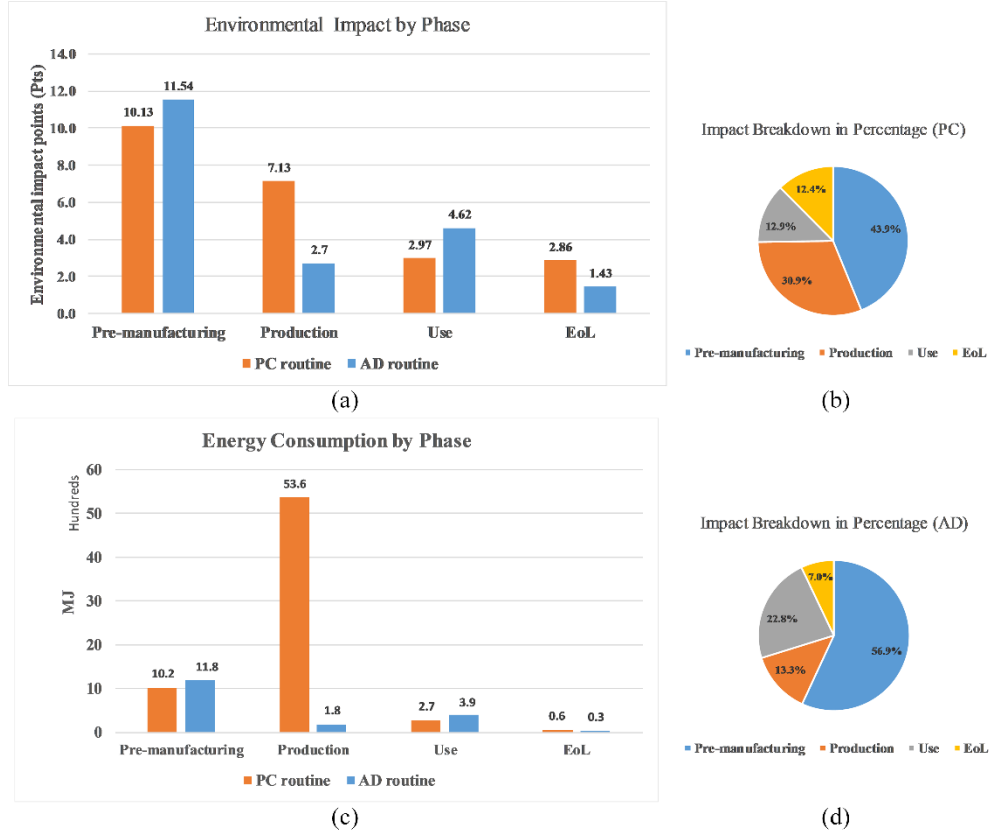


Figure 6 environmental impact and energy consumption breakdown of the two routines by lifecycle phases.

5.3 Effects of variables on PC decision

This section investigates the effect of variables including lightweight ratio (γ_1), lifespan ratio (γ_2), and performance ratio (γ_3) on the total environmental impact points, which consequently affects the choice of PC or AD routines. In this study, the assembly design is used as the baseline with pre-defined process and lifespan expectancy for each component. [With different variable settings and the multiple-lifecycle method, the environmental benefits of the PC routine can be examined.](#)

In the first place, the combinations of different scales of lightweight and lifespan ratios are investigated as discussed in Case 2 (see Table 8). As shown in [Figure 7](#), the horizontal axis represents the lifespan ratio of the consolidated part over the assembly. For example, the scale of 100% means that the occurrence of the consolidated part is equivalent to that of the assembly which needs 8 replacements throughout the lifespan of the vehicle. Similarly, if the lifespan ratio is 800%, it means that only one consolidated part is required for the whole lifecycle of the vehicle. With the baseline of total environmental impact points of 20.29 that is resulted from the AD routine, several observations can be made from Figure 7.

- (1) As lifespan ratio increases from 50% to 800%, the total environmental impacts of the PC routine decrease rapidly regardless of the percentage of weight reduction. More importantly, if the lifespan ratio is over 200%, the consolidated design will gain dominant advantages over the AD strategy even if there is no weight reduction (see wt 100% curve). The PC supremacy area is noted in Figure 7. This is because the extended lifespans of consolidated parts largely reduce the energy consumption that is needed to fabricate the same part in the production phase.
- (2) As the lightweight ratio decreases, the total environmental impacts are reduced as well regardless of whether lifespan of the consolidated design is prolonged or not. More importantly, if weight savings can be over 30% (see wt 70% curve), the PC routine is more sustainable than the AD

counterpart under the premise that the lifespan of the consolidated part will not be compromised by quality issues because of low technology maturity.

- (3) As the lifespan ratio decreases, the contribution of weight savings to reducing environmental impact is also reduced. As summarized in Table 8, taking the 10% weight savings from wt 80% to wt 70% for an example, environmental impacts have improved by 18% when the lifespan ratio is 800% but this value drops to 12.9% when the lifespan ratio is only 50%. This difference is derived from the increased occurrence of the consolidated part in the latter scenario. The higher occurrence leads to the decrease of percentages that the fixed amount of primary material production as discussed in Equation (23). As such, lifespan improvement amplifies the contribution of weight savings toward higher sustainability.
- (4) In the uncertainty area (see Figure 7), only having weight savings cannot secure the ecological advantages of the PC routine over the AD approach and vice versa. This observation highlights the necessity of full consideration of lifespan and weight reduction.

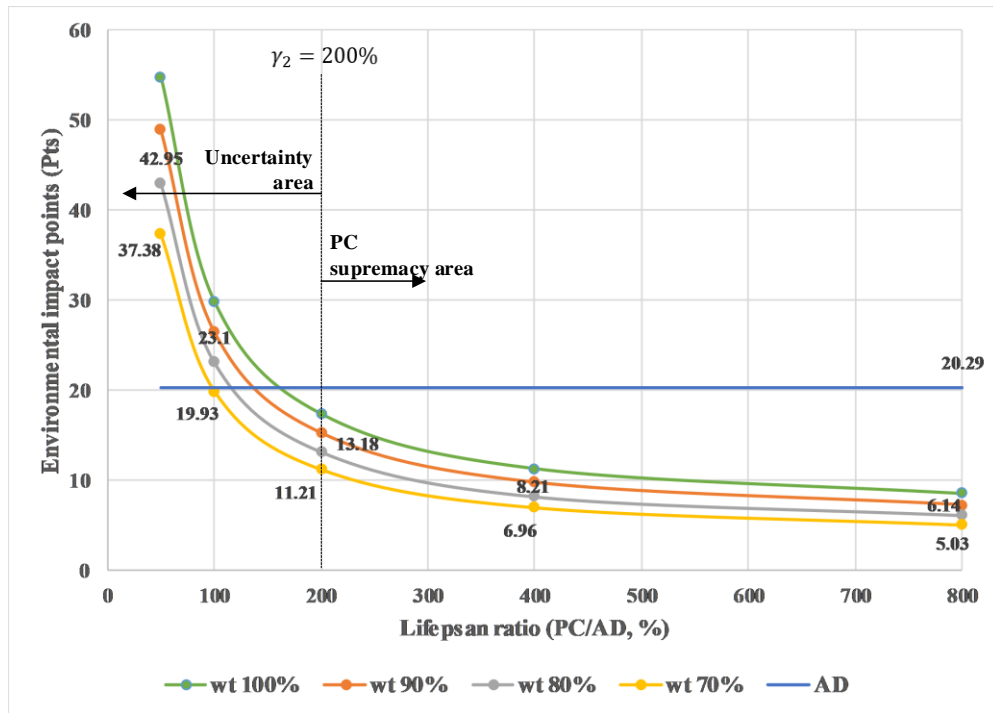


Figure 7 the relation between lifespan ratio, lightweight ratio and total environmental impact points.

Table 10 contribution of weight savings to environmental impacts with respect to lifespan ratios.

Weight savings of 10%	800%	400%	200%	100%	50%
wt 100% - wt 90%	14.8%	13.6%	12.2%	11.3%	10.7%
wt 90% - wt 80%	15.7%	14.5%	13.6%	12.6%	12.2%
wt 80% - wt 70%	18%	15.2%	14.9%	13.7%	12.9%

Numerical simulation experiments (i.e. Case 3) are also implemented to study the effects of performance improvement on environmental impacts. As mentioned early in this section, improvement of performance that is correlated to fuel efficiency (i.e. FRV) of the vehicle is not attainable for this pedal; therefore, a relatively big ratio of 200% is tested, signifying two times better for the PC routine, which is out of reach for most redesign effort. Similar to the lightweight ratio test, this test is also coupled with the lifespan scales to capture a more comprehensive view of performance ratio. As presented in Figure 8, the PF 100% curve and the PF 200% curve are very close to each other, which reveals that performance improvement

has limited contributions to the reduction of environmental impacts. The maximum deviation of 24% between these two curves occurs when the lifespan ratio is 800%, and this value decreases to 3% as the lifespan ratio is only 50%. Hereby, for consolidation of an assembly having a small part/vehicle weight ratio, performance improvement (if applicable) of the consolidated design needs to be tested only if the lifespans of the consolidated part and the legacy assembly design are very close. Otherwise, lifespan extension plays the deterministic role of guarantying the profitability of the PC routine.

Based on the above observations, some general design guidelines can be drawn as follows.

- Weight reduction, extended lifespan, and performance improvement contribute to reduced environmental impacts for the consolidated part; however, the PC routine is not necessary to be more sustainable than the assembly approach.
- Weight reduction in consolidated design is viable in most cases; however, if there are no significant mass savings, an increase of lifespan should be guaranteed to secure better sustainability of the PC routine.
- Lifespan expectancy plays a vital role of securing the profitability of the PC approach, especially when lifespan can be prolonged more than 2 times. As such, the consolidated design can be environmentally advantageous regardless of weight reduction. However, lifespan expectancy is highly case-dependent while some literatures (Frey et al., 2007; GE Capital, 2013) have been reported, but only a few have confirmed prolongation of lifespan of the consolidated part. The uncertainty of fabrication process and powder properties require physical tests to obtain the real lifespan of the additively manufactured part before the decision of whether to do part consolidation instead of an assembly design.
- Performance improvement in the use phase may affect less than 20% of the total environmental impacts if the studied part is too small (relative to a vehicle). For such assemblies (or parts), there is no need to consider the effects of performance improvement (if applicable) in the PC decision in the context of environment-benign design.

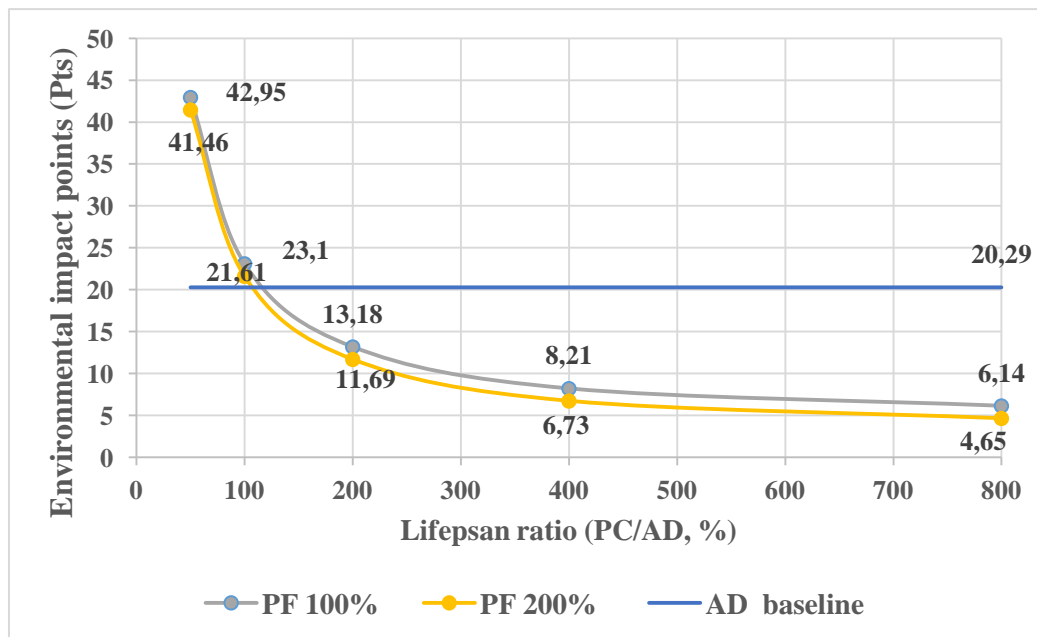


Figure 8 the relation between lifespan ratio, performance ratio, and environmental impacts with 20% weight reduction.

6. Conclusions and future research

Investigation of environmental impacts of product design is of high importance because 80% of the environmental damage of a product is established after 20% of the design activity is complete (Otto and Wood, 1998). As such, to find a more environmentally friendly design solution in the early design stage is of high importance. Part consolidation, as an alternative solution for assembly design, can help to reduce the number of parts, simplify product structure, minimize assembly operations and cost, and improve functional performance when combined with other degrees of freedom of AM. Due to the complex nature of part consolidation, the sustainability potential of PC is difficult to be intuitively determined. This paper is devoted to developing the preliminary understanding of the environmental performance of PC design and more importantly providing decision support for whether to choose the PC routine instead of the other way around.

Throughout the preliminary investigation, a general process of PC decision for elevated sustainability can be summarized as shown in Figure 9 with major contributions for each activity. The first step is to identify parts candidates for consolidation evaluation. The range of decision variables of lightweight ratio, performance ratio, and lifespan ratio must be estimated according to engineering requirements and other successful past instances. Then, the two routines are assessed in parallel based on the general LCA framework. The critical points must include the follows. First, the multiple-lifecycle method with part reuse is suggested avoiding a biased view towards the AD routine. Second, inventory analysis needs a consistently defined allocation method for both routines. It is also advised to simplify the lengthy process chain with a dominant process which contributes to the most significant environmental impacts. If the parts candidates are installed in a mobility system, a specific fuel consumption model must be developed to account for the possible fuel savings in the PC routine. Third, impact categories or indicators can be customized according to the specific environmental values or ethics of the organizations or sectors to enable more sound decisions. If trade-offs between different impact categories are favored, an Endpoint-based approach can be a good option. The final step of the decision process is to evaluate the profitable margins of the PC design. Based on which, the direction of design improvements can be identified.

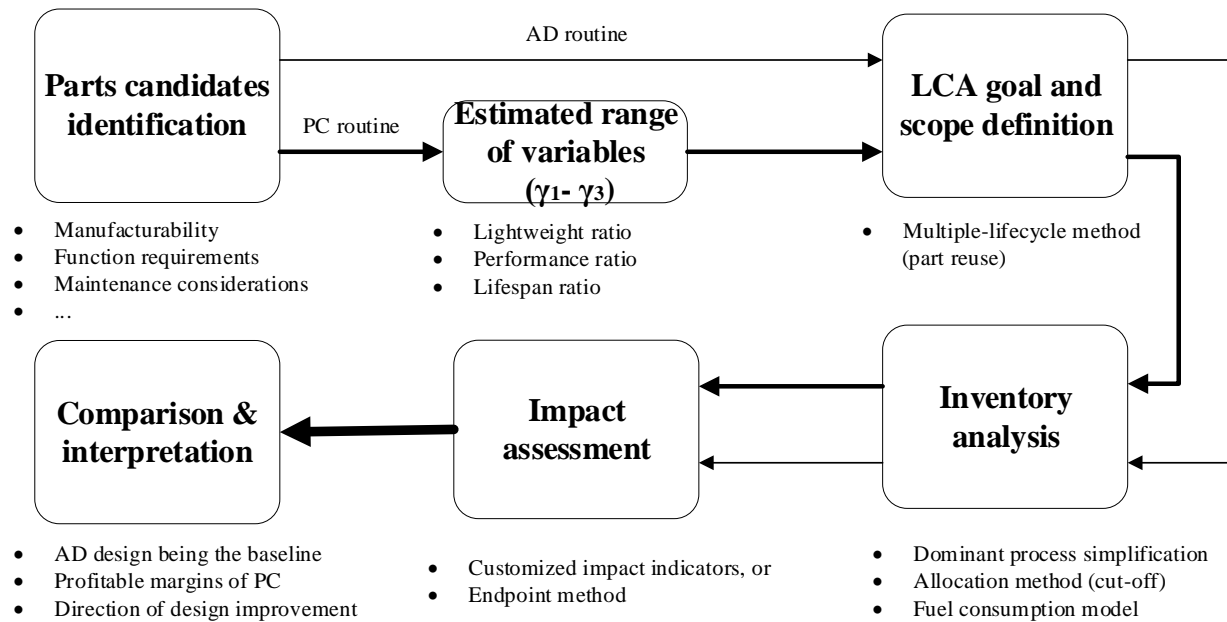


Figure 9 the summarized general process of part consolidation decision for elevated sustainability.

Following the steps of Figure 9, the comparative interpretation of throttle pedal case study indicates that the PC routine may be a more sustainable design solution when the lifespan of the consolidated part is prolonged over 200% or the weight savings (w.r.t. AD) exceeds 30%. It is also found that performance improvement (if applicable) in use phase only accounts for a limited percentage (less than 20%) of total environment impacts. This is because the use phase of the part only accounts for around 13% of lifetime environment impacts. For other conditions such as no significant weight reduction or no substantial lifespan extension or contraction, the environmental performances of both routines are very close; thus, other design requirements such as cost and ergonomics, should be emphasized to assist decision making. Moreover, the breakdown of the total environmental impacts reveals that the SLM process selected for the PC routine takes up significant high electricity energy (almost 30 times); thus, it must be compensated by the reduction of material usage throughout its lifetime via topology optimization or improving part quality (to increase lifespan expectancy). It should also be advised that the proposed LCA model and the way of evaluating lightweight ratio, lifespan ratio, performance ratio, and part reuse are generally applicable while the derived quantitative guidelines are more limited to similar parts (i.e. part/vehicle ratio) in the specific vehicle model (i.e. Toyota Camry). Readers are encouraged to find the profitable margins for each specific design solution by using the proposed LCA model and multiple-lifecycle method as indicated in Figure 9.

For future research, several factors are of high interest to be further explored in the planned study. First, all parts in the assembly design are made of the same type of material in this exploratory study. However, multi-material printing or a change of material is also viable for AM nowadays. It will be interesting to include the type of material as a new variable of PC decision in the next step. Second, the impacts embodied in auxiliary tools or equipment are not considered. A more accurate model of each unit process may change the advantageous margins of the PC routine. Third, the variable of performance improvement is not significant for a small component in a passenger vehicle while this conclusion may not hold for other types of transportation systems such as a powertrain or aircraft. Fourth, Renishaw AM250 and CNC milling are chosen as the default processes for printing and post-processing, but the proposed LCA model is also applicable for other systems. Designers can alter the comparative model according to the on-site machine availability, and then apply this tool for achieving more environment-benign design. Lastly, rules of thumb to assist the selection of dominant processes and the customized impact indicators require further development to match organization-specific environmental values or ethics and find the trade-offs between modeling accuracy and efficiency.

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