Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 10 (2017) 831 – 844

Procedia MANUFACTURING

45th SME North American Manufacturing Research Conference, NAMRC 45, LA, USA

A Generic Sustainability Assessment Model towards Consolidated Parts Fabricated by Additive Manufacturing Process

Sheng Yang[a], Tanushree Talekar[a], Mohamed A. Sulthan[a], and Yaoyao F. Zhao[a,*]

[a]*Department of Mechanical Engineering, McGill University*
Montreal, Quebec, H3A 0C3 Canada

Abstract

Part consolidation (PC) is one of the effective ways to simplify product structure. Through part consolidation, it is expected to reduce weight and size, minimize assembly operation, improve performance, and prolong service life. As additive manufacturing (AM) evolves into an end-of-use product manufacturing process, the possibility of part consolidation has further increased. However, the life-cycle sustainability aspect related to PC with AM is rarely known. To support design for environment, this paper proposes a framework to systematically investigate the environmental impact of PC on production, service, and end-of-life (EoL) activities. In this framework, generic quantitative models for PC-related sustainability assessment of these life-cycle stages are presented from an incremental perspective. In each model, change in sustainability indices are calculated with respect to the change propagated from the design change (PC) when PC is achieved. From the model, consolidated design shows definite promise at assembly and service stage; however, there is still uncertainty in deciding the sustainability benefit at manufacturing and EoL stage. In this paper, a case study with a redesigned floor attachment in a train is exemplified and binder jetting (BJ) AM process is chosen as the default manufacturing process. Due to the lack of data of EoL and minor effect on maintenance as well as fuel economy, only the environmental impact on production is analyzed. The result reveals two important implications: 1) consolidated design shows significant promise in reducing energy consumption and environmental impact (average 20%), but it results in an increase of health toxicity level; 2) reduction of environmental impact (up limit 13.2%) at assembly stage is not obvious. In the end, important conclusions and future research are outlined.

Keywords: part consolidation; sustainability assessment; additive manufacturing; binder jetting process;

* Corresponding author. Tel.: +1-514-398-2523
E-mail address: Sheng.yang@mail.mcgill.ca, yaoyao.zhao@mcgill.ca

2351-9789 © 2017 Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license
(http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of the 45th SME North American Manufacturing Research Conference
doi:10.1016/j.promfg.2017.07.086

1. Introduction

Part consolidation is one design philosophy favoring a reduction in part count. Through part consolidation, it helps to simplify the product structure, promote modularity, eliminate fasteners, joints, and connecters, and reduce assembly difficulties and cost [1]. Part consolidation effort may have three different scenarios [2]. The first scenario is to consolidate multiple parts into one or more complex part. In this scenario, the main contribution is to eliminate unnecessary connectors and minimize required assembly times. The second scenario is to eliminate a part and force other parts to take over the function in which coupling of functions may occur. In the third scenario, dramatic reconceptualization of the whole system and reallocate functions to other sub-systems is needed. The difficulty of design with respect to these three design scenario increases vastly. In this paper, only the first scenario is investigated because the other two introduce too much uncertainties in terms of design changes. Technically, the main constraint which restricts the possibility of part consolidation is the manufacturing process; therefore, the development of part consolidation research is synchronized with that of fabrication technologies as reported in injection molding [3], composite materials [4], and additive manufacturing [1, 5].

With the deterioration of environment and exhaustion of natural resources, design for environment [6] is highly demanded. Nominally, part consolidation is expected to reduce weight, shorten supply chain and assembly line, lower energy consumption, and even prolong product service life [2] . All these factors seem that part consolidation is promising in supporting sustainable design. However, consolidated parts may involve a change in material and geometry. This change imposes a deep influence on the after-design stages including manufacturing, assembly, supply chain, service, and EoL activities. For example, as the geometric complexity of the consolidated component increases, the manufacturing difficulty (energy consumption) soars drastically, which may compromise the gains from weight reduction. These conflicting factors urgently require a comprehensive quantitative assessment method to support eco-consolidated design. Unfortunately, sustainability research related to part consolidation is really rare and they only focus on one or two phases of product life cycle (e.g. production stage [7, 8]).

This paper aims at sustainability-wisely analyzing how the change in part consolidation propagates to downstream activities from a lifecycle point of view. In order to reduce the complexity of the studied problem, only AM-enabled part consolidation is considered. There are two reasons: 1) AM-enabled part consolidation can facilitate the maximum possibility of part count reduction; 2) research in this field is more challenging and rarely reported except our previous research [8]. The paper is structured as follows. Firstly, the current state of AM-related, part consolidation-related, and general life-cycle sustainability research is reviewed. Secondly, a generic framework to support sustainability assessment in part consolidation context is presented in Section 3.2 to 3.5 to discuss the manufacture model, assembly model, service model, and EoL model. After that, a case study is presented in Section 4 to quantitatively study the change of environmental impact resulted from the design change. In the end, it is wrapped up with conclusions and future research.

2. State of the art

In this section, current state of sustainability study of AM applications and part consolidation in general is reviewed. To develop a better understanding of lifecycle sustainability evaluation, dominant methods related to assembly process, service, and end-of-life activities are also reviewed.

AM is a new emerging technology that joins material typically in a layer by layer fashion and ideally wastes no extra material beside the building volume. Furthermore, AM can make a part directly from its digital model without using extra tools and fixtures. All these features distinguish AM from conventional manufacturing processes, making it intuitively considered to be a “clean” or “green” process [9]. In order to assess the environmental impact of AM process or AM related applications (e.g. optimized product), a bunch of research is reported and they are mainly trying to solve the following issues:

- Developing a quantitative environmental impact assessment model for a specific AM process (e.g. Binder Jetting process [10] and Selected Laser Melting process [11])
- Comparing environmental impact between different AM processes [12] or AM and conventional processes (e.g. [13, 14])

- Integrating sustainability results as a feedback into AM-related design activities (e.g. structure optimization [15], part consolidation and topology optimization [8])
- Optimization of process parameters to reduce environmental impact via minimizing the whole flux consumption (energy, material, and fluids) [9, 16, 17]

The environmental impact of AM-enabled part consolidation research belongs to the third group; however, current research [8] fails to examine part consolidation from a lifecycle perspective and there does not exist such a quantifiable model for part consolidation alone to provide sound feedback for designers, although researcher claimed that part consolidation may be beneficial in terms of sustainability [18].

Similarly, sustainability study of conventional manufacturing-enabled part consolidation was also limited [7, 19, 20]. Suresh et al. [7] presented a design framework to integrate design for environment (DFE) and design for manufacture and assembly (DFMA) with a redesign case study of charge alternator pulley. In their research, environmental impact is evaluated by using a commercial software (SolidWorks package) with inputs of CAD model, material, manufacturing process, manufacturing location, and distribution. The output is carbon footprint, air acidification, total energy consumed and water eutrophication. Through comparative study with the old design, by switching the material from cast alloy steel to aluminium alloy with respect to the same functional requirements, the resultant design is more environmental friendly. Chowdary and Harris [19] incorporated multiple design tools into the design flow including quality function deployment (QFD), DFMA, and DFE (using commercial software SimaPro 7). In their approach, DFE is applied in the detailed design stage with a main consideration of the impact of material selection. The impact is quantified by eco-indicator 99 system. Through their case study of a desktop organiser, the simplified design shows promise in reduction of mass, total cost, assembly time, and eco-indicator 99 values. However, the impact of the consolidated design on service life, reusability, recyclability, and manufacturability is not covered. Although DFMA principles [20] in general helps to reduce weight, assembly operations, and tooling usage, DFMA can only forecast a descending trend of environmental impact via a reduction of the flux of material, energy, and fluid used at manufacturing and assembly stage. A life-cycle investigation of a change in design is more persuasive. Besides, quantitative assessment across its lifespan can help to quantify whether it is a positive design change or not in terms of sustainability.

In the field of life-cycle assessment (LCA), environmental impact analysis of a product in its assembly operation, service life (e.g. usage and maintenance scheme), and EoL (e.g. disposal, reuse, remanufacture, and recycle) are indispensable. Huang et al. [21] built a cradle-to-gate manufacturing life cycle inventory (LCI) model and a fuel use model to estimate energy and greenhouse gas emission savings associated with replacing existing conventional manufactured components with AM ones for a full-scale US aircraft fleet with gradual adoption of AM through the year 2014 - 2050. In this manufacturing LCI model, the main phases include raw material production, raw material distribution, component manufacturing, and component distribution and the total savings in the primary energy consumption and greenhouse gas emission is a function of mass reduction with a consideration of buy-to-fly ratios and distribution distance. In the fuel use model, it is assumed that a reduction of 100kg in weight will save 13.4-20TJ over the service life of an aircraft. Considering Product Lifecycle as a closed loop, measures to improve sustainability of a product is explained by Fargnoli et al. [22] with a focus on assembly and disassembly. As claimed, economic feasibility is one of the issues which mostly weighs down assembly and disassembly. Thus, a recyclability index (R) is defined for every product to determine its financial profitability. When a product reaches the end of life stage, its physical and functional qualities are first analyzed and is then either reused, remanufactured, recycled or dumped. In this process, disassembly plays a vital role in product recovery. Much effort (Güngör and Gupta [23], Zussman et al. [24], and Pullen et al. [25]) has been made in the assessment of disassembly-orientated sustainability. However, these methods are unable to quantitatively support design decisions especially when it comes to conflicting factors along a product's lifecycle.

3. Methodology

Part consolidation decisions are made at the early design stage and it is estimated that these early-stage design decisions are responsible for up to 20% of the costs of a product and 80% of environmental damage [26]. A comprehensive understanding of the consequence of part consolidation at different lifecycle phases are valuable. In this section, a generic investigation framework with specific lifecycle boundaries is presented. Afterwards, sustainability analysis model for production, service, and EoL activities related to part consolidation are also discussed.

3.1. The framework of sustainability analysis for AM-enabled PC

A generic product lifecycle from cradle to grave normally includes processes of raw material production, material processing, product manufacture, product distribution, use & service, and end-of-life activities [27]. Due to the complexity of the studied problem, the proposed framework only focuses on the stages intensively related to part consolidation. Part consolidation in general sense is to modify the existing design to reduce part count, which may include a change in its geometry and material. This change will propagate to later stages such as manufacture and recycling [28]. The framework of sustainability analysis of AM-enabled part consolidation is presented in Figure 1. The affected activities in each stage are listed. Taking design stage for example, when different components are consolidated, the function delivered by the corresponding component is easily integrated, which results in the coupling of design parameters [2]. To solve a coupling problem, both development cycle and computational power increase rapidly.

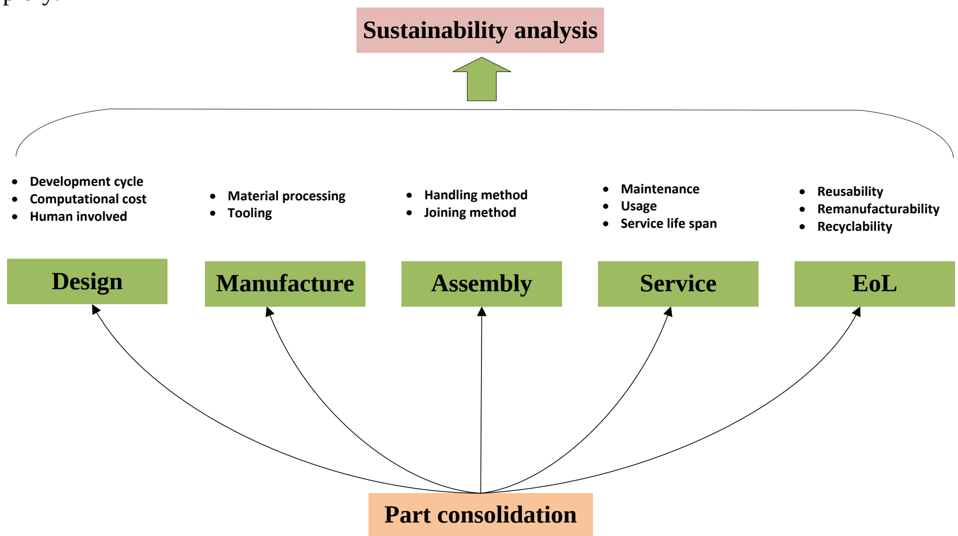

Figure 1. Sustainability analysis framework of AM-enabled part consolidation.

In this paper, sustainability is mainly evaluated by a triplet [environmental impact, energy consumption, health impact] in general to be noted as $[E, E, H]$. A change resulted from part consolidation can be written as $\delta(\text{material}, \text{geometry})$. Excessive information can be directly derived from δ, for instance, mass saving and geometric complexity (which decides material processing method to be used). Due to the lack of functional information, the degree of coupling in design parameters is difficult to be modeled; therefore, evaluation of how δ is propagated to design is neglected. The effect of δ on manufacture, assembly, service, and EoL is discussed in Section 3.2 – 3.5 respectively.

3.2. Sustainability analysis model of manufacture method change

Part consolidation easily leads to an increase of geometric complexity of the consolidated component. Manufacturing difficulty is normally proportional to the introduced geometric complexity. Besides, a change in material selection will also result in the alternation of material processing methods. To compensate the increase in manufacturing difficulty, AM is the optimal solution. But how the change of δ will reshape sustainability is unknown. In this subsection, the change of sustainability resulting from process change is analyzed. In general, the change in sustainability can be represented as:

$$S(Manuf(\delta)) = \Delta[E, E, H]_m \quad (1)$$

Where S is the sustainability evaluation function, $Manuf$ is the process function which is defined by its sub-activities including material, energy, and fluids usage. S function is normally difficult to be represented explicitly and normally it has highly non-linear relations with material consumption and energy consumption. One possible solution is to use inventory database such as Ecoinvent v3 [29] to calculate life-cycle environmental impact, energy consumption (in terms of auxiliary materials or powder), and health impact.

Taking binder jetting process for example, the $Manuf$ function can be constructed in the following flow based on its own step-wise process model [8] (as shown in Figure 2). In this process model, energy consumption and material consumption (binder, cleaner, and powder) can be estimated according to Equations (2)-(6) respectively.

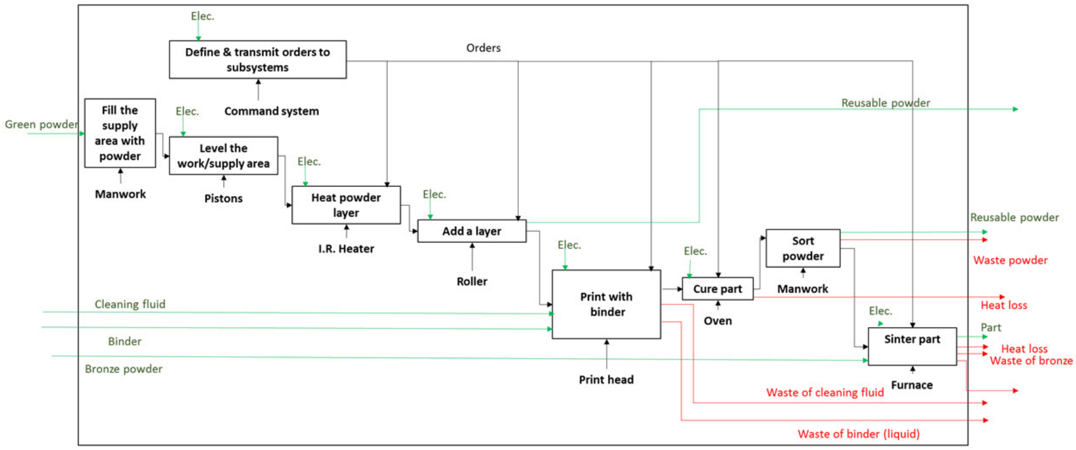

Figure 2. Step-wise model of binder jetting process [8].

Energy consumption model [8]:

$$E_{total} = \sum(E_{heater}, E_{heating}^{curing}, E_{heating}^{sinter}, E_{maintain}^{cure}, E_{maintain}^{sinter}, E_{idle}) \quad (2)$$

Where the total energy consumption of the manufacturing process is a function of volume and material and it is calculable when some of empirical coefficients is obtained. Therefore,

$$E_{total} = E(material, V(geometry)) \quad (3)$$

Where V is the volume of the model and it is a function of its geometry.

Material consumption model [8]:

$$M_{binder} = \rho_{binder}(material) * V(geometry) \quad (4)$$

$$M_{cleaner} = \rho_{cleaner}(material) * V(geometry) \quad (5)$$

$$M_{powder} = \varphi * \rho_{powder}\ (material) * V(geometry) \quad (6)$$

Where ρ is the density of corresponding materials and φ is the buy-to-fly ratio. For AM process, it is around 1.5, but for conventional manufacturing process, it varies from 2 to 20 for different processes[21]. Then,

$$Manuf(\delta) = [E_{total}, M_{binder}, M_{cleaner}, E_{powder}] \tag{7}$$

In the end, sustainability indices $[E, E, H]_m$ can be calculated with inputs of $Manuf(\delta)$. Similarly, sustainability indices of conventional manufacturing process (e.g. milling) can follow the same procedure to break machining process into sub-steps and energy, material, and fluids consumption model can also be built. This change in sustainability indices at the manufacturing process can be noted as $\Delta[E, E, H]_m$ by subtraction between that of AM model and conventional manufacturing model.

3.3. Sustainability analysis model of assembly method change

In general cases, part consolidation only affects the assembly operation within the assembly itself and it has no effect on the assembly with external systems. The main gain of consolidating multiple components into one is the saving of energy and materials in assembly operations. Taking welded assembly for example, highly intensive electrical power is not needed any more. To characterize the change in sustainability evaluation because of assembly method change, the change is defined as:

$$S(Assm(\delta)) = \Delta[E, E, H]_A \tag{8}$$

Generally, assembly joining methods can be classified as removable joints and non-removable joints. In removable joints (e.g. fasteners and connectors) situation, the savings mainly lie in materials of joints and assembly effort which can be represented by hourly energy saving. In non-removable joints situation, either adhesive binder or welding solder is applied, which normally has negative environmental impact. The savings include binder or solder mass and intensive electric energy (as shown in Equations (9)-(10)).

$$E_{joining} = E_{unit} * T_{Assembly} \tag{9}$$

$$Assm(\delta) = [M_{joints}, E_{joining}] \tag{10}$$

Where E_{unit} is one unit of energy required for one single joining operation (the magnitude in two situations is different), $T_{Assembly}$ is assembly time required, M_{joints} is the material saving from joint elimination (in the second situation, binder saving has dramatic effect on chemicals).

In the end, sustainability evaluation can be applied to calculate the triplets based on the saving of joints and joining energy. In general, consolidated part will enjoy a reduced environment impact at assembly stage, but the magnitude of energy consumption and fluids depends on specific applications.

3.4. Sustainability analysis model of service method change

In a product's service life, there are three main activities which may be affected by part consolidation due to improved performance and structure reliability: maintenance scheme, usage, and life span. As proved in consolidated turbo disk and blades [2] and GE fuel nozzle [30], consolidated part can possibly increase fuel efficiency by 15%, reduce stress-induced crack, and simplified maintenance. The quantification of environmental impact at service stage mainly covers fuel efficiency, longer service life, and simplified maintenance as shown in Equation (11).

$$S(Service(\delta)) = \Delta[E, E, H]_S \tag{11}$$

Fuel savings mainly comes from two aspects: mass reduction in the design and fuel efficiency improvement. Mass reduction in design is a function of geometry and material change (Equation (12)) and fuel efficiency improvement is assumed to be ε, so the fuel savings is:

$$M_{fuel} = \gamma * \Delta M_{design}(\delta) * N + \varepsilon * M_{flight} * T_{service} \quad (12)$$

Where M_{fuel} is the total fuel saving over the service span of the product (e.g. aircraft), γ is fuel consumption coefficient over its service life which is closely related to the total mass, ΔM_{design} is the reduced mass weight, N is the number of components applied in one aircraft, M_{flight} is the default amount of fuel used in one flight job, and $T_{service}$ is the service life† of the consolidated component.

To quantify the sustainability of the elongated service life, two factors are under consideration. Firstly, during the elongated life span, the need of a new identical component is unnecessary; therefore, all the savings in manufacturing should take into account (shown in Equation (13)). Secondly, the elongated service life makes it possible to save more fuel over a longer life span. Therefore, Equation (12) can be modified as:

$$\Delta[E,E,H]_{S1} = \mu * \Delta[E,E,H]_m \quad (13)$$

$$M_{fuel} = \gamma * \Delta M_{design}(\delta) * N + \varepsilon * M_{flight} * T_{service} * (1+\mu) \quad (14)$$

Where $\Delta[E,E,H]_{S1}$is the percentage of saving from no-replacement of a new component and μ is the percentage of elongation.

To quantify the sustainability of the simplified maintenance scheme, enough information should be acquired. These information should include maintenance frequency, maintenance method, and material consumption (e.g. lubrication, cleaning chemicals, etc.). Through part consolidation, the need of frequent maintenance is eliminated so that energy and fluids involved is also reduced. Due to the lack of available maintenance data, this portion is not discussed in this paper. To summarize, the change in sustainability can be quantified as:

$$S(Service(\delta)) = \Delta[E,E,H]_{S1} + S(M_{fuel}) = \Delta[E,E,H]_S \quad (15)$$

The calculation of $S(M_{fuel})$ is based on the LCI of diesel energy. Generally, part consolidation has a positive effect on its service life.

3.5. Sustainability analysis model of EoL method change

End-of-life parts have different options - land fill, reuse, remanufacture, and recycling, which depends on the status of each part. For consolidated components, two factors may be changed. Firstly, if consolidated part adopts functionally graded material, then the recyclability is obstructed. In this situation, the environmental impact is equivalent to a new round of raw material acquisition (Factor 1). Secondly, after consolidation, a minor defect of the part reduces the possibility of reuse. In contrast, the rest portion of the old assembly can be reused and the damaged part is supposed to be remanufactured. In this sense, the change in environmental impact can be equivalent to the difference between reuse and remanufacture (Factor 2). The change in environmental impact in general can be represented as:

$$S(EoL(\delta)) = \Delta[E,E,H]_E \quad (16)$$

To quantify Factor 1, raw material acquisition for AM process is a function of volume and material as shown in Equation (17)

$$\Delta[E,E,H]_{E1} = S(M(\delta)) \quad (17)$$

Where $M(\delta)$ is the total mass of the consolidated components which is un-recyclable. This imposes a negative

† Service life here is counted as a ratio over the average time of flight

impact on environment.

To quantify Factor 2, assume the possibility of landfill, reuse, remanufacture, and recycle is $\omega_1, \omega_2, \omega_3$, and ω_4 respectively and $\sum \omega_i = 1$. The possibility of reuse in part consolidation case is lower compared to the original design. Supposedly, the remanufacturing process for both design is the same, then the outcome of sustainability change can be represented as:

$$\Delta[E,E,H]_{E2} = (\omega_{21} - \omega_{22}) * [E,E,H]_{reuse} + (\omega_{31} - \omega_{32}) * [E,E,H]_{remanufacture} \quad (18)$$

Where ω_{i1} represents the possibility of retirement for consolidated part, ω_{i2} represents the possibility of retirement for assembled parts. $[E,E,H]_{reuse}$ and $[E,E,H]_{remanufacture}$ represents the environmental impact related to reuse and remanufacture application respectively. The quantification of these two activities can be modeled according to material, energy, and fluids consumption involved.

In the end, the change of sustainability in EoL can be represented as:

$$S\big(EoL(\delta)\big) = \Delta[E,E,H]_E = \Delta[E,E,H]_{E1} + \Delta[E,E,H]_{E2} \quad (19)$$

The total change in sustainability indices can be summarized as:

$$\Delta[E,E,H]=\Delta[E,E,H]_m+\Delta[E,E,H]_A+\Delta[E,E,H]_S+\Delta[E,E,H]_E \quad (20)$$

In Equation (20), $\Delta[E,E,H]_m$ is normally positive, $\Delta[E,E,H]_A$ is negative, $\Delta[E,E,H]_S$ is positive, and $\Delta[E,E,H]_E$ is negative. It would be difficult to tell whether part consolidation has a positive impact on sustainability or not without a specific case study.

4. Case study

4.1. Design considerations and redesign

A case study of a floor attachment component on an underground train is chosen for the sustainability evaluation using the proposed sustainability assessment model. For each train with ten cargos, 80 of this components are needed. As shown in Figure 3, the original component is formed by 4 panels including two identical vertical panels, one cylindrical tube, and one bottom panel. These four panels are made of stainless steel and then they are welded together by gas metal arc welding process. The process planning for each panel is listed in Table 1. Process planning for each panel. This assembly is designed to serve the function of “hold the pillar”, “position the block”, “attach the floor”, and “easy maintenance”.

To eliminate excessive welding operations, a part consolidation design concept is embraced with the consideration of taking AM-enabled geometric complexity and manufacturing constraints (Binder Jetting process, e.g. minimum clearance) into consideration. As depicted in Figure 4, several important design modifications are made. Firstly, both the length of the cylindrical tube and vertical panels are reduced (Figure 4 a). Originally, the vertical panels and the tube are needed to line up with the bottom panel at the bottom surface to ease the positioning effort, but there is no such a need any more. Secondly, the inner side of the tube is redesigned with some cut-outs to reduce weight (Figure 4 d). The reason why only regular cut-out is made inside the hidden area is because the uncertainty in loading direction and the outer area is supposed to guarantee safety and ease maintenance in the real working environment. Loading condition (horizontal load of 1120N is applied at each bolts) and stress analysis (the maximum stress is 45.8Mpa) is shown in Figure 4 e and f respectively. Compared with the original design, consolidated design enjoys the benefits of “no welding process needed”, “shorter process route”, and “weight reduction of 7.85g (material volume reduction of 1000 mm3)”. In this case study, the direct unit mass reduction of is small because it does not require any fasteners/connectors and further optimization cannot be done to this shell structure for maintenance and passenger safety reasons.

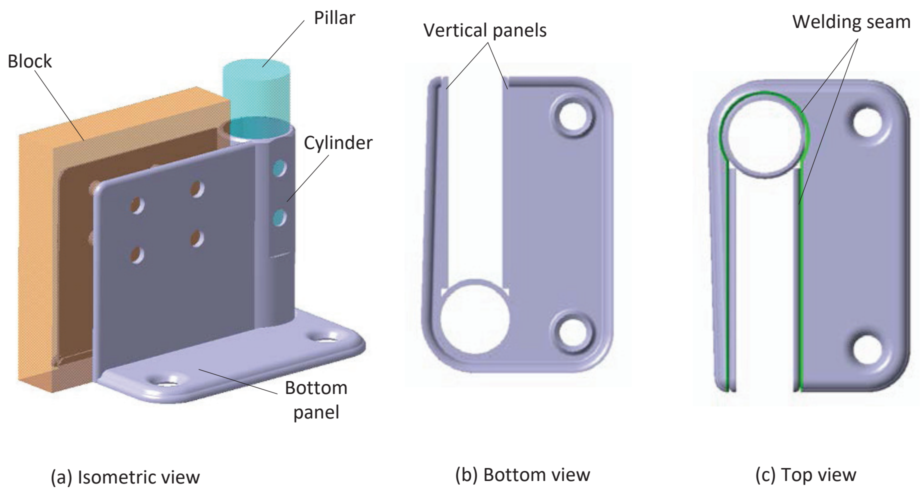

Figure 3. Original design of a floor attachment.

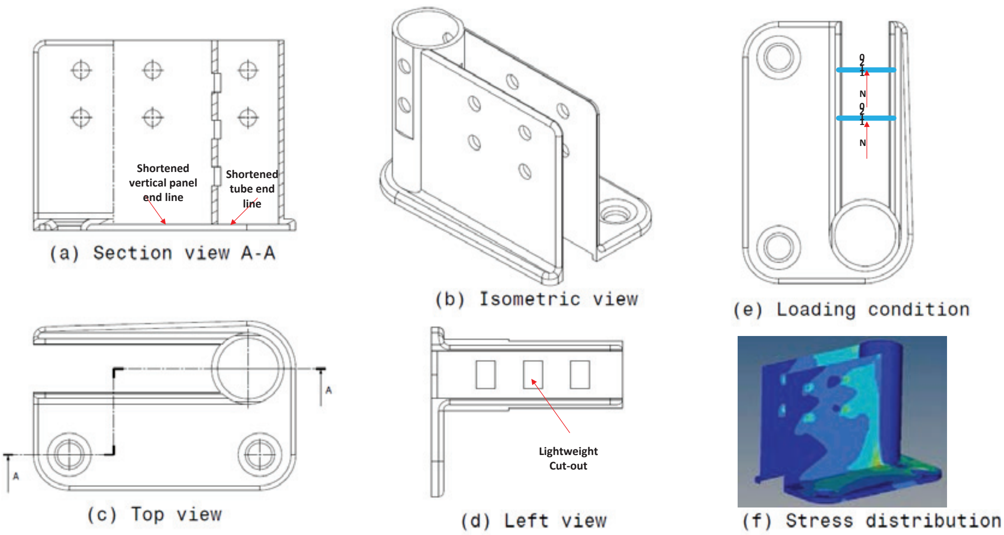

Figure 4. Consolidated component with modifications.

Table 1. Process planning for each panel.

Panel	Main process planning	Additional information
Cylinder (Part 1)	Pipe Drawing	
Bottom panel (Part 2)	Sheet metal forming- Stamping - milling	Welding seam
Vertical panel (Part 3 & 4)	Sheet metal forming- Stamping - milling	Welding seam

4.2. Sustainability evaluation

In this case study, since this component is not used on an aircraft and the mass reduction is not obvious (7.85g), the fuel consumption aspect is not critical. Besides, the maintenance method is the same so that the influence on sustainability at service stage is the same. In terms of EoL, not enough data has been obtained for its reuse and remanufacturing. Therefore, only the impact on manufacturing and assembly stage is studied here. Quantitative models have been built in "Umberto NXT universal" LCA software according to the decomposition of production process as shown in Figure 5 and Figure 6 respectively. To evaluate the environmental impact, "Ecoinvent 3" database [29] and "ReciPe Midpoint [H] w/o LT" impact assessment method [31] is used.

Conventional Manufacturing:

For the Lifecycle analysis of the original design of the floor attachment, sustainability evaluation in various impact categories of each manufacturing process mentioned in the main process plan is carried out. The net flow of all the manufacturing processes and assembly process is depicted in Figure 5. The main inputs in each process (represented as "blue block" in Figure 5) are summarized in the Appendix A. It should be mentioned that buy-to-fly ratio[‡] is considered to make the calculation as accurate as possible. The buy-to-fly ratio for sheet metal fabrication and additive manufacturing are 2.5 and 1.5 respectively [21].

In the assembly process, gas arc welding process is adopted; therefore, the main change at this stage is the material saving and energy consumption compared to AM process. In this case, M_{joints} and $E_{joining}$ in Equation (10) can be specified as the solder and electrical energy saving respectively.

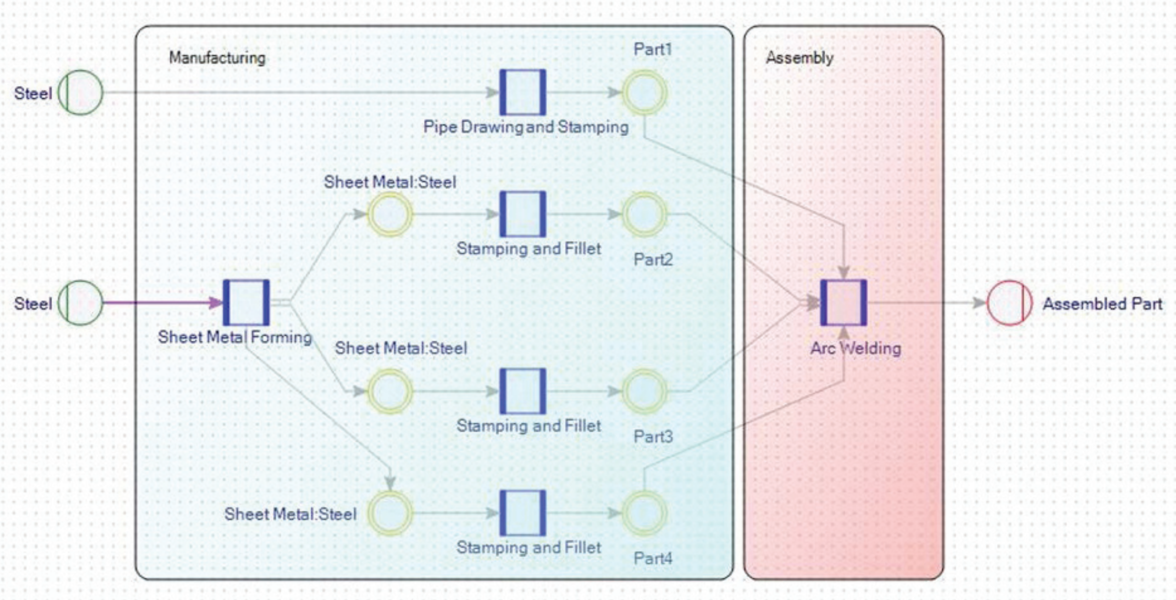

Figure 5. LCA unit process model for conventional manufacturing.

Binder jetting additive manufacturing process:

Data for binder jetting AM process used for manufacturing consolidated part is not available in Umberto. Thus, for the lifecycle analysis of consolidated part, binder jetting model defined by Meteye et al. [32] is used. In this model, electricity input is used for a few sub-processes in binder jetting AM process. Waste generated during various sub-process is included in the computation. Also, the reusable green powder produced in various stages is calculated. The case-specific inputs are summarized in Appendix B. The net flow process for this model is given in Figure 6.

‡ Buy-to-Fly ratio is the weight ratio between the raw material used for a component and the weight of the component itself.

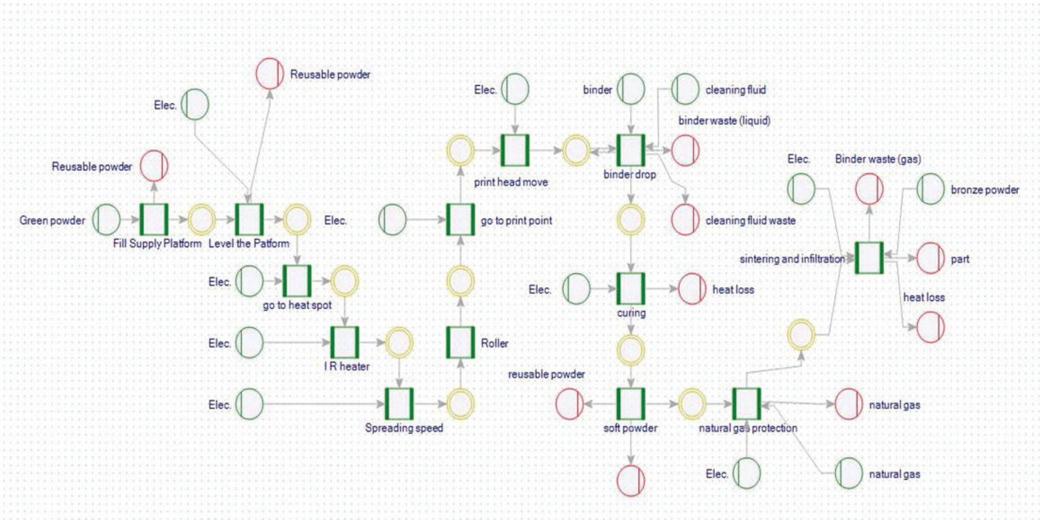

Figure 6. LCA unit process model for binder-jetting AM process.

4.3. Results analysis

Detailed numerical results of lifecycle analysis for both conventional and binder jetting AM production of the part is summarized in Table 2. Results of LCA on various impacts categories. The results for conventional production are calculated for manufacturing and assembly stage separately. The analysis categories covers the main concerns related to environmental impact (e.g. CO_2 emission and toxicity). As revealed by the comparison, most impact categories have more than 20% improvement in the consolidated design. The negative effect on Ozone layer formation and marine eutrophication almost decreases by 50% with the use of the new design. From the results, it can be observed that the impact on particulate matter formation is approximately the same with conventional design and consolidated part. Influence on fossil depletion reduces by 40%. This reduction is mainly due to reduced amount of metal used to build the part and electricity consumption. However, tremendous increase in human toxicity (168.8%) and ionising radiation (81.9%) is observed in binder jetting model. This is caused by use of binder and cleaner in the process.

When it comes to the environmental impact of assembly elimination, the percentage of CO_2 emission (12.8%) and fossil depletion (13.2%) is relatively low compared to those of the manufacturing process. It means that the gains of sustainability in assembly operation reduction is relatively few. It should also be emphasized that although consolidated design shows promise in manufacturing process in terms of energy consumption, this may result from the nature of low energy consumption of BJ AM process. In this sense, the consolidated design should be analysed by other AM processes as well.

Table 1. Results of LCA on various impacts categories.

Impact Category	Unit	Conventional Production of Original Design			Cons*. Part	Comp.
		Manuf.	Assm.	Total		
Climate Change	kg CO_2-Eq**	6.7460	0.9921	7.7381	5.5318	28.5%
Fossil Depletion	kg oil-Eq	2.1064	0.3222	2.4287	1.4944	38.4%
Freshwater Ecotoxicity	kg1,4-DCB-Eq	0.0049	0.0006	0.0055	0.0041	25.1%
Freshwater Eutrophication	kg P-Eq	0.0013	1.5E-04	0.0015	0.0011	23.7%
Human Toxicity	kg1,4-DCB-Eq	0.6258	0.1102	0.7361	1.9790	- 168.8%
Ionising Radiation	kg U235-Eq	0.3814	0.0596	0.4410	0.8026	- 81.9 %
Marine Ecotoxicity	kg1,4-DCB-Eq	0.0105	0.0021	0.0127	0.0176	- 38.3%
Marine Eutrophication	kg N-Eq	0.0017	0.0002	0.0019	0.0009	50.4%

Natural Land Transformation	m^2	0.0022	0.0003	0.0025	0.0019	22.4%
Ozone Depletion	kg CFC-11-Eq	1.1E-06	1.6E-07	1.2E-06	5.6E-07	53.8%
Particulate Matter Formation	kg PM10-Eq	0.0146	0.0022	0.0168	0.0170	-1.2%
Photochemical Oxidant Formation	kg NMVOC	0.0271	0.0040	0.0312	0.0228	27%
Terrestrial Acidification	kg SO_2-Eq	0.0466	0.0072	0.0538	0.0392	27.2%
Terrestrial Ecotoxicity	kg1,4-DCB-Eq	0.0008	0.0001	0.0010	0.0007	24.3%
Urban Land Occupation	m^2*a	0.0426	0.0024	0.0450	0.0553	- 22.8%
Water Depletion	m^3	0.022	0.0011	0.0237	0.0312	- 31.4%

* Consolidated

** Eq.= Equivalent. Most of the impact calculation in LCA is carried out in terms of a standard result. e.g. climate change is calculated as effect by greenhouse gas emission which is calculated in terms of Carbon dioxide equivalent.

5. Conclusions and future research

In this paper, the sustainability aspect of part consolidation design approach is quantitatively evaluated from a lifecycle point of view. Generic models are built to evaluate how this design change affects manufacture, assembly, service, and EoL respectively. Through the case study, part consolidation shows promise in reducing energy consumption and environmental impact at the manufacture stage while it also results in more health toxicity problems which is closely related to the fabrication process (BJ AM) selected. To conclude, the main contributions of this paper is that: 1) it provides a quantitative model to evaluate AM-enabled design alternatives in terms of sustainability assessment; 2) it is extendable to other AM processes such as Selective Laser Melting model [14].

It is also worth mentioning that only the production stage of the consolidated design is studied. The future work needs to investigate more deeply into the service life and EoL aspects. For example, as shown in Equation (18), $[E,E,H]_{reuse}$ and $[E,E,H]_{remanufacture}$ can be physically measured if "reuse" and "remanufacture" process can be decomposed; therefore, energy, material, and fluid usage at each sub-process can be calculated. One possible solution is shown as follows. IM_A and IM_C are considered as the environmental impact related to the assembled component and consolidated component respectively, then we can express them in the Reuse/Remanufacturing stage according to its sub-processes as:

$$IM_A = IM(disassembly\ process) + IM(Maintenance) + IM(repair) + IM(Reassemble) \quad (21)$$

$$IM_C = IM(Maintenance) + IM\ (repair) \quad (22)$$

Similar methods can be applied to the remanufacture process. Until then, the full lifecycle impact becomes clearly known. According to the impact values at each stage, the significance value can be drawn and some low-impact stage can be eliminated from the lifecycle calculation to roughly estimate if the design change is positive or not.

Acknowledgement

Financial support from the National Sciences and Engineering Research Council of Canada Discovery Grant RGPIN 436055-2013 and McGill Engineering Doctoral Award (MEDA) is acknowledged with gratitude.

Appendix A.

Table 1. The inputs data of sustainability evaluation model of conventional manufacturing process.

	Actual Mass (*kg*)	Processing	Final Mass (*kg*)
Part 1	0.350	Pipe drawing & stamping	0.231
Part 2	0.570	Sheet metal forming, stamping & milling	0.372
Part 3 & 4	0.325	Sheet metal forming, stamping & milling	0.221
Total Power consumed		23.54 MJ	

Appendix B.

Table 2. The input data of sustainability evaluation model for binder jetting process.

Ingredients	Input Mass (*kg*)
Green powder	0.69
Bronze powder	0.47
Binder	0.08
Energy consumed	13.7 MJ

References

[1] Yang, S., Tang, Y., and Zhao, Y. F., 2015, "A new part consolidation method to embrace the design freedom of additive manufacturing," Journal of Manufacturing Processes, 20, pp. 444-449.

[2] Frey, D., Palladino, J., Sullivan, J., and Atherton, M., 2007, "Part count and design of robust systems," Systems engineering, 10(3), pp. 203-221.

[3] Meyer, T. N., Kinosz, M. J., Bradac, E. M., Mbaye, M., Burg, J. T., and Klingensmith, M. A., 1999, "Ultra large castings to produce low cost aluminum vehicle structures," SAE Technical Papers: No. 1999-01-2252.

[4] Swanstrom, F. M., and Hawke, T., "Design For Manufacturing and Assembly (DFMA): A case study in cost reduction for composite wingtip structures," Proc. Proceedings of the 1999 31st International SAMPE Technical Conference: 'Advanced Materials and Processes Preparing for the New Millennium', October 26, 1999 - October 30, 1999, SAMPE, pp. 101-113.

[5] Schmelzle, J., Kline, E. V., Dickman, C. J., Reutzel, E. W., Jones, G., and Simpson, T. W., 2015, "(Re) Designing for Part Consolidation: Understanding the Challenges of Metal Additive Manufacturing," Journal of Mechanical Design, 137(11), p. 111711.

[6] Fiksel, J., and Fiksel, J. R., 1996, Design for environment: creating eco-efficient products and processes, McGraw-Hill Professional Publishing, USA.

[7] Suresh, P., Ramabalan, S., and Natarajan, U., 2016, "Integration of DFE and DFMA for the sustainable development of an automotive component," International Journal of Sustainable Engineering, 9(2), pp. 107-118.

[8] Tang, Y., Yang, S., and Zhao, Y. F., 2016, "Sustainable Design for Additive Manufacturing Through Functionality Integration and Part Consolidation," Handbook of Sustainability in Additive Manufacturing, Springer, pp. 101-144.

[9] Le Bourhis, F., Kerbrat, O., Dembinski, L., Hascoet, J.-Y., and Mognol, P., 2014, "Predictive model for environmental assessment in additive manufacturing process," Procedia CIRP, 15, pp. 26-31.

[10] Xu, X., Meteyer, S., Perry, N., and Zhao, Y. F., 2015, "Energy consumption model of binder-jetting additive manufacturing processes," International Journal of Production Research, 53(23), pp. 7005-7015.

[11] Kellens, K., Dewulf, W., Deprez, W., Yasa, E., and Duflou, J., "Environmental analysis of SLM and SLS manufacturing processes," Proc. Proceedings of LCE2010 Conference, pp. 423-428.

[12] Luo, Y., Ji, Z., Leu, M. C., and Caudill, R., "Environmental performance analysis of solid freedom fabrication processes," Proc. Electronics and the Environment, 1999. ISEE-1999. Proceedings of the 1999 IEEE International Symposium on, IEEE, pp. 1-6.

[13] Faludi, J., Bayley, C., Bhogal, S., and Iribarne, M., 2015, "Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment," Rapid Prototyping Journal, 21(1), pp. 14-33.

[14] Watson, J. K., and Taminger, K. M. B.,2015, "A decision-support model for selecting additive manufacturing versus subtractive manufacturing based on energy consumption," Journal of Cleaner Production, in press.

[15] Tang, Y., Mak, K., and Zhao, Y. F., 2016, "A framework to reduce product environmental impact through design optimization for additive manufacturing," Journal of Cleaner Production, 137, PP. 1560-1572.

[16] Mognol, P., Lepicart, D., and Perry, N., 2006, "Rapid prototyping: energy and environment in the spotlight," Rapid prototyping journal, 12(1), pp. 26-34.
[17] Griffiths, C., Howarth, J., De Almeida-Rowbotham, G., Rees, A., and Kerton, R., 2016, "A design of experiments approach for the optimisation of energy and waste during the production of parts manufactured by 3D printing," Journal of Cleaner Production, 139, pp. 74-85.
[18] Yang, S., Tang, Y., and Zhao, Y. F., 2016, "Assembly-level design for additive manufacturing: issues and benchmark," International Design Engineering Technical Conferences & Computers & Information in Engineering Conference. August 21-24. Charlotte, NC, USA.
[19] Chowdary, B. V., and Harris, A., 2009, "Integration of DFMA and DFE for development of a product concept: A case study," Proc. Seventh LACCEI Latin American and Caribbean Conference for Engineering and Technology - "Energy and Technology for the Americas: Education, Innovation, Technology and Practice". June,2-5, San Cristóbal, Venezuela.
[20] Boothroyd, G., Dewhurst, P., Knight, W. A., and Press, C., 2002, Product design for manufacture and assembly, M. Dekker New York, USA.
[21] Huang, R., Riddle, M., Graziano, D., Warren, J., Das, S., Nimbalkar, S., Cresko, J., and Masanet, E., 2015, "Energy and Emissions Saving Potential of Additive Manufacturing: The Case of Lightweight Aircraft Components," Journal of Cleaner Production, 135, PP. 1559-1570.
[22] Fargnoli, M., Pighini, U., and di Litta, E., "Design for assembly and design for disassembly: Two ways for the development of sustainable products," Proc. DS 31: Proceedings of ICED 03, the 14th International Conference on Engineering Design. August 19-21, Stockholm, Sweden.
[23] Güngör, A., and Gupta, S. M., 2002, "Disassembly line in product recovery," International Journal of Production Research, 40(11), pp. 2569-2589.
[24] Zussman, E., Kriwet, A., and Seliger, G., 1994, "Disassembly-oriented assessment methodology to support design for recycling," CIRP Annals-Manufacturing Technology, 43(1), pp. 9-14.
[25] Pullen, D., Kara, S., Pornprasitpol, P., and Kaebernick, H., 2005, "A selective disassembly methodology for end-of-life products," Assembly Automation, 25(2), pp. 124-134.
[26] Otto, K. N., and Wood, K. L., 1998, "Product evolution: a reverse engineering and redesign methodology," Research in Engineering Design, 10(4), pp. 226-243.
[27] Bras, B., 1997, "Incorporating environmental issues in product design and realization," Industry and environment, 20(1), pp. 7-13.
[28] Yang, S., and Zhao, Y., 2015, "Additive manufacturing-enabled design theory and methodology: a critical review," The International Journal of Advanced Manufacturing Technology, 80 (1-4), pp. 1-16.
[29] Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C., and Wernet, G., 2013, "Overview and methodology: Data quality guideline for the ecoinvent database version 3," Swiss Centre for Life Cycle Inventories.
[30] Gibson, I., Rosen, D. W., and Stucker, B., 2010, Additive Manufacturing Technologies:Rapid Prototyping to Direct Digital Manufacturing, Springer US.
[31] Heijungs, R., Goedkoop, M., Struijs, J., Effting, S., Sevenster, M., and Huppes, G., 2003, "Towards a life cycle impact assessment method which comprises category indicators at the midpoint and the endpoint level," Report of the first project phase: Design of the new method VROM report. Online: http://www. leidenuniv. nl/cml/ssp/publications/recipe_phase1. pdf. Accessed: 01/19/2017.
[32] Meteyer, S., Xu, X., Perry, N., and Zhao, Y. F., 2014, "Energy and material flow analysis of binder-jetting additive manufacturing processes," Procedia CIRP, 15, pp. 19-25.