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Research Paper

Sustainable part consolidation model for customized products in closed-loop supply chain with additive manufacturing hub

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ABSTRACT

In recent years, additive manufacturing (AM) has gained considerable interest because of its capacity to facilitate the fabrication of products of various shapes better than conventional manufacturing (CM). Moreover, it can respond to the growing demand for customized products and can reduce the impact on the environment by minimizing production waste. To maximize these benefits and overcome entry barriers, researchers have conducted part consolidation (PC) research to improve sustainability by reducing the number of components, or hybrid supply chain studies involving local AM service providers. This study aims to present a new supply chain that combines the advantages of both AM and CM systems to create and analyze the potential of an AM machine that can be made available for rent at a lower cost. In this study, a closed-loop supply chain with an AM hub (CLSCAM) is first designed. Thereafter, to support manufacturers in making the decision to adopt AM, two models are developed: sustainability (cost, environment, and time) evaluation model from the lifecycle perspective of CLSCAM, and a PC method is developed to maximize the three sustainability indices. Since the PC problem with complex product structure is an NP-hard problem, the genetic algorithm is employed as a solution method. Furthermore, an experimental analysis is conducted to validate the proposed model through a real-world application (testbed product). The results reveal that the AM hub and PC model can effectively improve the sustainability of the entire lifecycle. In particular, the results of improved sustainability per unit product in mass production scenarios demonstrate the practical applicability of the proposed model. These results also demonstrate that the pre-manufacturing stage has the greatest impact on the cost sustainability index in the CLSCAM. It is further confirmed that the sustainability improvement effect of PC increases with increasing AM raw material consumption efficiency, volume reduction rate of PC.

1. Introduction

Additive manufacturing (AM) is a set of production methods in which materials are stacked layer by layer to create the desired shape [1]. Compared to conventional manufacturing (CM) methods such as injection molding and CNC production, AM processes can manufacture more complex-shaped products. Recently, as AM technology advances, it is also advantageous in terms of manufacturing flexibility as it can produce products with various raw materials [2]. Since AM does not require a dedicated tool for fabrication, production lead time may be reduced. Unlike CM processes, AM stacks raw materials; hence, the left-over materials can be easily reused, which indicates that it has a less severe negative effect on the environment [3].

In view of these advantages, many companies have actively adopted AM in product fabrication, thereby strengthening their market competitiveness [4,5]. For example, large corporations, such as Siemens [6] and GE aviation [7], have built 3D printing centers to produce tools and parts. However, most of the small and medium enterprises (SMEs) still hesitate to adopt AM because of the entry barriers, such as expensive machinery, slow build speed, printing size limitations, and lack of operational knowledge [8]. Despite these problems, a number of manufacturers are keen to adopt AM to satisfy the demand for customized products.

To compensate for the limitations, some researchers have argued that the most significant advantages of AM can be part consolidation (PC). PC is a design method which decreases the number of parts in a product to minimize the assembly workload, weight, and cost. For example, when GE aviation produces fuel nozzles with AM, the company consolidates the 20 components of each nozzle and fabricates them as a single unit so that they can reduce cost and weight while improving durability [9]. In academia, a few attempts have been made to formulate

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Nomenclature

Manufacturing type

AM	Additive manufacturing
CM	Conventional manufacturing
E	Electronic/standard part

Lifecycle stage

De	Design stage
Pr	Pre-manufacturing stage
Mfg	Manufacturing stage
Lg	Logistics stage
Ser	Service stage
EOL	EOL stage

Process

rm	Raw material
pp	Pre-processing
A	Additive manufacturing
pm	Part manufacturing for CM part
post	Post-processing for AM part
assy	Assembly
cd	Collecting & disassembly
rec	Recycling
dis	Disposal
ip	Intermediate part

a rule-based PC guideline for a specific case and analyze the relevant costs and environmental impacts of PC [10,11]. However, most of the studies have not considered the whole aspects of sustainability, including economic and environmental sustainability, only in the AM stage.

Other researchers have focused on increasing the efficiency of AM from the perspective of supply chain management. An ongoing study proposes the creation of a hybrid AM supply chain where parts are fabricated by external AM facilities and shipped after customer orders are received [11]. In this regard, for example, Siemens and HP, a 3D printing service company, provides B2B and B2C services in its own 3D printing factory. However, most of the previous studies and examples have been restricted to a limited scope of AM such as producing components or spare parts of final products. To overcome this limitation, this study expands the manufacturing scope to make the final products have the manufacturer's effective decision-making of AM adoption when they use both AM hubs and PC at the same time.

Therefore, this study proposes a closed-loop supply chain with AM hub (CLSCAM), where the manufacturers, having CM systems, can either purchase AM machines to produce customized parts or rent the AM processes from an AM hub provider. Also, the sustainability evaluation model is developed in terms of the three criteria: cost, environment, and time, and a PC method is developed to maximize the three sustainability indices. With consideration of the problem size of PC, the genetic algorithm (GA) is employed as a solution approach. After, the experimental analysis is carried out using a testbed product, and the sensitivity analysis is conducted to draw managemental insights when manufacturers adopting AM in the CLSCAM.

This paper is organized as follows. In Section 2, previous studies on PC using AM and supply chain management with AM are reviewed to highlight the differences of our study. Section 3 elaborates on the designed closed-loop supply chain with AM hub and the developed sustainability evaluation model capable of assessing the sustainability (cost, environment, and time) of products fabricated in the CLSCAM. In Section 4, a PC model that employs GA to maximize sustainability is proposed. Section 5 presents the experimental analysis and sensitivity analysis using a testbed product. Conclusions and implications are summarized in Section 6.

2. Literature review

2.1. Part consolidation for AM

As the design freedom of AM gains considerable attention, PC is acknowledged as one of the most significant advantages of AM [12,13]. Early works on PC followed the three rules to identify available designs: no relative motion, no material variance among parts, and no access blockage to other components caused by the assembly [12]. These rules can be easily applied to CM processes since their capabilities and limitations are widely known. For AM process, however, a redesigned plan may violate one or more of the three consolidation rules above but still be a feasible solution of PC [14,15]. Thus, traditional PC methods for CM processes result in an inefficient solution for AM processes since AM makes product designers have a greater solution space.

Therefore, an increased interest in developing a new PC rule for AM processes has emerged. For example, Schmelzle et al. [14] present a PC flowchart using laser-based powder bed fusion for metal AM. Yang et al. [16] propose a generalized consolidation framework with seven rules for manufacturing sub-assembly parts with AM machines. Ghiasian et al. [17] suggest a new design modification system for AM processes to identify feasible product geometrics. However, in most of the research on PC, AM processes were understood as a prototyping tool without considering the potential of AM as a rapid manufacturing machine [18].

Meanwhile, other researchers focused on quantifying the pros and cons of PC with AM. Stevenson et al. [10] develop a PC cost model for the development and production stages. Case analysis has indicated that AM reduced the number of parts and associated costs by up to 93% and 85%, respectively. Thereafter, Knofius et al. [15] extend the model to include logistics and repairing stages; however, their results show that consolidation with AM typically leads to higher costs, mainly because of flexibility loss. Recently, research attention has moved towards the sustainability of PC with AM. Yang et al. [19] have developed generic quantitative models to analyze the environmental impacts of PC on production, service, and end-of-life activities. In addition, researchers state that AM technology will have positive effects on the lead time, time-to-market, and customer demand satisfaction [20]. In this context, Villamil et al. [21] found out that AM helps reduce lead time during the production phase in a life cycle. Lee et al. [22] develop an alternative evaluation model to derive sustainable software design solutions and considered lead time as one of the objective.

Although studies on the PC method with AM processes have been implemented, the methods have been developed for successful cases used as examples. Moreover, in most PC studies, AM has been regarded as a replacement of CM without considering their compatibility. Accordingly, this study attempts to develop a PC model that considers lifecycle impact and to extend the scope to a supply chain that presents both AM and CM processes.

2.2. Supply chain management with AM

In a company, the utilization of AM ranges from a part of processes to the entire manufacturing processes of the firm. From the perspective of supply chain management, the fast-growing manufacturing technology leads to the introduction of an independent agent to the supply chain: the AM service provider. Either way, the consequence spreads to the supply chain and results in structural shifts [23].

At first, a separate facility having AM machines is proposed for low-volume, customized, and highly urgent production [24,25]. Researchers have performed the quantitative analyzes to understand the cost elements of integrating AM facilities to the supply chains [26,27]. Based on the quantitative analysis, studies about the optimal configuration of supply chains with AM processes have been carried out with methods

Table 1
Task performed by lifecycle stage.

Lifecycle stage	Task	Lifecycle stage	Task
Design	- CAD modeling and design change	Service	- Product delivery
Pre-manufacturing	- Purchase of raw materials(AM/CM)	EOL	- Collection and disassembly
	- Pre-processing of raw materials		- Recycling
	- Purchase of intermediate parts		- Disposal
Manufacturing	- Manufacture of AM/CM parts	Logistics	- Procurement of raw materials and intermediate parts
	- Assembly		- Part logistics

such as a facility location model to a two-stage supply network [28] and an integrated decision-making process for supply chain with AM [29].

Recently, the concept of AM facility has been combined with the supplier hub in a multi-echelon supply chain [11]. According to Khajavi et al. [30]'s work, the AM hub configuration shows higher economic efficiency and effectiveness than the distributed supply chain configuration, mainly due to the reduction in equipment downtime.

Although researchers have focused on the AM facility in supply chains, only a few attempts have been made to investigate the function of AM hub and the resulting supply chain configuration. Also, previous studies on supply chain with AM have disregarded the possibility of PC, which may lead to the changes in supply chain costs. Moreover, instead of owning an AM hub, manufacturers can rent some of the AM processes from the hub and use them as replacements for some of their production resources. Accordingly, in the present study, the rental service of AM processes in the AM hub is considered, and a mathematical model is developed to exploit AM production while minimizing cost.

3. Sustainability evaluation model in CLSCAM

3.1. Structure of closed-loop supply chain with additive manufacturing hub

3.1.1. Product lifecycle

The lifecycle used in previous research is divided into two categories: Cradle-to-gate and Cradle-to-grave. More recently, Ma et al. [31] defined a new lifecycle, Conception-to-grave, which includes the design stage, to evaluate the lifecycle impact of the products manufactured by AM processes. However, this study has several limitations. First, it considers a pure AM system that produces entire parts at once. But, pure AM lacks applications in the real world, and it is difficult to apply it to the hybrid manufacturing system. In a hybrid manufacturing system, as the impact on sustainability differs depending on which production method is used for each part, it should be reflected in the sustainability evaluation model. Moreover, the logistics stage for raw materials, parts, intermediate parts, and tools are excluded from the lifecycle. Based on the limitation, we enlarged its scope to cover logistic stages from/to inside and outside AM machines in a closed-loop supply chain—such as raw material supplying and pre-processing for AM processes, and shipping parts from AM hubs to the factory. In sum, the lifecycle stage consists of six stages, each stage and its tasks are summarized in Table 1.

3.1.2. Network structure

The CLSCAM proposed in this study is based on the hybrid manufacturing system combining AM and CM. It is a highly practical supply chain, especially in that, unlike previous studies, manufacturing scope has been expanded to the product levels. In addition, to reduce the difficulty of adopting AM (expensive machinery, lack of operational knowledge, etc.), the AM hub has been introduced for renting AM machines. Thus, the manufacturer has two options for producing AM parts inside and outside the factory at a lower cost. In the latter option, the distance between the factory and the external AM hub can increase the workload in the logistics stage. The logistics is included in the framework as an independent stage, and its sustainability is measured from

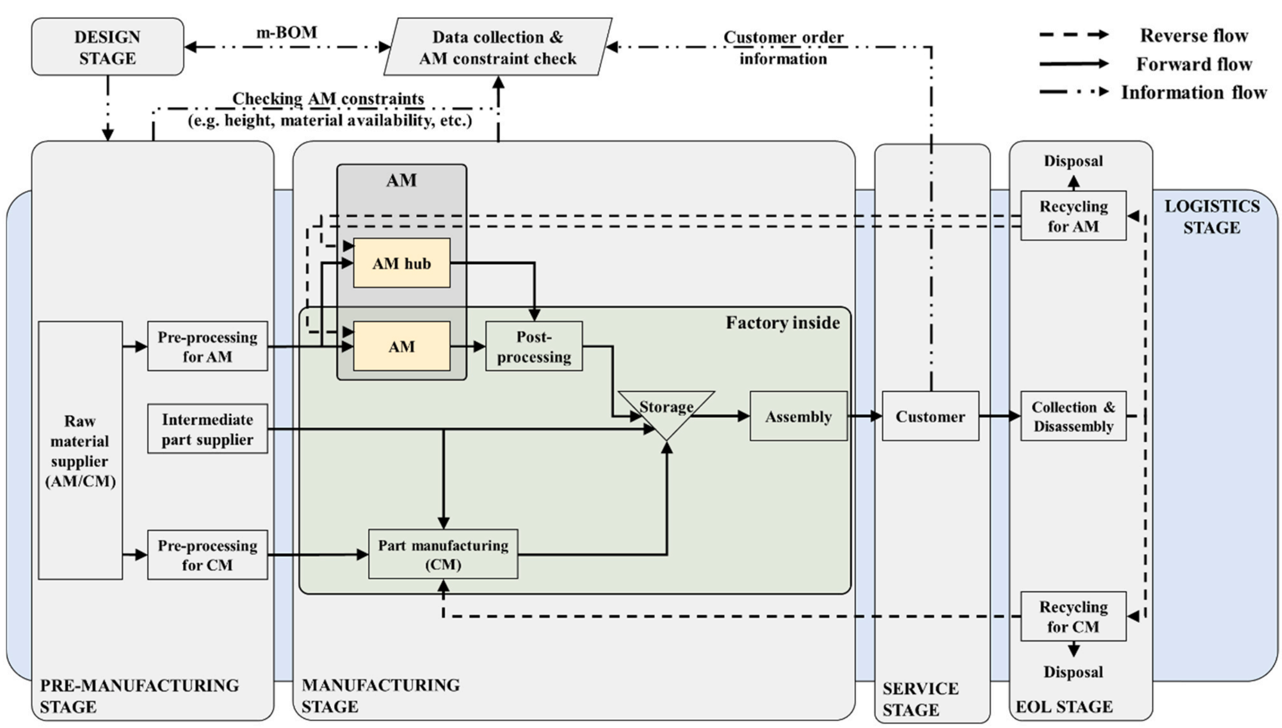


Fig. 1. Closed-loop supply chain with AM hub (CLSCAM) considering lifecycle stage.

Table 2
Indices for sustainability evaluation model.

i	Index of customer
j	Index of product
k	Index of BOM level, K indicates the lowest BOM level
c	Index of component ($c = l \cup e$)
l	Index of part
e	Index of electronic part
r	Index of raw material
tl	Index of tool
h	Index of AM hub (h = 0,1,…,H) (in this model, 0 for AM zone in main factory)
o	Index of AM method
x	Lifecycle stage
y	Manufacturing type
z	Supply chain process
L_{jk}	Set of components in product j at BOM level k ($L_j = L_{j1} \cup L_{j2} \cup \ldots \cup L_{jK}$)
$C_{c_{jk}}$	Set of children of component c in product j at BOM level k
$P_{c_{jk}}$	Set of parents of component c in product j at BOM level k
TL_j	Set of dedicated tools for manufacturing operation of product j

Table 3
Parameter for sustainability evaluation model.

d_{ij}	Demand for product j of customer i	pd_{jc}^{k}	Demand for component c of product j at BOM level k
δ_l	Customization level of part l ($l \in L_j$)	$cx(\delta_l)$	Design complexity of part l ($l \in L_j$)
V_{jl}	Volume for part l of product j	h_l	Height of part l
β_{jc}^{k}	BOM coefficient of component c of product j at BOM level k	u	Strategic utilization ratio of AM hub
π_i	Expected number of design changes of customer i	at_i	Available AM time for customer i's order
cus_i	Customer i's location		
$M_z^{y,in}$	Input amount of material for process z using y	$M_z^{y,out}$	Output amount of material for process z using y
TW_i	Total weight delivered to customer i	wp_{ij}	Weight for product j of customer i
mp_l^y	Weight of part l manufactured by y	mt_{tl}	Weight of dedicated tool tl
mt_{assy}	Weight of assembly tool set	me_e	Weight of electronic part e
v_c	Binary value whether component c has children	cv_{lo}	Whether part l can be manufactured using o
bv_{oh}	Whether AM hub h has method o	$tv_{l,tl}$	Whether tool tl can be used to manufacturing part l
E_z^y	Energy consumption of process z using y	E_o	Energy consumption of AM machine using o
E_a/E_d	Energy consumption of each assembly/disassembly operation	ρ	Electricity conversion factor
e_{price}	Electricity price	f_{price}	Fuel price
e_{cf}	CO_2 emission coefficient of electricity consumption	f_{cf}	CO_2 emission coefficient of fuel consumption
pow_{PC}	Power of computer	pow_o	Power of AM machine using o
fe	Average fuel efficiency of the vehicle		
dt	Average time per each design change	WT	Working hour of AM machine per day
tc_l	CAD modeling time of part l	tc_{tl}	Design and production lead time of tool tl
t_z^y	Processing rate of process z using y (h/kg)	t^{assy}/t^{cd}	Processing time of unit assembly/disassembly task
θ	Return rate of EOL product	λ	Inspection and disassembly rate
rec^y	Recycling rate of part manufactured by y	σ_r	Density of material r (kg/cm^3)
α_z	Yield of process z	btf	Buy-to-fly ratio ($= 1/\alpha_A$)
pr_r^y	Purchasing cost of raw material r for y	pt_{tl}	Purchasing cost of dedicated tool tl
pt_{assy}	Purchasing cost of assembly tool set	pe_e	Purchasing cost of electronic part e
ac/dc	Unit cost of assembly/disassembly task	ec^{dis}	Unit disposal cost
ω_1	Hourly wage of CAD designer	ω_2	Hourly wage of machine operator
pa_o	Purchasing cost of AM machine using o	ra_o	Rental cost of AM machine using o
h_cap_o	Maximum height of AM machine using o	rc_o	Material consumption rate of AM machine using o (kg/h)
ap_o	Build rate of AM process using o	wr	Number of workers required per AM machine
ld_{tl}	Life of dedicated tool tl	ld_{assy}	Life of assembly tool set
v	Average speed of vehicle	vc	Vehicle capacity
ε_r^y	Discount factor for recycled raw material r for y	$dist(a, b)$	Distance between supply chain member a and b

the view of CLSCAM. Both network structure and lifecycle stage of CLSCAM are designed as shown in Fig. 1. First, consider the manufacturing process in the CLSCAM. Once the customer order information (product, quantity, customization level, etc.) is entered into the manufacturer's information system, the part and dedicated tool design stage commences. Upon the completion of the design stage, manufacturers produce parts using their CM system (e.g., CNC milling, injection molding, etc.), or adopt AM to produce customized parts. The AM machine can be purchased and used in the factory (AM) or rented from the AM hub. When the parts are produced at the AM hub, the required raw materials are supplied to the AM hub. After the part production, the parts are procured to the main factory. The products are assembled and delivered to the customer. Lastly, EOL products are collected, disassembled, and sent to the recycler. The raw materials obtained in the recycling stage can be reused.

3.2. Sustainability evaluation model in CLSCAM

A sustainability evaluation model for cost, environment, and order response in terms of the lifecycle in the CLSCAM is presented. The use of resources, such as processed raw material throughout the lifecycle stage, fuel and energy consumptions, labor, and equipment, are measured in this model. The indices and parameters are presented in Tables 2 and 3. Control variables and expressions are summarized in Tables A.1–A.3 of Appendix A.

In the CLSCAM, the following assumptions are made for evaluating the sustainability:

- All parts that do not violate the AM constraints (e.g., material availability, height limit) can be manufactured with AM.
- For AM methods, the buy-to-fly ratio is 2 [28].
- The processing rate and yield ratio of each process are known.
- For each AM hub, one AM method can be used, and one raw material is available to each AM method; some parts can be printed in more than two raw materials, and in this case, the most sustainable raw material can be selected.
- Selective laser sintering (SLS), direct metal laser sintering (DMLS), and Polyjet are available AM methods.
- A manufacturer rents the AM machine from AM hubs with no fixed cost and pays a rental fee per unit AM machine depending on the rental duration.
- All logistics processes use a type of small truck.
- The atomization process is not considered for model simplification because it consumes a lower amount of energy than that in the actual printing process [32].

3.2.1. Cost sustainability index ($) evaluation model

Many studies use the total AM production cost as an economic sustainability index [10,31,33]. Therefore, in this study, the cost ($)

incurred in the CLSCAM is employed as a cost sustainability index.

The design stage cost (C_{De}) includes computer-aided design (CAD) modeling and design changes costs. Design work utilizes 0.5 h for each part, and it is increased by the customization level. Taking these into account, design stage time (R_{De}) is obtained, and the designer wage (C_{wage}) and electricity consumption cost (C_{elec}) are calculated using hourly wage rate of the designer (ω_1), electricity price (e_{price}), and power of computer (pow_{PC}) as in Eq. (1).

$$C_{De} = C_{wage} + C_{elec} = R_{De}\left(\omega_1 + e_{price} \cdot pow_{PC}\right) \tag{1}$$

The pre-manufacturing stage cost (C_{Pr}) include the purchasing cost of the primary/recycled raw materials for AM/CM (C_{rm_AM}/C_{rm_CM}), electricity consumption cost for pre-processing raw materials (C_{pr_AM}/C_{pr_CM}), and the purchasing costs of electronic parts (e.g., Bluetooth antenna, battery) and tools (C_{ip_e}/C_{ip_tl}); recycled raw materials can be purchased at discounted prices ($\varepsilon_r^{AM} pr_r^{AM}/\varepsilon_r^{CM} pr_r^{CM}$). It is calculated by Eqs. (2)–(5).

$$C_{Pr} = \left(C_{rm\_AM} + C_{rm\_CM}\right) + \left(C_{pr\_AM} + C_{pr\_CM}\right) + \left(C_{ip\_e} + C_{ip\_tl}\right) \tag{2}$$

$$C_{rm\_AM} + C_{rm\_CM} = \sum_r \left[pr_r^{AM} \sum_h \left[\left(\mathrm{M}_{pp,h}^{AM,in} + \varepsilon_r^{AM} \mathrm{M}_{rec,h}^{AM,out} \right) \right] + \left[pr_r^{CM} \left(\mathrm{M}_{pp}^{CM,in} + \varepsilon_r^{CM} \mathrm{M}_{rec}^{CM,out} \right) \right] \right] \tag{3}$$

$$C_{pr\_AM} + C_{pr\_CM} = \rho \cdot e_{price} \cdot \left(E_{pp}^{AM} \mathrm{M}_{pp}^{AM,\ \ in} + E_{pp}^{CM} \mathrm{M}_{pp}^{CM,\ \ in} \right) \tag{4}$$

$$C_{ip\_e} + C_{ip\_tl} = \sum_k \left[\sum_{e \in L_{jk}} \frac{(1 - v_e)}{(\alpha_{assy})^k} \left(\mathrm{pd}_{je}^k pe_e \right) \right] + \left[\sum_{tl \in TL_j} pt_{tl} NT_{tl} + pt_{assy} NT_{assy} \right] \tag{5}$$

The manufacturing stage cost (C_{Mfg}) includes the cost of purchasing or renting an AM machine (C_{mc_p}/C_{mc_r}), electricity consumption cost for AM/CM part manufacturing (C_{AM}/C_{pm}), and for the post-processing of AM parts (C_{post}), assembly cost (C_{assy}), and administrative wages (C_{admin}). The electricity consumption costs and administrative wages for AM are only considered in the main factory. The number of AM machine rentals ($\mathrm{N}_{rent\,oh}$) are calculated using the raw material input ($m_{oh}^{AM,in}$) and the material consumption rate(rc_o). The rental fee (ra_o) is paid on a daily basis, and the manufacturing cost equations are expressed by Eqs. (6)–(10).

$$C_{Mfg} = \left(C_{mc\_p} + C_{mc\_r}\right) + \left(C_{AM} + C_{pm} + C_{post}\right) + C_{assy} + C_{admin} \tag{6}$$

$$C_{mc\_p} + C_{mc\_r} = \sum_{o,h=0} \left[pa_o \cdot \mathrm{N}_{buy\,oh} \right] + \sum_{o,h \geq 1} \left[\mathrm{ra}_o \cdot \mathrm{N}_{rent\,oh} \cdot \left\lceil \frac{WT \cdot m_{oh}^{AM,\ \ in}}{rc_o \cdot \mathrm{N}_{rent\,oh}} \right\rceil \right] \tag{7}$$

$$C_{AM} + C_{pm} = \sum_{o,h=0} \left[e_{price} \cdot pow_o \cdot \left\lceil \frac{m_{oh}^{AM,\ \ in}}{rc_o} \right\rceil \right] + \rho \cdot e_{price} \cdot E_{pm}^{CM} \cdot \mathrm{M}_{pm}^{CM,\ \ in} \tag{8}$$

$$C_{post} = \rho \cdot e_{price} \cdot E_{post}^{AM} \cdot \mathrm{M}_{post}^{AM,\ \ in} \tag{9}$$

$$C_{assy} = acNA_{ij} \tag{10}$$

$$C_{admin} = \sum_{o,h=0} \left\lceil wr \cdot \omega_2 \cdot at_i \cdot WT \cdot \mathrm{N}_{buy\,oh} \right\rceil \tag{11}$$

Service stage cost(C_{Ser}) is the shipping cost of the product to the customer. It is affected by the total delivered weight (TW_i) and distance ($dist(mf, cus_i)$), as expressed by Eq. (12).

$$C_{Ser} = f_{price} \cdot \frac{dist(mf, cus_i)}{fe} \cdot \left\lceil \frac{TW_i}{\mathrm{vc}} \right\rceil \tag{12}$$

In the EOL stage (C_{EOL}), collection and disassembly (C_{cd}), electricity consumption for the recycling process (C_{rec_AM}/C_{rec_CM}), and disposal costs (C_{dis}) are measured, as shown in Eqs. (13)–(16).

$$C_{EOL} = C_{cd} + \left(C_{rec\_AM} + C_{rec\_CM}\right) + C_{dis} \tag{13}$$

$$C_{cd} = \theta \cdot dc \cdot d_{ij} \cdot na_{ij} \tag{14}$$

$$C_{rec\_AM} + C_{rec\_CM} = \rho \cdot e_{price} \left(E_{rec}^{AM} \cdot \mathrm{M}_{rec}^{AM,in} + E_{rec}^{CM} \cdot \mathrm{M}_{rec}^{CM,\ \ in} \right) \tag{15}$$

$$C_{dis} = ec^{dis} \left(\mathrm{M}_{dis}^{AM} + \mathrm{M}_{dis}^{CM} \right) \tag{16}$$

The logistics stage cost (C_{Lg}) includes that the procurement cost of pre-processed raw materials (C_{rmp_AM}/C_{rmp_CM}), intermediate parts (C_{ip_ep}/C_{ip_tlp}), and recycled raw materials ($C_{rpi\_AM}/C_{rpi\_CM}/C_{rpo\_AM}/C_{rpo\_CM}$), and transportation cost of the AM parts (C_{hubp}), as calculated by Eqs. (17)–(22).

$$C_{Lg} = \left(C_{rmp\_AM} + C_{rmp\_CM}\right) + \left(C_{ip\_ep} + C_{ip\_tlp}\right) + C_{hubp} + \left(C_{rpi\_AM} + C_{rpo\_AM}\right) + \left(C_{rpi\_CM} + C_{rpo\_CM}\right) \tag{17}$$

$$C_{rmp\_AM} + C_{rmp\_CM} = f_{price} \cdot \left[\sum_{h \in \{0\} \cup H} \left[\frac{dist(pp, h)}{fe} \cdot \left\lceil \frac{\mathrm{M}_{pp,h}^{AM,out}}{\mathrm{vc}} \right\rceil \right] + \frac{dist(pp, mf)}{fe} \cdot \left\lceil \frac{\mathrm{M}_{pp}^{CM,out}}{\mathrm{vc}} \right\rceil \right] \tag{18}$$

$$C_{ip\_ep} + C_{ip\_tlp} = f_{price} \cdot \frac{dist(ip, mf)}{fe} \cdot \left[\left\lceil \frac{\mathrm{M}_{assy}^{E,in}}{\mathrm{vc}} \right\rceil + \left\lceil \frac{\mathrm{M}_{pm}^{TL} + \mathrm{M}_{assy}^{TL}}{\mathrm{vc}} \right\rceil \right] \tag{19}$$

$$C_{hubp} = f_{price} \cdot \sum_{h \geq 1} \left[\frac{dist(mf, h)}{fe} \cdot \left\lceil \frac{\mathrm{M}_{A,h}^{AM,out}}{\mathrm{vc}} \right\rceil \right] \tag{20}$$

$$C_{rpi\_AM} + C_{rpo\_AM} = f_{price} \cdot \left[\frac{dist(mf, rec1)}{fe} \cdot \left\lceil \frac{\mathrm{M}_{rec}^{AM,\ \ in}}{\mathrm{vc}} \right\rceil + \sum_h \left(\frac{dist(rec1, h)}{fe} \cdot \left\lceil \frac{\mathrm{M}_{rec,h}^{AM,out}}{\mathrm{vc}} \right\rceil \right) \right] \tag{21}$$

$$C_{rpi\_CM} + C_{rpo\_CM} = f_{price} \cdot \frac{dist(mf, rec2)}{fe} \cdot \left(\left\lceil \frac{\mathrm{M}_{rec}^{CM,\ \ in}}{\mathrm{vc}} \right\rceil + \left\lceil \frac{\mathrm{M}_{rec}^{CM,\ \ out}}{\mathrm{vc}} \right\rceil \right) \tag{22}$$

The cost sustainability index (CSI) of CLSCAM can be expressed as Eq. (23).

$$CSI = C_{De} + C_{Pr} + C_{Mfg} + C_{Ser} + C_{EOL} + C_{Lg} \tag{23}$$

3.2.2. Environmental sustainability index (kgCO$_2$-eq) evaluation model

Most studies on the environmental sustainability of AM [31,32,34] analyze the effect of AM as a replacement of CM without considering their compatibility. In reality, however, it is more practical that parts are manufactured through different manufacturing processes (AM/CM) and assembled. Therefore, the environmental sustainability evaluation model suitable for CLSCAM is required. In addition, as with CSI, the environmental sustainability model includes the logistics stage, and evaluates the carbon emission (kgCO_2-eq) considering two main factors: energy and fuel consumption during the lifecycle.

The carbon emissions at the design stage (E_{De}) are affected by the design stage time (R_{De}). This is due to the increase in power consumption relative to the time consumed using PC (pow_{PC}) during the design work, as shown in Eq. (24).

$$E_{De} = e_{cf} \cdot pow_{PC} \cdot R_{De} \tag{24}$$

The pre-manufacturing stage involves pre-processing AM/CM raw materials. As described in existing studies [34,35], the AM/CM raw materials are assumed to have the same energy consumptions. However, because the weights of AM/CM parts ($M_{pp}^{AM,\ in}/M_{pp}^{CM,\ in}$) differ, the energy consumption at the pre-manufacturing stage(E_{Pr}) may vary depending on how the parts are produced by manufacturing types. CO_2 emissions calculation is shown in Eq. (25).

$$E_{Pr} = E_{pr\_AM} + E_{pr\_CM} = \rho \cdot e_{cf} \cdot \left(E_{pp}^{AM} \cdot M_{pp}^{AM,\ in} + E_{pp}^{CM} \cdot M_{pp}^{CM,\ in}\right) \tag{25}$$

The environmental sustainability of the manufacturing stage (E_{Mfg}) is effected by the energy consumption in three processes: AM/CM part manufacturing (E_{AM}/E_{pm}), AM part post-processing (E_{post}), and assembly (E_{assy}). The energy consumption rate for each manufacturing process (AM, CM, assembly, etc.) is fixed (Table B.2). It is calculated by Eqs. (26)–(29):

$$E_{Mfg} = \left(E_{AM} + E_{pm}\right) + E_{post} + E_{assy} \tag{26}$$

$$E_{AM} + E_{pm} = \rho \cdot e_{cf} \cdot \left(\sum_{o,h} E_o m_{oh}^{AM,\ in} + E_{pm}^{CM} \cdot M_{pm}^{CM,\ in}\right) \tag{27}$$

$$E_{post} = \rho \cdot e_{cf} \cdot E_{post}^{AM} \cdot M_{post}^{AM,\ in} \tag{28}$$

$$E_{assy} = \rho \cdot e_{cf} \cdot E_a \cdot NA_{ij} \tag{29}$$

In the service stage, environmental sustainability (E_{Ser}) is measured based on total fuel consumption considering the total shipping weight (TW_i) and distance ($dist(mf, cus_i)$) from the customer, as shown in Eq. (30).

$$E_{Ser} = f_{cf} \cdot \frac{dist(mf, cus_i)}{fe} \cdot \left\lceil \frac{TW_i}{vc} \right\rceil \tag{30}$$

The environmental sustainability of the EOL stage (E_{EOL}) contains carbon emissions in terms of three processes: disassembly of collected EOL products (E_{cd}), recycling of AM/CM parts (E_{rec_AM}/E_{rec_CM}), and disposal (E_{dis}), as calculated by Eqs. (31)–(34).

$$E_{EOL} = E_{cd} + (E_{rec\_AM} + E_{rec\_CM}) + E_{dis} \tag{31}$$

$$E_{cd} = \rho \cdot \theta \cdot e_{cf} \cdot E_d \cdot d_{ij} \cdot na_{ij} \tag{32}$$

$$E_{rec\_AM} + E_{rec\_CM} = \rho \cdot e_{cf} \left(E_{rec}^{AM} \cdot M_{rec}^{AM,in} + E_{rec}^{CM} \cdot M_{rec}^{CM,\ in}\right) \tag{33}$$

$$E_{dis} = \rho \cdot e_{cf} \cdot E_{dis} \cdot \left(M_{dis}^{AM} + M_{dis}^{CM}\right) \tag{34}$$

In the logistics stage (E_{Lg}), the procurement of raw materials (E_{rmp_AM}/E_{rmp_CM}) and intermediate parts (E_{ip_ep}/E_{ip_tlp}), and AM parts (E_{hubp}), and the recycling-related logistics process ($E_{rpi\_AM}/E_{rpi\_CM}/E_{rpo\_AM}/E_{rpo\_CM}$) affect environmental sustainability. Total fuel consumption related to those processes is measured and converted into carbon emissions, depending on the shipping weight and the distance (Eqs. (35)–(40)).

$$E_{Lg} = \left(E_{rmp\_AM} + E_{rmp\_CM}\right) + \left(E_{ip\_ep} + E_{ip\_tlp}\right) + E_{hubp} + \left(E_{rpi\_AM} + E_{rpo\_AM}\right) + \left(E_{rpi\_CM} + E_{rpo\_CM}\right) \tag{35}$$

$$E_{rmp\_AM} + E_{rmp\_CM} = f\_cf \cdot \left[\sum_h \left[\frac{dist(pp,h)}{fe} \cdot \left\lceil \frac{M_{pp,h}^{AM,out}}{vc} \right\rceil\right] + \frac{dist(pp,mf)}{fe} \cdot \left\lceil \frac{M_{pp}^{CM,out}}{vc} \right\rceil\right] \tag{36}$$

$$E_{ip\_ep} + E_{ip\_tlp} = f\_cf \cdot \frac{dist(ip,mf)}{fe} \cdot \left[\left\lceil \frac{M_{assy}^{E,in}}{vc} \right\rceil + \left\lceil \frac{M_{pm}^{TL} + M_{assy}^{TL}}{vc} \right\rceil\right] \tag{37}$$

$$E_{hubp} = f\_cf \cdot \sum_{h \geq 1} \left[\frac{dist(mf,h)}{fe} \cdot \left\lceil \frac{M_{A,h}^{AM,out}}{vc} \right\rceil\right] \tag{38}$$

$$E_{rpi\_AM} + E_{rpo\_AM} = f\_cf \cdot \left[\frac{dist(mf,rec1)}{fe} \cdot \left\lceil \frac{M_{rec}^{AM,\ in}}{vc} \right\rceil + \sum_h \left(\frac{dist(rec1,h)}{fe} \cdot \left\lceil \frac{M_{rec,h}^{AM,out}}{vc} \right\rceil\right)\right] \tag{39}$$

$$E_{rpi\_CM} + E_{rpo\_CM} = f\_cf \cdot \frac{dist(mf,rec2)}{fe} \cdot \left(\left\lceil \frac{M_{rec}^{CM,\ in}}{vc} \right\rceil + \left\lceil \frac{M_{rec}^{CM,\ out}}{vc} \right\rceil\right) \tag{40}$$

Overall, the environmental sustainability index(ESI) of CLSCAM is expressed as Eq. (41).

$$ESI = E_{De} + E_{Pr} + E_{Mfg} + E_{Ser} + E_{EOL} + E_{Lg} \tag{41}$$

3.2.3. Order response sustainability index (hour) evaluation model

The order response time from product design to delivery is a significant decision-making factor for the manufacturer to satisfy the market demands by using AM. Certain studies have been conducted to measure the AM building time, but only the AM stage have been considered. Accordingly, the order response time (hour) during the lifecycle is more appropriate for sustainability assessment, and it is used as a sustainability index in this study.

First, the design stage (R_{De}) includes the design time of parts (tc_l), the design and production times of the dedicated tool for CM parts (tc_{tl}), and the average time for design change ($dt\pi_i$), as shown in Eq. (42).

$$R_{De} = \sum_{l \in L_j} \left(\left(z_l^{AM} + z_l^{CM}\right) cx(\delta_l) tc_l + z_l^{CM} \left(\sum_{tl \in TL_j} tv_{l,tl} tc_{tl}\right)\right) + dt\pi_i \tag{42}$$

The order response time at the pre-manufacturing stage (R_{Pr}) includes pre-processing AM/CM raw materials (R_{pr_AM}/R_{pr_CM}). It is measured using the time (t_{pp}^{AM}/t_{pp}^{CM}) required to process 1 kg of raw material ($M_{pp}^{AM,\ in}/M_{pp}^{CM,\ in}$) and is expressed by Eq. (43).

$$R_{Pr} = R_{pr\_AM} + R_{pr\_CM} = t_{pp}^{AM} M_{pp}^{AM,\ in} + t_{pp}^{CM} M_{pp}^{CM,\ in} \tag{43}$$

The manufacturing stage (R_{Mfg}) evaluates the time including AM/CM part manufacturing (R_{AM}/R_{pm}), AM part post-processing (R_{post}), and assembly (R_{assy}). The AM part production time of each AM hub is derived using the raw material consumption rate (rc_o); the longest production time among AM hub is considered as the AM production time. The assembly time is calculated as multiplying the total number of assemblies (NA_{ij}) by the unit assembly time (t^{assy}) (Eqs. (44)–(47)).

$$R_{Mfg} = \left(R_{AM} + R_{post}\right) + R_{pm} + R_{assy} \tag{44}$$

$$R_{AM} + R_{post} = \max_{\forall o,h} \left\lceil \frac{m_{oh}^{AM,\ in}}{rc_o N_{oh}} \right\rceil + t_{post}^{AM} M_{post}^{AM,\ in} \tag{45}$$

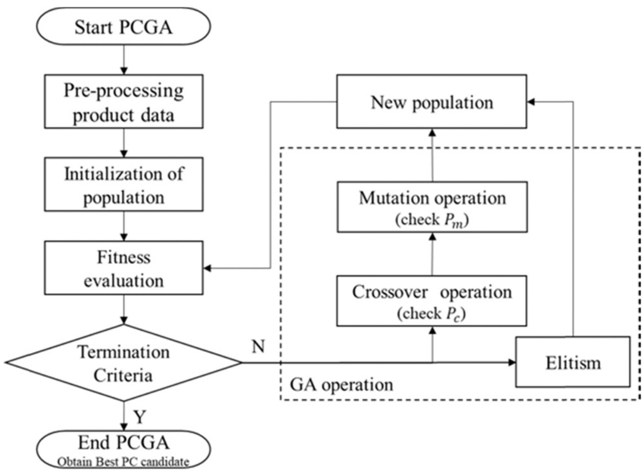


Fig. 2. Overall procedure of Part Consolidation using Genetic Algorithm.

$$R_{pm} = t_{pm}^{CM} \mathrm{M}_{pm}^{CM,\ in} \tag{46}$$

$$R_{assy} = t^{assy} NA_{ij} \tag{47}$$

In the service stage (R_{Ser}), delivery time for the product is evaluated. It is only affected by the distance and can be calculated as $\frac{dist(mf, cus_i)}{v}$.

The order response time at the EOL stage (R_{EOL}) includes the disassembly (R_{cd}) and recycling of AM/CM parts (R_{rec_AM}/R_{rec_CM}). Disassembly time is calculated the same as assembly, and the recycling time is evaluated using the time required($t_{rec}^{AM}/t_{rec}^{CM}$) to recycling 1 kg of raw materials ($\mathrm{M}_{rec}^{AM,in}/\mathrm{M}_{rec}^{CM,in}$) (Eq. (48)).

$$R_{EOL} = R_{cd} + (R_{rec\_AM} + R_{rec\_CM}) = \theta \cdot t^{cd} \cdot d_{ij} \cdot na_{ij} + \left(t_{rec}^{AM} \mathrm{M}_{rec}^{AM,in} + t_{rec}^{CM} \mathrm{M}_{rec}^{CM,in}\right) \tag{48}$$

In the logistics stage, the procurement of raw materials (R_{rmp_AM}/R_{rmp_CM}) and intermediate parts (R_{ip_ep}/R_{ip_tlp}), and AM parts (R_{hubp}), and the recycling-related logistics process ($R_{rpi\_AM}/R_{rpi\_CM}/R_{rpo\_AM}/R_{rpo\_CM}$) affect the order response time sustainability. The time for the logistics stage (R_{Lg}) is calculated depending on the distance (Eqs. (49)–(54)).

$$R_{Lg} = \left(R_{rmp\_AM} + R_{rmp\_CM}\right) + \left(R_{ip\_ep} + R_{ip\_tlp}\right) + R_{hubp} + \left(R_{rpi\_AM} + R_{rpo\_AM}\right) + \left(R_{rpi\_CM} + R_{rpo\_CM}\right) \tag{49}$$

$$R_{rmp\_AM} + R_{rmp\_CM} = \max_{\forall h} \frac{dist(pp, h)}{v} + \frac{dist(pp, mf)}{v} \tag{50}$$

$$R_{ip\_ep} + R_{ip\_tlp} = \frac{2dist(ip, mf)}{v} \tag{51}$$

$$R_{hubp} = \max_{\forall h \geq 1} \frac{dist(h, mf)}{v} \tag{52}$$

$$R_{rpi\_AM} + R_{rpo\_AM} = \frac{dist(mf, rec1)}{v} + \max_{\forall h} \frac{dist(rec1, h)}{v} \tag{53}$$

$$R_{rpi\_CM} + R_{rpo\_CM} = \frac{dist(mf, rec2)}{v} \tag{54}$$

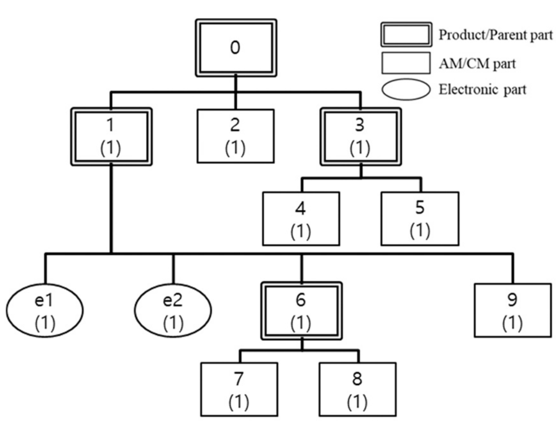
Finally, the order response sustainability index (RSI) of CLSCAM can be expressed as Eq. (55).

$$RSI = R_{De} + R_{Pr} + R_{Mfg} + R_{Ser} + R_{EOL} + R_{Lg} \tag{55}$$

4. Part consolidation using genetic algorithm

4.1. Part consolidation

The best approach to exploit the design freedom of AM is part consolidation (PC) [34]. In particular, the number of parts can be



(a)

	Part No.									
Part No.	0	1	2	3	4	5	6	7	8	9
0	1									
1	1									
2	1									
3	1									
4				1						
5				1						
6		1								
7							1			
8							1			
9		1								

(b)

Fig. 3. Illustrative example: (a) manufacturing Bill-of-Material, (b) BOM Relationship Matrix.

Parent layer	6	3	0	1
Module layer	2	1	2	4
Module configuration layer	{7}, {8}	{4,5}	{1}, {2,3}	{6}, {9}, {e1}, {e2}

Fig. 4. Possible illustrative chromosome based on Fig. 3(a).

reduced by redesigning the product and reduced the assembly workload. Then, weight and cost savings can be achieved compared with those of unconsolidated products. A number of recent studies [10,15,16,19] investigated the PC guidelines and impact of PC on production cost. However, only a few studies have analyzed the effects of PC in terms of sustainability in the supply chain. This study addresses a PC problem that aims to maximize sustainability in CLSCAM. The main tasks of the PC problem are to determine the feasible PC candidates including the manufacturing technology (z_l^{AM}/z_l^{CM}), AM hub (hv_{lh}), and AM method (ah_{lo}) for each part by considering AM/CM constraints (e.g., raw material availability, height limitation, assembly block list). The goal is to maximize the integrated sustainability index (ISI) that represents the improvement of sustainability depending on whether a PC solution is applied (Eq. (56)). The problem is represented by the following model, and the notations are shown in Appendix A. Since the formulation itself is not our purpose, we omit a detailed explanation of the equations.

(PC problem)

$$\mathit{max}\ \mathrm{ISI} = f(\mathrm{CSI}, \mathrm{ESI}, \mathrm{RSI})$$

subject to

$$z_l^{AM} + z_l^{CM} = 1, \quad \forall \quad l \in L_j$$

$$hv_{lh} \le \sum_{ro} av_{ro} bv_{oh} z_l^{AM}, \quad \forall l, h$$

$$\sum_h bv_{oh} hv_{lh} \le ah_{lo}, \quad \forall \quad l$$

$$\sum_o ah_{lo} = 1, \quad \forall \quad l$$

$$\max_{l \in \mathrm{g}_j^m} h_l z_l^{AM} \le h\_cap_o, \quad \forall \quad l, o, h$$

$$z_l^{AM} \le \sum_m \mathrm{Y}_{lm}, \forall \quad l$$

$$z_l^{AM}, \quad z_l^{CM}, \mathrm{Y}_{lm}, hv_{lh}, ah_{lo} \in 0, 1$$

where $\mathrm{g}_j^m = \{l | z_l^{AM} = 1 and l \notin ab_j\}, L_j = \mathrm{g}_j^1 \cup \mathrm{g}_j^2 \cdots \cup \mathrm{g}_j^M$

g_j^m=m$^{\mathrm{th}}$ set of consolidated parts for product j

ab_j=Assembly block list of product j

Y_{lm}=Binary variable for whether part l is included in g_j^m

If the number of parts is small, it may be possible to derive the optimal PC solution by calculating all PC candidates. However, as product size increases, the problem size exponentially increases and it becomes a NP-hard problem; hence, GA is used as a solution approach. Fig. 2 shows the overall procedure of part consolidation using genetic algorithm (PCGA).

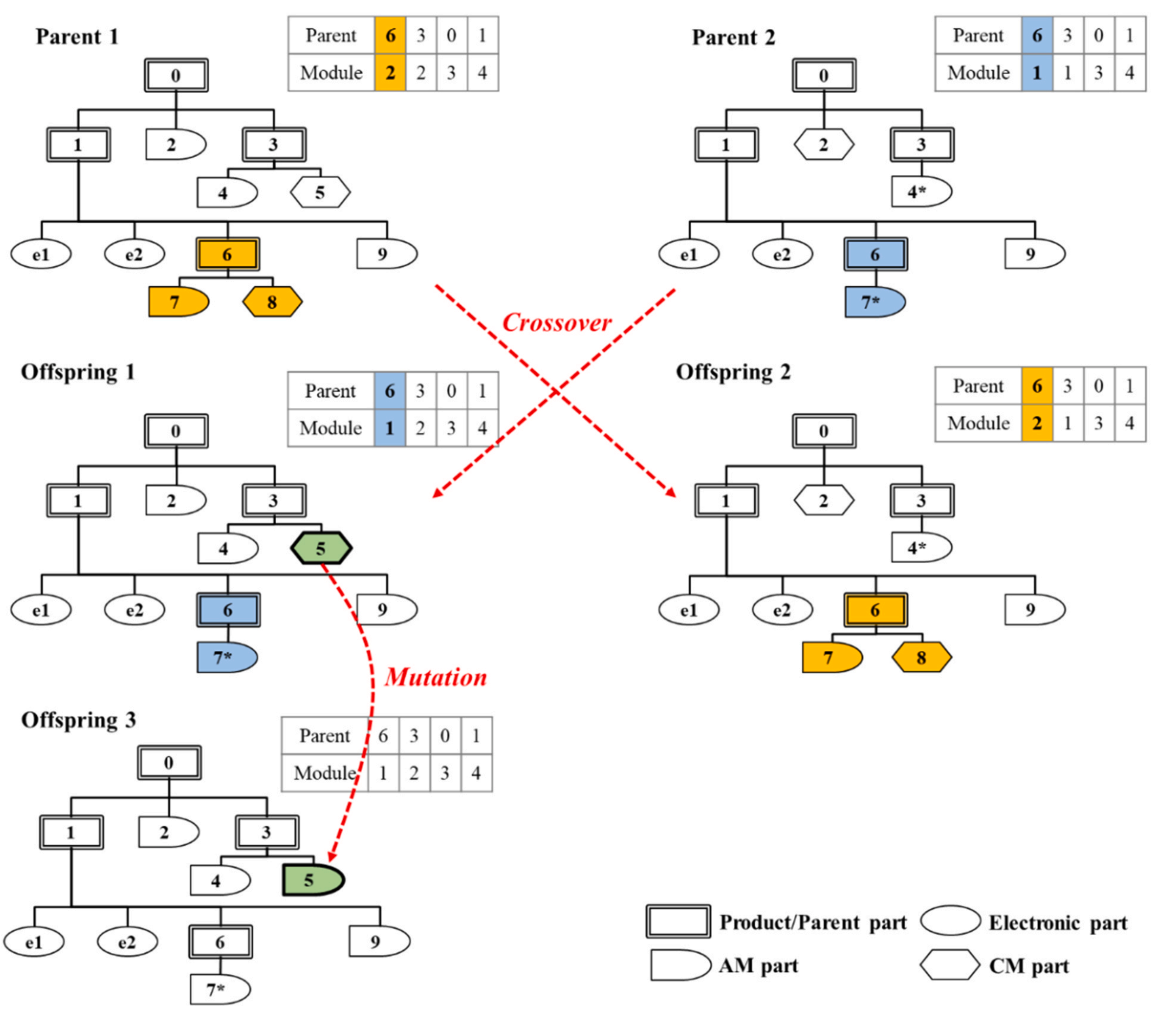


Fig. 5. Crossover and mutation operation.

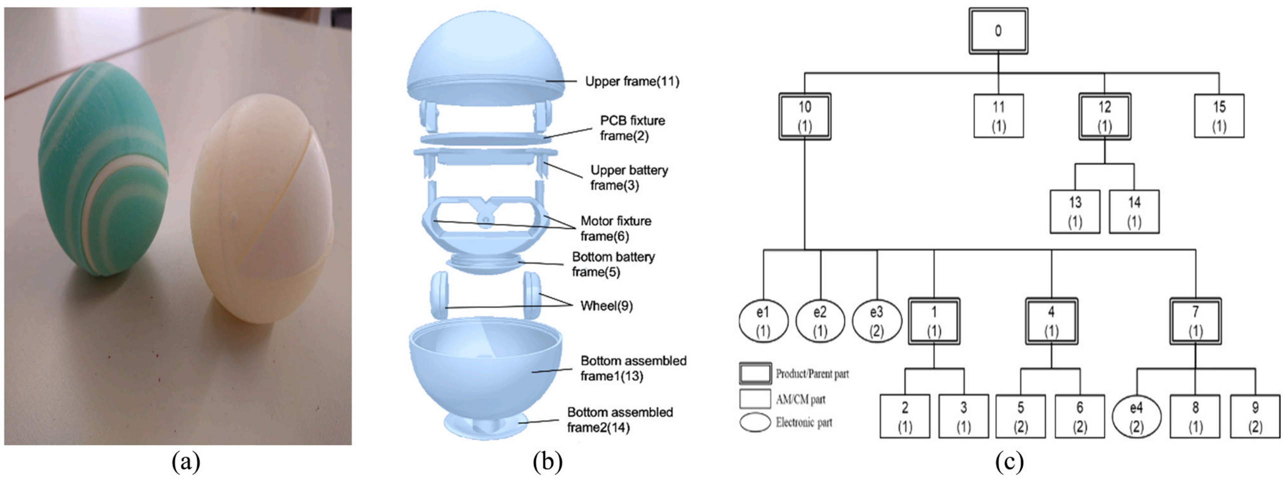


Fig. 6. Case product: (a) Shape, (b) CAD model, and (c) manufacturing Bill-of-Material.

4.2. Genetic algorithm

4.2.1. Pre-processing

Fig. 3(a) and (b) are illustrative examples of manufacturing Bill-of-Material and the BOM relationship matrix presented to clarify the GA implementation procedure. First, Fig. 3(a) is the m-BOM of the virtual product, which represents the list containing information (hierarchical structure, required quantity, etc.) necessary for the manufacturing of each part of the product. When the manufacturer solves the PC problem using GA, part information is essential, so m-BOM is presented. Next, Fig. 3(b) represents the BRM that has to be generated in advance to quantify the parent-child relationship of parts belong to m-BOM. BRM is a matrix used in PCGA to derive the information required to encode chromosomes. In the BRM, row(i) and column(j) represent a child and parent part, respectively; if part i is a child of part j, then the value(br_{ij}) is 1. The BR value for each part is calculated by multiplying the row sum and column sum of br_{ij}. For example, BR_1 is equal to 2 (row sum (1) = 1, column sum (1) = 2). If BR_i is greater than 1, it means part i consists of at least two children parts. Otherwise, the part has no children part and consists of itself. We define a set of the former parts as $S1$, and the latter parts are included in a set $S2$. In the example, $S1 = \{0, 1, 3, 6\}$ and $S2 = \{2, 4, 5, 7, 8, 9\}$.

4.2.2. Initialization

We assume that an electronic part cannot be consolidated with any other parts. For chromosome encoding, $S1$ is subdivided into two subsets, $L1$ and $L2$. $L1$ is a set of parts that has only the children parts i with $BR_i = 0$ and $L2$ includes the remainder of $S1$. For example, in Fig. 3(a), $L1 = \{3,6\}$ and $L2 = \{0,1\}$. Next, a chromosome representation is defined for PCGA. The length of the chromosome is $|S_1|$, and the first layer is a parent layer. In this layer, the parts in $L1$ are constructed first, followed by the parts in $L2$. The second layer is the module layer, where the newly consolidated part belonging to the parent part is called a module. Each part in $L1$ can have one or more modules along with the other existing children parts. The number of modules constructed for a parent part in $L1$ is determined arbitrarily. For instance, since part 3 has two child parts, a maximum of two modules can be assigned. In Fig. 4, the number of modules allocated to part 3 is 1, so child part 4 and 5 are consolidated and manufactured as a single part. For feasible consolidation, AM constraints (height limit, material availability, assembly block) are checked internally. Since the consolidation in $L1$ creates a new BOM structure, we repeat pre-processing and creates a new BOM again for remaining parent parts. Finally, in the third layer, the module configuration layer, a set of child parts for each module is described. An example of a constructed chromosome is shown in Fig. 4.

When consolidating parts, the volume is reduced through an effective redesign using the volume reduction ratio($\tau = 0.15$). Accordingly, the control variables (Table A.1) for calculating the sustainability index are allocated to each consolidated part.

4.2.3. Fitness evaluation

The individuals(chromosomes) in each generation are evaluated using the proposed sustainability model. The integrated sustainability index (ISI) is defined as a fitness function (Eq. (56)).

$$ISI_i = \sum_{j,stage} ISI_{ij,stage}(B_{ij}) = \sum_{j,stage}\left[w_{i1}\frac{C^{UC}_{ij,stage} - C^{PC}_{ij,stage}}{C^{UC}_{ij,stage}} + w_{i2}\frac{E^{UC}_{ij,stage} - E^{PC}_{ij,stage}}{E^{UC}_{ij,stage}} + w_{i3}\frac{R^{UC}_{ij,stage} - R^{PC}_{ij,stage}}{R^{UC}_{ij,stage}}\right] \quad (56)$$

B_{ij} is the PC candidate for product j of customer i; w_{in} is the weight of each sustainability (n), and total weight is 1. Sustainability, when the products are fabricated without PC in a pure CM system, is defined as a reference value. This value is used to evaluate ISI when the products are manufactured using PC candidates. It is normalized to integrate different scales of each sustainability indices, and evaluates the total ISI. For each sustainability index (CSI, ESI, and RSI), a smaller value indicates a more favorable result. Meanwhile, ISI is formulated to have a positive relationship with the difference between the three indices (PC) and their

Table 4
Part information.

Part	PCB fixture frame	Upper battery frame	Bottom battery frame	Motor fixture frame	Wheel shaft	Wheel	Upper frame	Bottom assembled frame (1)	Bottom assembled frame (2)	Outer cover
Volume (cm^3)	4.46	4.74	2.69	15.13	0.5	2.33	14.79	13.80	3.32	14.67
Height (cm)	0.16	1.28	0.80	3.28	0.3	0.7	3.6	3.3	1.1	3.37
Available material	Plastic	Plastic	Plastic	Plastic	Plastic, Metal	Plastic	Plastic, Metal	Plastic, Metal	Plastic, Metal	Plastic, Silicon

Table 5
Basic PCGA parameters.

Parameter	Value
Population size	30
Maximum number of generations	200
Crossover probability	0.85
Mutation probability	0.15

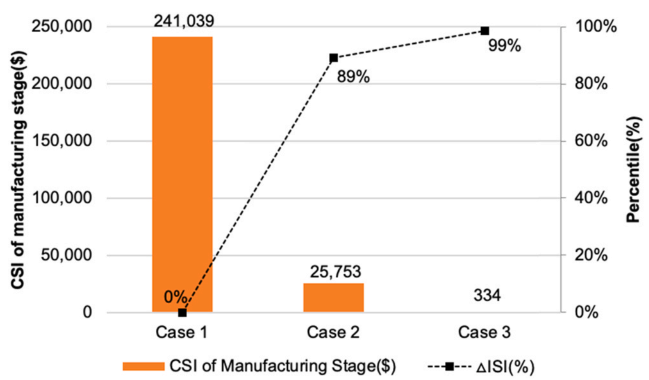


Fig. 7. Changes in Cost Sustainability Index of manufacturing stage and Integrated Sustainability Index growth rate (%).

reference values (UC). For example, as the value of a sustainability index is improved (decreases), the difference with the index's reference value increases so that the value of ISI is increased too.

4.2.4. Selection operation

In the selection operation, elitism is first used for preserving two individuals with the best fitness value for the generation. The tournament selection is then conducted. Two individuals are randomly selected, if the random number generated is less than the selection pressure, then the individual with a larger ISI is a parent; otherwise, the other individual is the parent. This process is repeated twice to select the parent pair for crossover. Selected parents have at least one different module number in their chromosome.

4.2.5. Crossover and mutation operation

The crossover and mutation operations are shown in Fig. 5. First, a single-point crossover is employed to randomly select and exchange one of the genes with different module number. The module number of a parent part represents the number of bundles of each parent part in the PC candidate. In exchanging the module number, module configuration of the parent part and other parameters are also exchanged or reassigned to maintain the feasibility of the chromosomes. In particular, parent parts should always be able to consider PC regardless of other parts. Therefore, crossover operation should be performed for parent parts in *L1* that can be consolidated freely. Since parent parts in *L2* are affected by the PC results of *L1* parts, the recalculation process is carried out to maintain the feasibility after crossover. Next, in the mutation operation, an individual exceeding the mutation probability changes the randomly selected CM part ($z_l^{CM} = 1$) to AM part ($z_l^{AM} = 1$). Other parameters are recalculated to complete the mutation where the module number does not change. However, the manufacturing method is changed to AM by randomly selecting the part manufactured by CM among the parts belonging to *S2*. By doing so, it diversifies the solution space and increases the number of AM parts.

Finally, the fitness value of individuals in the generation is evaluated, and the termination conditions are checked. The PCGA terminates when the number of iterations is at max or a same result is obtained for a given number of generations.

5. Case-based experimental analysis

This section addresses the case-based experiments focusing on the impacts of PC and AM hubs on the sustainability of CLSCAM. In the experimental analysis, a single product and a single customer is considered with a demand of 50 units for small production environment. Later, the demand is increased to have a mass production environment. For the sensitivity analysis, several key parameters are changed in order to observe their influences on the ISI. In addition, to simplify the experimental analysis, the weights for each sustainability index are equally set to 0.33. Although there are differences in units and scales of the three different sustainability indices, this problem is processed by normalizing each sustainability index (Eq. (56)) to its reference value. Lastly, the proposed sustainability evaluation model and the PCGA m45odel were developed using python[36]. To obtain the best solution, PCGA was executed on a desktop with Intel Core i3 with 3.4 GHz processor and 8.0 GB of RAM.

5.1. Case description

We select a pet toy as a testbed product for the experimental analysis (Fig. 6). This ball-shaped product is activated by a direct-current (DC) motor and moves automatically with an LED light to attract a pet's attention. Consumers can customize some part designs of the product, and the part sizes are small enough to be produced by AM machines. The pet toy consists of 15 mechanical parts and 4 electronic parts, such as Bluetooth antenna and battery, and the company manufactures only 10 of the non-electronic parts. The basic part information—including volume, height, and raw materials—is given in Table 4, and key parameters for the sustainability model are presented in Appendix B. The other parameters (emission coefficient, electricity price, wage, etc.) are referenced in the existing studies [34,35,37–41].

5.2. Results

5.2.1. Small production

To verify the effects of PC and AM hub on sustainability, the basic scenario is designed as a control condition (case 1), and the PC option and AM hub are available in case 2 and 3, respectively. To obtain a PC

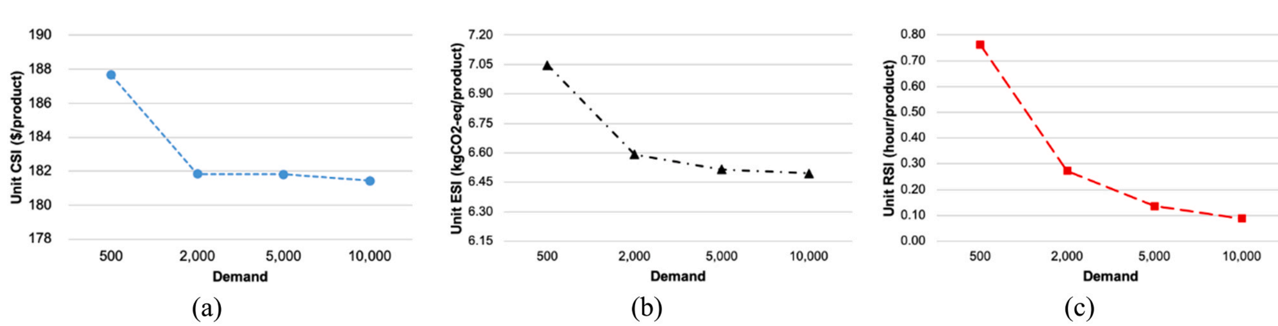


Fig. 8. Changes of sustainability index in mass production environment (per unit product): (a) CSI (b) ESI, and (c) RSI.

Table 6
Sustainability indices of mass production cases compared to small production.

Demand	ISI	Lifecycle stage					
		Design	Pre-manufacturing	Manufacturing	Logistics	Service	EOL
500	−0.783	0.780	0.546	−1.940	−1.079	0.338	0.573
2000	1.260	0.780	0.519	−0.414	−0.537	0.338	0.573
5000	2.019	0.780	0.515	0.039	−0.226	0.338	0.573
10,000	2.279	0.780	0.513	0.194	−0.120	0.338	0.573

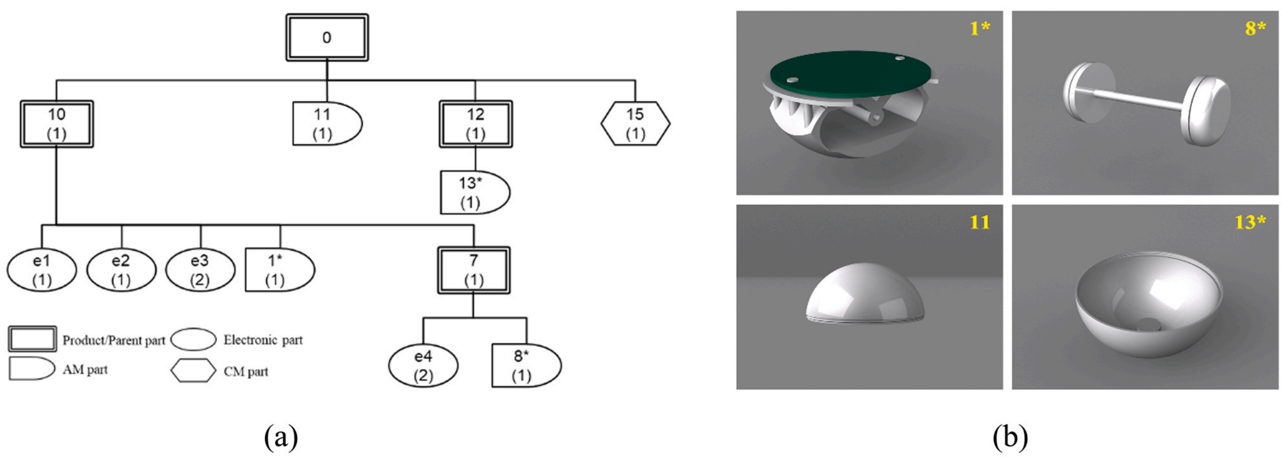


Fig. 9. Result of part consolidation: (a) manufacturing Bill-of-Material and (b) CAD model of the part-consolidated product.

Table 7
Effects of buy-to-fly ratio on lifecycle sustainability of PC case.

Sustainability index	Pre-manufacturing				Manufacturing			
	btf ratio = 1.5	2	2.5	3	btf ratio = 1.5	2	2.5	3
CSI	0.617	0.745	0.872	1.000	0.659	0.782	0.885	1.000
ESI	0.795	0.864	0.932	1.000	0.656	0.770	0.885	1.000
RSI	0.795	0.863	0.932	1.000	0.999	1.032	1.052	1.000

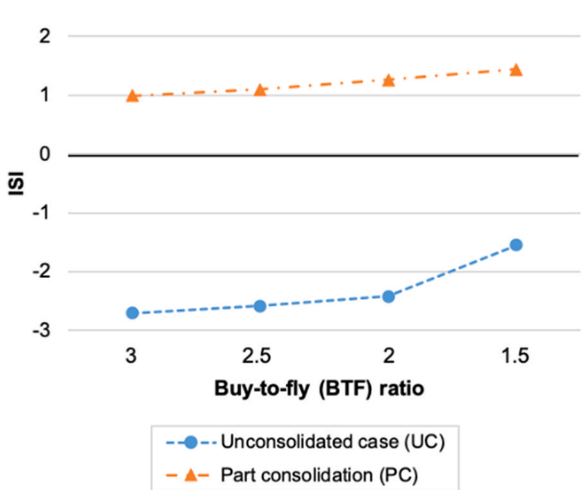


Fig. 10. Effects of changes in btf ratio by Integrated Sustainability Index (UC) and Integrated Sustainability Index (PC) cases.

solution in case 2 and 3, the parameters for the PCGA are set as shown in Table 5. The results are compared in terms of CSI, ESI, and RSI.

Among the three indicators of sustainability, the most significant improvement by PC and AM hub is found in CSI. The CSI of case 2 ($49,759.84) is reduced to about a fifth of the CSI of case 1 ($267,260.2). While an AM machine is purchased to produce two parts in case 2, the supply chain plan for case 3 includes leasing an AM machine from the second AM hub, which reduces the CSI to $21,199.68. In addition to the overall cost reduction, the cost of the manufacturing stage has been significantly reduced. In case 1, the manufacturing costs account for 90.2% of the total cost, but the ratio decreases to 51.76% (case 2) and 1.57% (case 3).

In terms of ESI, the CO_2 emission has decreased from 1577.51 kg (case 1) to 1163.08 kg (case 2) and 894.12 kg (case 3) due to PC and AM hubs. Meanwhile, RSI was also improved, but the change was small. The RSI of case 1 is 231.97 h, and the value is reduced to 206.85 h in case 2 and 192.83 h in case 3. In case 1, 56% of the total RSI is related to the manufacturing stage. However, in case 2, the ranking is changed as the design stage is the first rank (87.44%) followed by manufacturing (7.50%) and logistics (3.45%). The design stage also ranks first in case 3, with a slightly lower proportion (68.37%).

Fig. 7 shows the CSIs ($) of the manufacturing stage and increasing rates of ISI (%) of three cases. For small production, the ISI is significantly improved when parts are consolidated by PCGA.

5.2.2. Mass production

Based on case 3, we increase demand to 500, 2000, 5000, and 10,000 as if the production environment changes to mass production. As the demand increases, all the sustainability indices per unit product are improved (Fig. 8). In terms of CSIs, the manufacturing cost is reduced due to the lease of AM machines from the AM hub. However, the

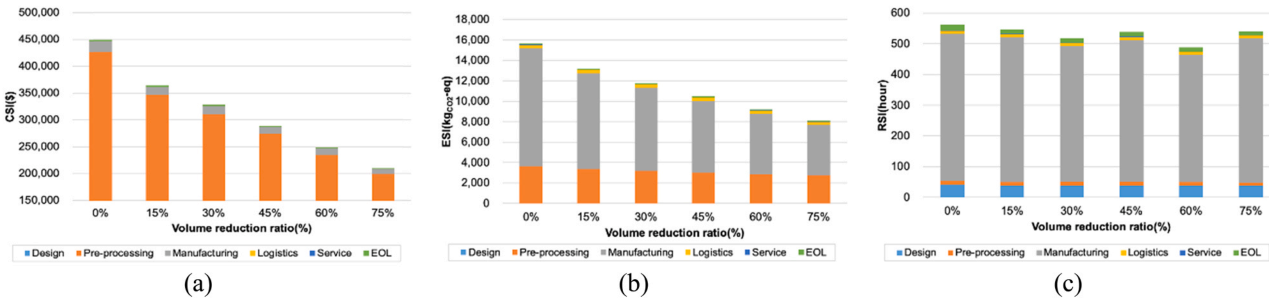


Fig. 11. Changes in sustainability index (a) CSI, (b) ESI, and (c) RSI with increases in volume reduction ratio.

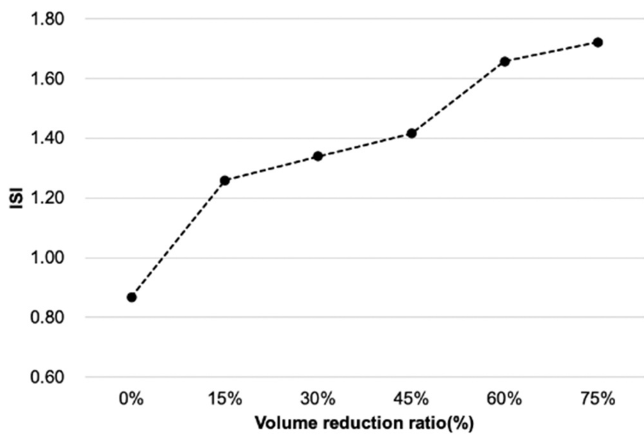


Fig. 12. Changes in Integrated Sustainability Index with increases in volume reduction ratio.

reduction is partially offset by the increment of pre-manufacturing costs since the price of the materials for AM machines is considerably high. The ESI of the manufacturing stage accounts for the largest portion due to high energy consumption of AM machines.

The ISIs of the four demand cases are presented in Table 6. It indicates that the sustainability index of manufacturing stage is improved as the demand increases. For manufacturing stage, the ISI continues to increase, resulting in a steady increase in the total ISI. While most of the indices have positive values, the sustainability index of logistics is negative because using the AM hub increases the travel distance. It implies that the manufacturer would achieve a better performance if it puts additional efforts to improve the sustainability of the logistics stage. Although the impacts on each stage are different, the PCGA results in the same PC solution (Fig. 9). Therefore, the sustainability indices of the design stage are constant.

5.3. *Sensitivity analysis*

5.3.1. *Effect of raw material consumption efficiency (buy-to-fly ratio) of AM*

The analysis of the mass production scenario confirms that the price of AM raw materials is the main factor that affects the CSI. In this section, the impact of the efficiency of AM raw material consumption, called buy-to-fly (btf) ratio, on sustainability is analyzed. The btf ratio represents the mass of raw material required for a unit mass of the finished component, represents the efficiency of AM, a lower value indicates a higher efficiency. Previous studies present that the btf ratio has a value between 1 and 3 [28]; therefore, we have adjusted the btf ratio from 1.5 to 3, and fixed the product demand at 2000.

Table 7 presents the impacts of changing btf ratio on the sustainability indices of pre-manufacturing and manufacturing stages. Note that each index is normalized by the worst btf ratio (i.e., 3). The results

Table A.1
Control variable for sustainability evaluation model.

z_l^y	If part l is manufactured using y, $z_l^y = 1$, o/w 0	C_x	Cost sustainability of stage x
hv_{lh}	If part l is manufactured in h, $hv_{lh} = 1$, o/w 0	E_x	Environmental sustainability of stage x
ah_{lo}	If part l is manufactured by o, $ah_{lo} = 1$, o/w 0	R_x	Responsiveness sustainability of stage x

Table A.2
Expression for sustainability evaluation model.

na_{ij}	Number of disassembly jobs for unit product	$\sum_k \left(\left(\sum_{c \in L_{jk}} \beta_{jc}^k \right) - \left(\sum_{c \in L_{j,k-1}} v_c \right) \right), \forall i,j$
NA_{ij}	Total number of assembly jobs	$d_{ij} \lceil \sum_k \left(\frac{\left(\sum_{c \in L_{jk}} \beta_{jc}^k \right) - \left(\sum_{c \in L_{j,k-1}} v_c \right)}{(\alpha_{assy})^k} \right) \rceil, \forall i,j$
NT_{tl}	Number of dedicated tool tl purchased	$\left\lceil \frac{1}{\mathrm{ld}_{tl} \alpha_{pm}} \sum_k \left[\sum_{l \in L_{jk}} \frac{(1 - v_l)}{(\alpha_{assy})^k} \left(\mathrm{pd}_{jl}^k z_l^{CM} tv_{l,tl} \right) \right] \right\rceil, \forall i, j, tl$
NT_{assy}	Number of assembly tool set purchased	$\left\lceil \frac{NA_{ij}}{ld_{assy}} \right\rceil, \forall i,j$Number of rented AM machine using
$\mathrm{N}_{buy\,oh}$	Number of purchased AM machine using o	$\left\lceil \frac{m_{oh}^{AM,in}}{u \cdot WT \cdot at_i \cdot rc_o} \right\rceil, \forall i,j,o,h = 0$
$\mathrm{N}_{rent\,oh}$	Number of rented AM machine using o in hub h	$\left\lceil \frac{m_{oh}^{AM,in}}{u \cdot WT \cdot at_i \cdot rc_o} \right\rceil, \forall i,j,o,h \geq 1$

show significant improvements of CSI and ESI as the btf ratio increases. Specifically, as the btf ratio decreases from 3 to 1.5, the amount of materials required for AM is decreased by 50%, which reduces the purchasing cost of raw materials, electricity consumption cost for the pre-processing process, and AM machine rental cost.

In addition, we analyzed the impact of btf ratio on deciding whether or not to apply PCGA. In Fig. 10, the blue and orange lines represent the ISI for the unconsolidated case (UC) and the PC case using the PCGA, respectively. As a result, the ISI of UC and PC increased by 1.16 (42.8%) and 0.45 (45.4%), respectively. The PC case is more sustainable because it has a positive ISI. Moreover, as demand increases, the effect of btf ratio improvement will be greater, which can be a technical incentive for manufacturers to adopt AM in the CLSCAM.

5.3.2. *Effect of volume reduction ratio*

While we assume that PC reduces the volume of the combined part by 15%, some researchers [15,42] show that the weight can be reduced by 25–90% by consolidating parts. Instead of speculating the actual volume reductions, we changed the reduction ratio from 0% to 75% and measure the resulting sustainability indices.

As the volume reduction ratio increases, the CSI, ESI, and RSI is

Table A.3
Input amount of material(kg) in each process for sustainability evaluation model.

Process	Additive Manufacturing ($M_z^{AM,in}$)	Conventional Manufacturing($M_z^{CM,in}$)
rm	$\mathrm{M}_{rm}^{AM}(=\mathrm{M}_{pp}^{AM,in})$	$\mathrm{M}_{rm}^{CM}(=\mathrm{M}_{pp}^{CM,in})$
pp(AM)	$\mathrm{M}_{pp}^{AM,\ in} = \sum_{h\in\{0\}\cup H} \mathrm{M}_{pp,h}^{AM,\ in} = \sum_{h\in\{0\}\cup H}\sum_{o} m_{pp,oh}^{AM,\ in}$ $m_{pp,oh}^{AM,\ in} = \frac{1}{\alpha_A\alpha_{pp}\alpha_{post}}\sum_k\left[\sum_{l\in L_{jk}}\frac{(1-\nu_l)(1-\lambda\theta \mathrm{rec}^{AM}\alpha_A\alpha_{post}(\alpha_{assy})^k)}{(\alpha_{assy})^k}(\mathrm{pd}_{jl}^k z_l^{AM} mp_l^{AM} h\nu_{lh} ah_{lo})\right]$	
pp(CM)		$\mathrm{M}_{pp}^{CM,in} = \frac{1}{\alpha_{pp}\alpha_{pm}}\sum_k\left[\sum_{l\in L_{jk}}\frac{(1-\nu_l)(1-\lambda\theta \mathrm{rec}^{CM}\alpha_{pm}(\alpha_{assy})^k)}{(\alpha_{assy})^k}(\mathrm{pd}_{jl}^k z_l^{CM} mp_l^{CM})\right]$
A	$\mathrm{M}_{A}^{AM,\ in} = \sum_{h\in\{0\}\cup H} \mathrm{M}_{A,h}^{AM,in} = \sum_{h\in\{0\}\cup H}\sum_{o} m_{A,oh}^{AM,\ in}$ $\mathrm{M}_{A,h}^{AM,in} = \alpha_{pp}\mathrm{M}_{pp,h}^{AM,in} + \mathrm{rec}^{AM}\mathrm{M}_{rec,h}^{AM,in}$ $m_{A,oh}^{AM,in} = \frac{1}{\alpha_A\alpha_{post}}\sum_k\left[\sum_{l\in L_{jk}}\frac{(1-\nu_l)}{(\alpha_{assy})^k}(\mathrm{pd}_{jl}^k z_l^{AM} mp_l^{AM} h\nu_{lh} ah_{lo})\right]$	
pm		$\mathrm{M}_{pm}^{CM,in} = \alpha_{pp}\mathrm{M}_{pp}^{CM,in} + \mathrm{rec}^{CM}\mathrm{M}_{rec}^{CM,in} = \frac{1}{\alpha_{pm}}\mathrm{M}_{assy}^{CM,in}$
post	$\mathrm{M}_{post}^{AM,in} = \alpha_A\mathrm{M}_{A}^{AM,\ in} = \frac{1}{\alpha_{post}}\mathrm{M}_{assy}^{AM,in}$	
assy	$\mathrm{M}_{assy}^{AM,in} = \sum_k\left[\sum_{l\in L_{jk}}\frac{(1-\nu_l)}{(\alpha_{assy})^k}(\mathrm{pd}_{jl}^k z_l^{AM} mp_l^{AM})\right]$	$\mathrm{M}_{assy}^{CM,in} = \sum_k\left[\sum_{l\in L_{jk}}\frac{(1-\nu_l)}{(\alpha_{assy})^k}(\mathrm{pd}_{jl}^k z_l^{CM} mp_l^{CM})\right]$
cd	$\mathrm{M}_{cd}^{in} = \theta TW_i$	
rec	$\mathrm{M}_{rec}^{AM,in} = \sum_{h\in\{0\}\cup H}\mathrm{M}_{rec,h}^{AM,in}$ $\mathrm{M}_{rec,h}^{AM,in} = \lambda\theta\sum_{o,k}\left[\sum_{l\in L_{jk}}(1-\nu_l)\left(\mathrm{pd}_{jl}^k z_l^{AM} mp_l^{AM} h\nu_{lh} ah_{lo}\right)\right]$	$\mathrm{M}_{rec}^{CM,in} = \lambda\theta\sum_k\left[\sum_{l\in L_{jk}}(1-\nu_l)\left(\mathrm{pd}_{jl}^k z_l^{CM} mp_l^{CM}\right)\right]$
dis	$\mathrm{M}_{dis}^{AM} = \left(1-\mathrm{rec}^{AM}\right)\mathrm{M}_{rec}^{AM,in}$	$\mathrm{M}_{dis}^{CM} = \left(1-\mathrm{rec}^{CM}\right)\mathrm{M}_{rec}^{CM,in}$
ip	$\mathrm{M}_{assy}^{E,in} = \sum_k\left[\sum_{e\in L_{jk}}\frac{(1-\nu_e)}{(\alpha_{assy})^k}\left(\mathrm{pd}_{je}^k me_e\right)\right]$, $\mathrm{M}_{pm}^{TL} = \sum_{tl\in \mathrm{TL}_j}[mt_{tl}NT_{tl}], \mathrm{M}_{assy}^{TL} = mt_{assy}NT_{assy}$	

Table B.1
AM hub information and input data of each AM method for sustainability evaluation.

Hub	Method	AM Machine	Raw material	Energy consumption[a] (E_o, MJ/kg)	Build rate[a] (ap_o, cm^3/h)	Machine Purchase[b,c] (pa_o, \$/yr)	Machine Rent[c] (ra_o, \$/day)	Power[c] (pow_o, kW)	Height limit[c] (h_cap_o, cm)
1	DMLS	EOS M290	Stainless 316 L	352.53 [37]	7.2 [38]	107,000	240	8.0	46
2	SLS	3D systems ProX SLS 6100	PA plastic	113.66 [39]	95.04 [38]	25,000	60	3.2	32.5
3	Polyjet	Staratasys Objet500 Connex3	Silicon	49.52 [38]	5.18 [38]	70,000	330	1.2	20

[a] Referenced from related literature.
[b] Depreciation cost by yearly.
[c] Obtained or calculated from Senvol database [40].

Table B.2
Input data of energy consumption of each process for sustainability evaluation.

	E_z^y(MJ/kg)	pp	pm	post	assy	cd	rec
Energy consumption	AM	19.3 [35]	–	44.84 [41]	0.0035 [34]		5.45 [41]
CM	22.8 [41]	–					

improved by 53%, 48%, and 4%, respectively (Fig. 11). Increasing the volume reduction ratio decreases the amounts of the raw materials for AM machines, and the ESI of the manufacturing stage is significantly improved. However, a fluctuation of RSI is found because RSI depends on the utilization rate of the machines. If the number of AM machines is fixed, increasing the volume reduction ratio lowers the machines' utilization rates, which results in a decline in RSI. However, if the volume reduction ratio increases enough so that the number of AM machines is decreased, the utilization rates of the machines suddenly rise, and the RSI rebounds. Nonetheless, significant improvements in the CSI and ESI offset the fluctuations in RSI, so the ISI is steadily increasing (Fig. 12). Therefore, manufacturers can improve ISI by determining an appropriate number of AM machines as well as by increasing the volume reduction ratio through effective PC design.

6. Conclusions

With the increasing demand for customized products in various industries, the AM technology has attracted considerable attention as a key technical factor. In particular, AM technology has flexibility to fabricate products of desired shapes without dedicated tools. As many manufacturing companies are considering the adoption of AM, this study proposes a new closed-loop supply chain model with AM hubs to lower the barriers to incorporate AM. A sustainability evaluation model and PC model are developed to maximize the sustainability of the supply chain. Since the PC problem with complex m-BOM is an NP-hard problem, a solution is found using a genetic algorithm. In the case-based experimental analysis, the proposed model is verified using a testbed product, and the effects of the key factors on sustainability are analyzed.

From the experimental analysis, all sustainability indices are improved when PC options and AM hubs are available. Also, most of the sustainability indices per testbed product (cost, environment, and time) improve when demand increases. The results of the experimental analysis could be helpful to the decision-makers, particularly those contemplating the adoption of AM to meet customization demand. The results also indicate that when utilizing AM hubs, manufacturers should focus on improving pre-manufacturing stage cost since the costs of AM raw materials are relatively high.

According to sensitivity analysis, the impact of PC on sustainability increases when the efficiency of raw material consumption (buy-to-fly ratio) improves. This indicates that a PC-based AM adoption could have a greater impact if the btf ratio further improves with a lower value according to the development of AM. The result also shows that when the volume reduction ratio of PC increases, it leads to the improved sustainability of CLSCAM. Therefore, it suggests that manufacturers should put more effort into the redesigning process in order to obtain a PC plan with a higher volume reduction ratio.

Despite the inferences presented above, this study has certain limitations that indicate future research directions. First, unlike recent studies on PC conducting experimental analyzes on various products [33,43], this study utilized only one testbed product. A multi-product and multi-customer environment is left for later work. Second, some assumptions and parameters are set arbitrarily for unavailable data. For example, the number of rentable AM machines from AM hub was set to be unlimited although the limit on the number of rentable AM machines from each AM hub would produce more practical results. Also, this study did not consider recycling or reusing scraps from the manufacturing processes in the CLSCAM framework. Paying more attention to various reverse flows could lead to deriving other valuable insights. In addition, the sustainability evaluation model has to be extended to reflect more realistic circumstances, such as the interdependent relationships between design parameters, AM part quality, and energy consumption [44,45]. Also, depending on how manufacturers set weights of each sustainability indices, different PC solutions can be derived even for the same product. Studies that deriving the optimal level of PC are needed in the future. Finally, we did not consider the fact that AM machines can be used not only for customized products but also for dedicated tools of standard products. Expanded scope of utilizing AM may result in a different insight on the research area of CLSCAM with PC.

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Author contributions

Dongmin Son designed the study, conducted the whole experiment analyzes, wrote the manuscript and participated in all phases. Songi Kim specially participated in reviewing the existing studies and the design of sustainability evaluation model. Bongju Jeong conceived the theme of this study, guided the whole research process, and responded to the reviewers. All authors have read and approved the final manuscript.

CRediT authorship contribution statement

Dongmin Son: Conceptualization, Investigation, Methodology, Software, Validation, Data curation, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **Songi Kim:** Investigation, Writing - original draft preparation, Writing - review & editing, Visualization. **Bongju Jeong:** Supervision, Writing - original draft, Writing - review & editing, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

(See Tables A.1–A.3).

Appendix B

(See Tables B.1 and B.2).

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