

# Additive manufacturing-enabled part count reduction: a lifecycle perspective

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## Abstract

*Part count reduction (PCR) is one of the typical motivations for using additive manufacturing (AM) processes. However, the implications and trade-offs of employing AM for PCR are not well understood. The deficits are mainly reflected in two aspects: 1) lifecycle-effect analysis of PCR is rare and scattered; 2) current PCR rules lack full consideration of AM capabilities and constraints. To fill these gaps, this paper first summarizes the main effect of general PCR (G-PCR) on lifecycle activities to make designers aware of potential benefits and risks, and discusses in a point-to-point fashion the new opportunities and challenges presented by AM-enabled PCR (AM-PCR). Second, a new set of design rules and principles are proposed to support potential candidate detection for AM-PCR. Third, a dual-level screening and refinement design framework is presented aiming at finding the optimal combination of AM-PCR candidates. In this framework, the first level down-samples combinatory space based on the proposed new rules while the second one exhausts and refines each feasible solution via design optimization. A case study of a motorcycle steering assembly is considered to demonstrate the effectiveness of the proposed design rules and framework. In the end, possible challenges and limitations of the presented design framework are discussed.*

**Keywords:** *part count reduction, additive manufacturing, design for additive manufacturing, part consolidation*

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## 1. Introduction

Part count reduction (PCR) has been widely studied under different names such as product simplification, part consolidation, and multifunctional design. PCR is one design philosophy favoring a reduction in part count. Through PCR, it helps to simplify product structure, promote modularity, eliminate fasteners, joints, and connectors, and reduce assembly difficulties and cost [1]. Due to these tremendous benefits, PCR has been exercised in various product design methodologies including Design for Manufacture and Assembly (DfMA) [1], Design for Assembly (DfA) [2], Design for Disassembly (DfD) [3], Theory of Inventive Problem Solving (TRIZ) [4], and Axiomatic Design (AD) [5]. In this paper, all the conventional practices of PCR are defined as general PCR (G-PCR). However, there is no consistent and sound decision-making support tools for G-PCR when trade-offs need to be made (e.g. possible gain in higher performance and increased manufacturing difficulty). As Frey et al. [6] pointed out, even though there is a broad trend towards (G-)PCR applications, not every step of reduction in part count is done in its right direction. Without complete understanding of lifecycle constraints (e.g. manufacturability and serviceability), technical maturity, and reliability, PCR will oppositely cause an increase in product cost. Existing rules to support G-PCR design are scattered and sometimes contradictory to each other. For example in TRIZ [7], the principle of “joining” suggests “joining homogenous objects or those destined for continuous operation”, while the principle of “fragmentation” recommends “dividing the object into independent parts”.

As additive manufacturing (AM) becomes one possible manufacturing method, PCR has been widely practiced in both academia [8, 9] and industry [9-12]. Design freedoms of material, geometry, and topology have extremely expanded and conventional manufacturing constraints (e.g. material difference and tooling accessibility) have largely been removed [13, 14]. These applications are defined as AM-enabled PCR (AM-PCR) in this paper. However, most research either serves as proof of concept or focuses on the refinement of post-consolidation design with AM-enabled freedoms (e.g. lattice) and AM

constraints (e.g. support structure). Rare attention has been drawn to justify the necessities of AM-PCR. In other words, what kind of components can be considered as AM-PCR candidates?

This paper intends to shed light on three questions: 1) what rules or considerations have been employed in G-PCR applications? 2) How do AM opportunities and constraints reshape G-PCR rules? And 3) what new rules should be followed in AM-PCR applications. The paper is structured as follows. First, considerations including constraints and objectives of G-PCR are investigated from a lifecycle perspective in Section 2.1. This overview provides a complete picture of how PCR decision which is made in the conceptual design stage affects other downstream lifecycle phases, such as functional design and manufacturability. Conventional rules of G-PCR are summarized afterwards. Second, the definition, scope, and current status of AM-PCR research are elaborated to understand the critical unsolved issues related to AM-PCR in Section 2.2. To address the issue of lacking a support tool for AM-PCR candidate detection, a point-to-point comparison between G-PCR rules and AM-PCR opportunities are conducted. The comparative study strongly indicates the need of a new set of design rules by which the design freedoms of AM can be maximally applied (Section 2.3). To meet this goal, a new set of rules and principles for AM-PCR design is proposed in Section 3. After that, the new ruleset is integrated into a dual-level screening and refinement design framework with the aim of finding the optimal design solution by the criterion of the minimum cost-to-performance ratio in Section 4. Main techniques and challenges are discussed in Sections 4.2 and 4.3 respectively. A case study of a motorcycle steering assembly is given to demonstrate how to apply the new ruleset and the dual-level design framework (see Section 5). In the end, this paper is wrapped up with conclusions and future research.

## 2. Literature review

Because AM-PCR is a new topic, a comprehensive study of the considerations and constraints of G-PCR research is necessary. In this section, reported studies related to G-PCR are first reviewed in Section 2.1.

The definition, scope, and state-of-art of AM-PCR research is elaborated afterwards. The efficacy of conventional rules of G-PCR in the context of AM-PCR is analyzed in Section 2.3.

## 2.1 G-PCR: constraints, objectives, and rules

### 2.1.1 Lifecycle constraints

In this section, the impacts of PCR decision on downstream lifecycle phases are analyzed. The affected phases in turn impose constraints on the number or choice of components to be consolidated. In general, affected lifecycle phases include functional design, manufacturing, assembly, service, and end of life (EoL).

#### (1) **Functional design**

Functional design is the design process to synthesize function carriers from functions. Ideal design should satisfy one-to-one mapping from function to its physical entities/function carriers as suggested by the independence axiom of AD [5]. However, PCR may easily result in coupled design where one function-carrier fulfills more than one function. For example, engines in old cars fulfill a function of providing power and a function of providing heat source for passengers in winters. However, this coupling will make conjugate failure of another function if one malfunctions. Another issue of a coupled design is the increased difficulty of finding the optimal design because more design iterations are needed. This prolonged development time will lead to an increase of cost and even loss of market share [15]. Closely-related literatures about the influence of G-PCR on functional design or design process are rare and they normally have no consideration of other lifecycle constraints. Frey et al. [6] examined whether PCR agreed with principles of TRIZ, AD, and Highly Optimized Tolerance (HOT) [16] respectively from a system point of view. In their results, the number of conflict resolution principles which favor increasing part count outnumbers the counterparts in TRIZ. But the fundamental rule of “law of ideality” suggests to do PCR if reduced part count can achieve better performance or suppress side effect or cost. In the theory of HOT, an increase of part count especially the number of unique parts escalates system robustness.

Similar phenomenon was observed by Mann [17]; However, the increase of part count comes from newly added functions. In brief, PCR is still favored from design point of view. By default, the function structure of the given system remains unchanged after PCR.

## **(2) Manufacture and assembly**

Manufacturability and assemblability issues are the most frequently investigated topics in G-PCR [1, 2]. PCR increases geometric complexity which in turn results in a rise of manufacturing difficulties and cost for most conventional manufacturing (CM) methods. Therefore, the total number of parts to be consolidated highly depends on the capabilities of manufacturing technologies. Composite material fabrication [18] and injection molding [19] played a vital role to stimulate PCR design in the past. To support consolidated design, Boothroyd et al. [1] proposed three widely-applied heuristic rules:

- (a) Does the part move with respect to all the parts already assembled?
- (b) Must the part be made of a different material or be isolated from all other parts already assembled?
- (c) Must the part be separate from all other parts already assembled because necessary assembly or disassembly would otherwise be impossible?

If the answer to any of these three questions is positive, the selected components are advised to be separate. However, these three heuristic rules have some drawbacks, such as inefficiency of conflict handling [6], no consideration of specific manufacturing processes, and exceptionalism exclusiveness (e.g. elastic deformation V.S. relative motion). The deficits of these design rules will be detailed in Section 2.1.3.

## **(3) Service and EoL**

Consolidated design may avoid leakage and contact fatigue, thereby reducing maintenance frequency and difficulty [6]. Meanwhile, reduced weight and better impermeability can increase fuel efficiency for transportation systems (e.g. aircrafts) [20]. However, consolidated design does not necessarily lead to elimination of maintenance issues; thus, disassembly for inspection and replacement is still essential for some cases. If there are dramatic differences in maintenance frequency, downtime, or skill requirements

[21] between a couple of components, assembly design is still favored. Disassembly need is also required for certain product retirement treatment (e.g. reuse and remanufacture) in EoL [22]. Due to the conjugate failure, the chance of being reused or remanufactured is jeopardised for a consolidated design in contrast with an assembly design where subcomponents can be replaced. In brief, similarity of components in terms of life expectancy and material recyclability also puts a string on the freedom of G-PCR.

### 2.1.2 Global objectives

Different from the studies which focus on feasibility of PCR because of functional requirements or manufacturing issues, some other researches related to G-PCR are trying to understand the relations between PCR and objectives of performance [1, 6], cost [23-26], or sustainability [27, 28]. Lucchetta et al. [23] advocated “minimum part count criterion” by combining DfMA and TRIZ to find alternative solutions to reduce part count. Nevertheless, the authors failed to provide more details on how to use TRIZ to find the solution with the minimum part count. Johnson and Kirchain [24] compare the costs of product development, fabrication, and assembly between an assembly design and its consolidated counterpart. Their results indicated a decrease of monetary cost in the consolidated design. Toward one step further, Fagade and Kazmer [25] built a general profit model and a cost model of tooling, lead time, material, and processing with respect to change of part count for injection molded parts. Their study revealed that further consolidation was favored if consolidation does not lead to a significant increase of design complexity. Fukushige et al. [26] tried to minimize the mass of connecting materials between separate “primary bodies” (i.e. functional entity) by optimizing the total 2D link distance. Their approach offers a new perspective towards component grouping (in essence, PCR is a type of component grouping as well). However, there are two deficits to be overcome. First, a shorter overall link distance between components cannot necessarily guarantee the reduction in the total material consumption because physical embodiment (e.g. diameters) of all links are heterogeneous. Second, feasibility and economic considerations of clustering are not investigated. Sustainability aspects of PCR are rarely quantitatively investigated although some research indicated that PCR helps to reduce the material consumption because

of elimination of fasteners and assembly interfaces. However, this statement may not stand when EoL treatment is also considered. Suresh et al. [27] presented a sequential design framework to integrate design for environment (DfE) and DfMA. Their comparative study of material change from cast steel alloy to aluminum showed promise of being more environment-friendly. Chowdary and Harris [28] incorporated quality function deployment (QFD), DfMA, and DfE into their proposed design flow. The consolidated design enjoyed reduction of mass, total cost, assembly time, and environmental impact.

### 2.1.3 Conventional design rules

Conventional rules of justifying the PCR feasibility or potentiality of a couple of components (noted as G-PCR rules for simplicity) were developed between the late 1980s and early 2000s [1, 4, 5, 23-25]. These rules are scattered in different design methods which are focusing on various lifecycle phases and objectives (e.g. ease of manufacture and assembly in DfMA [1] and design evaluation in AD [5]). Available G-PCR rules are summarized as follows.

- (1) **Decoupling of functions (r1)**: functions should not have overlapped physical design parameters as suggested by AD [5] and TRIZ [4]. Coupled design may have issues of increased development time and conjugate failure. Therefore, components to achieve different functions need special attention.
- (2) **No relative motion (r2)**: if there exists relative motion between components, PCR is not suggested.
- (3) **No material variance (r3)**: if components are made of different materials, separation is favored.
- (4) **No blockage of assembly access of other components (r4)**: if consolidation jeopardizes the assembly access of other components, consolidation is forbidden.
- (5) **No extra tooling (r5)**: consolidated part should not need extra tooling.
- (6) **No vast difference of quality requirements (r6)**: similar GD&T requirements simplify process routes.

- (7) **No significant increase of manufacturing cost (r7)**: consolidated part tends to be more geometrically complex, which may increase manufacturing cost.
- (8) **Trade-offs should be made between PCR and standardization & modular design (r8)**: consolidated parts are normally irregular which is against modularization and standardization.
- (9) **Increase the possibility of part re-usage and material recyclability (r9)**: similarity in terms of part lifespan and material recyclability helps to boost a more sustainable design. DfD [29] also benefits part re-usage and material recyclability.

These rules vary in constraining effects. In other words, some rules which belong to “recommended” level are defined as weak constraints while those ranked as “must follow” level are defined as hard constraints. For example, rules r2-4 are closely related to whether the consolidated design can be fabricated or not (in the context of CM); therefore, these three rules are hard constraints. Other rules including r1 and r5-9 are weak constraints. Violation of r1 may cause coupling of functions, but it will not predict a poor or failed design; in contrast, coupled design sometimes can increase system compactness or performance improvement (e.g. a case of thermos-casting mold design [30]). Besides, PCR sometimes only lead to physical integration<sup>2</sup> which is also advocated in Suh’s third corollary [5]. Violation of Rules r5-9 affects the economic or sustainable performance of the consolidated design but trade-offs are needed when consolidation leads to dramatic gains in functional performance. Although these rules are widely practiced, some criticism are also received in case of some exceptions. For example, some parts with relative motion are still manufacturable if elastic deformation is permitted [6]. These rules show two main deficits: 1) rules r1-9 work at the conceptual level without considering any specific manufacturing constraints; and 2) these rules overemphasize the feasibility and cost sides without touching the performance aspect, which leads to more conservative designs.

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<sup>2</sup> Physical integration refers to integrated components which fulfill independent functions and these components are only physically merged. One typical example is *Swiss army knife*.



## 2.2 AM-PCR: definition, scope, and status

Since AM-PCR is a new topic, the definition and scope are vague. This section will give an overview of the state-of-art of AM-PCR research with the goal of highlighting the unsolved issues.

### 2.2.1 Definition and scope

AM-PCR is defined as a design method where a product/ assembly is redesigned in terms of part count, architecture, and material subject to AM constraints and freedoms thereby reducing lifecycle cost and improving product performance. The specific goal of AM-PCR is to find the optimal combinations of components to be consolidated via optimization of the triplet (*part count, architecture, material*) by the criteria of minimum cost-to-performance ratio in AM context. Opportunistic and restrictive AM and optimization of architecture and material are well studied in the design for AM (DfAM) community [13, 14]. Detailed techniques and considerations (e.g. manufacturing constraints of AM) of shape synthesis can be found in review paper [31]. However, most of these DfAM research (e.g. lattice structure design) deal with only one part; therefore, this research alike is concluded as part-level DfAM in this paper. In contrast, AM-PCR which is also called assembly-level DfAM in other research [32-34] works in the conceptual design stage before part-level DfAM techniques can be applied. In general, the research scope of AM-PCR can be defined from a functional design point of view. As shown in Figure 1, a design process is corresponding to the mappings among function, component, and architecture & material. First, components (physical entities) and assembly interfaces are determined to achieve the desired functions. Then, each physical entity (e.g. C1) is enriched with detailed attributes which include architecture (geometry) and material information in Layer 3. From the design flow, we know that PCR in Layer 2 will determine the choices of architecture and material in Layer 3. Therefore, simultaneous considerations of part count, architecture, and material have to be taken in AM-PCR research. In a broad sense, all techniques that reduce part count belong to the scope of AM-PCR including embedding foreign components [35], multi-material AM [36], part consolidation [11], articulated mechanism printing [37, 38], etc.

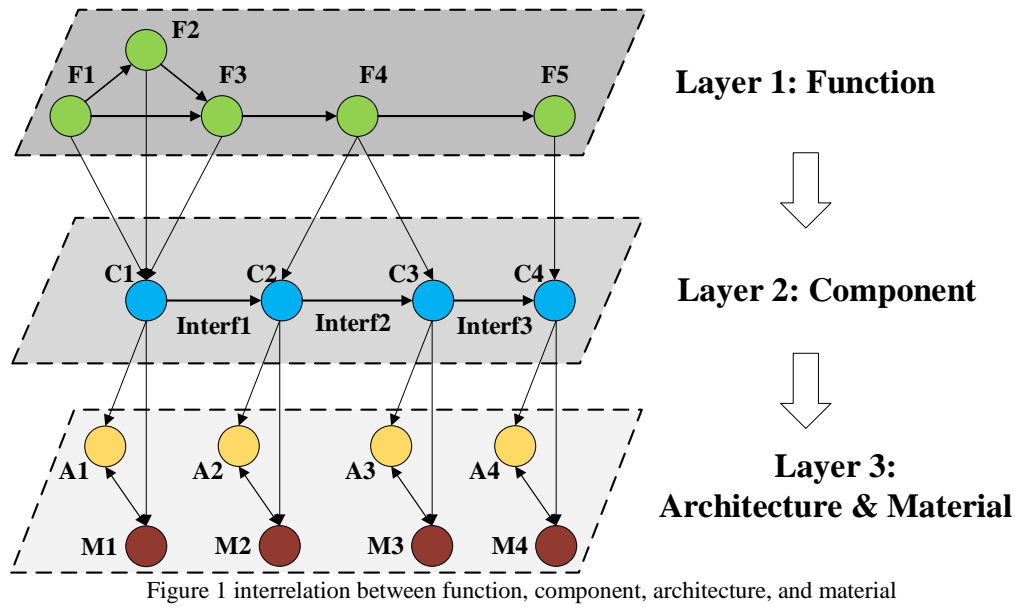


Figure 1 interrelation between function, component, architecture, and material

### 2.2.2 Current research status

Apart from research showing the capabilities and associated design considerations of a specific AM-PCR technique (e.g. embedding a foreign component), general AM-PCR research can be classified into three main topics: 1) develop criteria or methods to identify potential AM-PCR candidates (Topic 1); 2) develop strategies of how to redesign, fabricate, and test the consolidated design (Topic 2); and 3) investigate cost and sustainability performance of consolidated design (in contrast with the assembly counterpart) (Topic 3).

**Topic 1.** Current AM-PCR research either directly starts with a carefully-selected assembly which can be consolidated as one [10, 11] or still uses the three conventional rules (r2-4) to identify potential candidates [9]. A new ruleset which considers all the degrees of freedom of AM is highly demanded [33].

**Topic 2.** This topic has witnessed a rapid increase in the past 5 years [8, 9, 32-34, 39]. These papers contribute to integrating AM-PCR considerations into a general assembly-level design process (V.S. part-level DfAM). A typical design flow starts with functional analysis and design synthesis. Then AM design freedoms and constraints kick in to inspire AM-related redesign (e.g. part consolidation and structural optimization) to reduce part count and improve strength-to-weight ratio, heat dissipation, or other properties. This general design flow makes designers aware of critical steps to follow but it is insufficient

in providing more concrete design support at each step especially in PCR-related ones. In the general framework proposed by Kumke et al. [39], redesign of an existing assembly is equivalent to eliminating the assembly interfaces, which results in a very similar design. Reconceptualization with the aid of design for function (DfF) is highly demanded to avoid stereotypical design; however, only very limited research has been reported in this area [40, 41]. Schmelzle et al. [9] made an explanatory case study of a consolidated hydraulic manifold from design, print, and test perspectives, which provides a clearer insight of AM-PCR research. However, the drawn design guidelines are only suitable for stationary parts.

**Topic 3.** Both PCR and AM create opportunities for cost reduction and better sustainability. However, related studies are conducted either on PCR [27, 28] or AM [42-44] separately. Rare studies are devoted to investigating the cost or sustainability performance of AM-PCR [45, 46]. To gain an intuitive perception, Pugh Analysis is conducted for both G-PCR and AM-PCR by using functionally-equivalent assembly design as the reference. All criteria are measured with a scale of 3 and “+” indicates positive impacts. With the increased freedoms provided by AM in material design and shape complexity, more parts can be consolidated with AM-PCR regardless of increased geometry and material complexity in contrast with G-PCR. Following this lead, we can know that AM-PCR augments the beneficial sides of G-PCR in terms of “structure simplification”, “manufacturability”, “simplify assembly operation”, and “performance improvement” because of further reduced part count and “complexity for free” characteristics of AM. However, consolidation naturally leads to issues of function coupling and part reusability; therefore, AM-PCR may perform poorly against these two criteria. Besides, AM-PCR depicts different characteristics related to efficiency improvement [11], remanufacturing [47] or recycling [13]. The cons and pros of AM-PCR against G-PCR are listed in Table 1. It should be advised that the scoring intuitively reflects the trend of getting better or worse for AM-PCR but the magnitude needs more studies in the future if weighted decision making is expected for the selection of assembly design, G-PCR, or AM-PCR. In addition, quantitative study of AM-PCR in terms of its lifecycle cost and sustainability is highly needed to gain more comprehensive insights of its advantageous margins.

Table 1 Pugh Analysis of G-PCR and AM-PCR

		Criteria	Reference (assembly design)	G-PCR	AM-PCR
<b>Lifecycle phases</b>	Design	Reduce function coupling	0	-1	-3
		Structure simplification	0	+1	+3
	Manufacture	Manufacturability	0	-1	+2
		Reduce cost	0	+1	?*
	Assembly	Simplify assembly operation	0	+1	+2
	Service/ use	Improve efficiency	0	+1	+2
		Reduce maintenance effort	0	+1	+1
	EoL	Reusability	0	-1	-2
		Re-manufacturability	0	0	+1**
		Recyclability	0	0	-1***
<b>Global objectives</b>	Performance improvement		0	+1	+3
	Lifecycle cost reduction		0	+1	?
	Reduce ecology impacts		0	+1	?

\* “?” means undetermined.

\*\* Repair can be done by some AM processes such as Direct Energy Deposition [47].

\*\*\* Recyclability is hampered when multi-material AM is adopted [13].

### 2.3 Discussion of G-PCR design rules in AM-PCR context

Aiming at addressing the issues of Topic 1 discussed in Section 2.2.2, the efficacy of conventional design rules which are set for G-PCR is tested in AM context. By following a point-to-point manner, these rules are examined with progress reported in current AM-PCR as shown in Table 2.

- For r1: 1) coupling issues can be solved by decomposing coupled problems into decoupled ones using individual discipline feasibility (IDF) technique or directly applying multidisciplinary optimization (MDO) techniques; however, computational burden is the new issue. 2) Conjugated failure can be avoided by performance improvement through consolidation, but consolidation does not guarantee such an increase.
- For r2: parts with relative motion can be printed by AM, but the technique is still immature. Typical problems include poor quality and proximity of parts (i.e. clearance).
- For r3: material variance issue can be conquered by embedded components, multiple-material printing, and functional graded material, but the techniques cannot be applied to all materials.
- For r4: if all components can be printed in one shot, assembly operation is eliminated. 1) all-in-one printing means direct-print of an assembly, which depends on specific design and selected

process. Separation and quality are the top two issues. 2) all-in-one design is achieved by consolidating all parts into one. Only stationary parts are consolidated in reported literature.

- For r5: AM has eliminated tooling requirements for most building process. The remaining issue is post-processing which still needs tooling (e.g. support structure removal).
- For r6: the main reason of having customized quality requirements for different parts is to reduce manufacturing cost. Parts with various quality requirements can be fabricated by different conventional processes. However, cost of additively manufactured parts is not significantly sensitive to quality requirements. Nevertheless, some high-quality parts especially electronics are still far from production by AM.
- For r7: in conventional logic, consolidation increases architecture complexity and manufacture cost. This is no longer true for 3D printed parts. However, a lifecycle cost model is still missing.
- For r8: similar with r6, standardization and modularization can help to reduce manufacture and supply chain management cost. In contrast, AM enables more flexible production regardless of batch size and more parts can be customized and even printed on site. However, simple-geometry, highly-standardized, or massively-produced parts are still cost-competitive by using conventional machining.
- For r9: AM shows increased possibility of material saving and energy efficiency in production; therefore, ecological benefits grow. However, material toxicity, recycle of parts with functionally graded materials, and reuse of unfused raw materials are new challenges.

All the conventional rules are challenged and it seems that there is no top limit for AM-PCR anymore. In fact, such a limit still exists. Most opportunistic applications of AM still remain as proof of concept with low quality; meanwhile, these conventional rules (r1-9) specify no process-specific constraints but AM-PCR does. Detailed rules of AM-PCR are presented in Section 3.

Table 2 point-to-point comparison of opportunities and challenges of AM-PCR

Rules	AM opportunities	Remaining challenges
r1	individual discipline feasibility (IDF) [48, 49] multidisciplinary optimization (MDO) [50]	high computational burden
	improved performance: hydraulic manifold [9], Airbus duct [10], GE nozzle [11], conformal cooling device [30]	case-specific
r2	universal joints [51], classic mechanisms [37, 38], chains [10], compliant mechanism [52]	still in proof-of-concept stage, poor quality, clearance issue
r3	embedded components [35], printed circuit [53], functionally graded material (FGM) [36]	still in proof-of-concept stage, not all materials are compatible and available
r4	all-in-one printing [54]	process-specific, size limitation, separation issue
	all-in-one design [10, 11]	only stationary parts are consolidated
r5	almost no tooling is needed in printing process [10]	post-processing tools are needed
r6	adaptive slicing [55] or multi-resolution printing can achieve controlled quality	It can only vary the surface roughness along building orientation
	manufacture cost of high or low-quality part is not significantly different; therefore, higher quality standard can be followed	Some high-quality parts especially electronics are still far from production by AM
r7	manufacture cost is no longer a function of geometric complexity	Lifecycle cost model of additively manufactured part is still under development
r8	mass customization is enabled by AM regardless of batch size	Simple-geometry, highly-standardized, or massively-produced parts are cost-efficient
r9	material saving, energy-efficient process [56]	material toxicity, material recyclability of FGM and unused raw material

### 3. A new set of design rules

Comprehensive review has signified the urgent need of a new set of design rules to support AM-PCR. However, advantages in lifecycle cost and sustainability potential of AM-PCR over conventional assembly or G-PCR have not been well examined or understood. In this paper, only rules closely related to feasibility and quality aspects of AM-PCR are drawn. This new ruleset will aid designers to efficiently narrow down the potential combinations of AM-PCR candidates, thereby speeding up the decision process in the early conceptual design stage. In general, these rules should help designers be aware of the new design potentials as well as possible constraints imposed by AM. According to the comparison between conventional rules and AM-enabled opportunities in Section 2.3, all the listed conventional rules seem invalid and all components in an assembly can be fabricated as one part. This illusion ignores two important premises: 1) consolidation may lead to issues of low printing quality and cost-efficiency although technically feasible; and 2) AM processes still have their manufacturing constraints (e.g. working volume and available materials). It should be advised that this beta version ruleset is not exclusive while it can effectively eliminate infeasible combinations. Continuous support from the broader

design and AM communities are necessary to keep it updated with respect to the advancement of AM technologies.

To simplify the expression, an unevaluated, infeasible, or feasible pair of components are marked as  $(C_i?C_j)$ ,  $(C_i;C_j)$ , or  $(C_i, C_j)$  respectively. A concept of “conflict code” is introduced to document the specific conflict when a certain rule in the ruleset is violated by  $(C_i;C_j)$ . The new ruleset is presented as follows.  $\forall$  Component pair  $(C_i?C_j)$ , if and only if the following rules are all met, AM-PCR happens; otherwise, separation  $(C_i;C_j)$  takes effect.

- (1) **Relative motion (R1)**: there should exist no relative motion within  $(C_i?C_j)$ . If false, a conflict code “CF\_RelativeM” is associated with the pair  $(C_i?C_j)$ . The action of association is defined as “return” in the following text.
- (2) **Material variance (R2)**: there should be no material difference within  $(C_i?C_j)$ . If false, return a conflict code “CF\_MaterialV”;
- (3) **Assembly access (R3)**: consolidation of  $(C_i?C_j)$  should not block the assembly access of any other internal components  $(C_k)$ . If access is blocked, return a conflict code “CF\_AssemblyX” and  $(C_i;C_j) \& (C_k)$ ;
- (4) **High-quality electronic/standard device (R4)**: neither  $C_i$  nor  $C_j$  should be a low-cost standardized component (e.g. a round pipe) or a high-quality electronic/standard device (e.g. precision ball bearing). If false, return a conflict code “CF\_StandardD” and  $(C_i;C_j) \& (C_j;C_i)$ ;
- (5) **Size limitation (R5)**: size limitation is defined by a triplet (Length, Width, Height) which normally is the volumetric working space of printers. If any of this meta element is not met, return a conflict code “CF\_SizeLimit” and corresponding component groups. This rule is applicable to both a single component and properly assembled component groups.

- (6) **Material availability (R6)**: not all the engineering materials are currently available for AM processes. If the material of the component is not available, return a conflict code “CF\_Material0” and corresponding node  $C_i$ ;
- (7) **Maintenance frequency difference (R7)**: there should be no significant maintenance frequency difference within  $(C_i, C_j)$ . If the maintenance frequency differs drastically, return a conflict code “CF\_MaintenanceDiff” and  $(C_i, C_j)$ .

All new rules and conflict codes are classified in Table 3. Although FGM, articulated mechanism, embedded sensors, etc. have been proved feasible, they are either case-specific or still at the proof-of-concept stage. Therefore, R1 and R2 remain effective. Rules R4-6 are special to AM processes. Currently, AM still have issues of printing high-quality electronics and precise standard component (e.g. loaded ball bearings); meanwhile, cost disadvantage over conventional manufacturing methods is another issue (e.g. massively produced bolts). For manufacturability constraints, only general constraints (R5 and R6) of AM process are considered to reduce complexity of decision making. For other specific manufacturing constraints, e.g. minimum wall thickness, surface quality, and overhanging structure, are postponed in part-level DfAM stage because these constraints take effect only when the new consolidated design is ready. Rules R3 and R7 are necessary because other rules may have already eliminated the possibility of all-in-one design. Ruleset is used to directly reduce the possible combinations of consolidation candidates while conflict code is used for further investigating the possibility of consolidation for those which are treated as non-feasible parts in the beginning by the criteria of the ruleset (details are presented in Figure 2). Inclusion of potential solutions for each conflict code in Table 3 is to help designers with some redesign hints, but these potential solutions do not necessarily guarantee that each couple of components violating the rule can be successfully built. Much higher AM expertise is needed in dealing with conflict code in contrast with the ruleset. This specific conflict code will serve as the unique identifier to find a possible AM-enabled design solution. Taking “CF\_RelativeM” as an example, articulated mechanism can be printed as one part but special attention is needed to avoid fusion of interfaces due to proximity issues



or irremovable support structure. Application sequence of these rules depends on time cost of manual implementation and degree of constraining strength. Time cost for implementing each rule is evaluated on the basis of unit time expense of material information acquisition. Although all these rules are hard constraints, some rules are more likely to affect the feasibility of consolidated design solution than others. For example, high-quality electronic device (R4) has to be firstly singled out before studying relative motion (R1). The order of constraining strength of rules are:  $R4 > R1 > R2 > R3 > R6 > R5 > R7$ . Constraining strength is assessed according to current AM capabilities and the order may fluctuate as AM processes upgrade. Manual implementation sequence is shown in Table 3.

Apart from the listed seven feasibility rules, three basic principles should also be followed to boost product innovation and cost reduction.

- (1) **Principle of minimum part count (Principle I):** if all feasibility rules of AM-PCR are met, the very design solution with the minimum part count should be favored because it is believed that lifecycle cost decreases in proportion to reduced part count in general [23, 25].
- (2) **Principle of performance (Principle II):** if AM-PCR results in significant performance improvement, R1-7 can be ignored and the only concern is cost-efficiency. Typical performance gains include compactness, weight reduction, prolonged lifespan, and elimination of maintenance needs, etc.
- (3) **Principle of modularity (Principle III):** intra-module component pairs are more functionally proximal than their inter-module counterparts. This functional proximity determines the priority of consolidation if all-in-one design is impossible. This principle can also lower possibility of propagated failure because it helps to reduce inter-module interactions (e.g. assembly interfaces).

These feasibility rules and principles can efficiently eliminate design solutions that lead to low-quality or costly 3D-printed parts. But, designers should be advised that conformance to the rules R1-7 and the three principles does not guarantee a printable design with the best performance and cost advantages. As

mentioned above, these potential candidates should undergo a more detailed part-level DfAM process to satisfy desired quality and cost objectives.

Table 3 conflict type codes and potential solutions

Rule #	Rule name	Conflict code	Potential solutions	Time cost	Apply sequence (manual)
R1	Relative motion	CF_RelativeM	universal joints [51], classic mechanisms [37, 38], chains [10], compliant mechanism [52]	2	2
R2	Material variance	CF_MaterialVar	embedded components [35], printed circuit [53], functionally graded material (FGM) [36], or change material	2	3
R3	Assembly access	CF_AssemblyX	all-in-one design [10, 11]	$n^* - 1$	7
R4	High-quality electronic/standard device	CF_StandardDev	embedded components [35], printed circuit [53]	1	1
R5	Size limitation	CF_SizeLimit	new AM process or reduced size	$\sim 4$	6
R6	Material availability	CF_Material0	change material or find new material	1	5
R7	Maintenance frequency difference	CF_MaintenanceDiff	if consolidation can overcome maintenance-related problems	2	4

\* n is the total number of components and time cost varies from  $n-1$  to 1 which depends on sequence of verification.

## 4. A dual-level screening and refinement framework

In accordance with Topic 2 discussed in Section 2.2.2, a dual-level screening and refinement design framework is proposed. The framework aims at synthesizing the optimal solution(s) with the minimum cost-to-performance ratio through optimization of the triplet (*part count, architecture, material*). In the level of screening, the proposed new ruleset and principles are applied to filter a given product/assembly for potential candidates of consolidation. In the second level, selected candidates are consolidated and optimized by using all degrees of AM-enabled part-level freedoms towards the goal of minimizing cost-to-performance ratio. Details of the framework are presented in Section 4.1. Potential challenges in both levels are discussed in Sections 4.2 and 4.3 respectively.

### 4.1 Overall framework

The design framework is comprised of two sequential levels: screening and refinement. The objective of screening is to maximally reduce the combinatory space of components and find the bottom limit of part count while ensuring conformance to all the new rules. Assume that a product/assembly has  $n$

components and  $m$  connections among components. In theory, the combinatory solution space can be as large as  $\min(2^n, 2^m)$ . To avoid exhaustion of all combinations, feasibility rules should be applied to down-select feasible solutions before proceeding to design refinement stage. As shown in the flow chart (see Figure 2), Level 1 is comprised of 5 main steps.

- Step 1: function analysis is conducted to figure out the functional relations between components. The acquired functional information can also feed into the refinement level to support “design for function”.
- Step 2: adjacency graph can be drawn according to the explicit functional relations, from which functional proximity of components can be easily visualized.
- Step 3: the principle of modularity (Principle III) requires consolidation to take account of functional proximity of components. This step helps to group components in different modules where intra-module connections are intense and inter-module ones are sparse. Through module division operations, several intra-module groups and one inter-module group can be obtained.
- Step 4: feasibility check is conducted separately for all intra-module component groups as well as the inter-module group (the flow is highlighted in blue) to find the potential candidates. Rules R4, 1, 2, 7, 6, and 5 are verified in sequence. Rules R1, 2, and 7 are associated with pair-wise relations (e.g. material variance) so that they are grouped together. If any of these rules is violated, the corresponding links in the intra-module group or the inter-module group are broken and specific conflict codes summarized in Table 3 are archived in the conflict info hub. After applying all the rules above, intra-module groups and the inter-module group are reunited as one graph in preparation for the verification of R5 and R3. All the remaining links are rejoined into bigger groups to reduce final part count as requested by Principle I.
- Step 5: with the input of conflict codes from feasibility check module, conflict info hub helps to justify whether the encountered conflict can be solved or not with the aid of AM. As requested by the principle of performance (Principle II), the synthesized AM solutions (as summarized in Table 3) have to contribute to either performance improvement or cost reduction. If such an AM solution is found,

the broken links in Step 4 are resumed and rules R5 and R3 have to be re-evaluated again in case of size or assembly access issues.

Through all these steps, the final feasible solution  $S_0$  with the minimum group count can be found. However, this solution may not be the best one because more detailed study has to be conducted in terms of printed quality, building time, overall cost, environmental impact, and so on.

In the level of refinement, selected potential candidates are redesigned and refined towards lower cost-to-performance ratio. Lifecycle cost of a design solution is associated with its monetary cost resulted from production, use/service, and EoL. For example, production cost can be estimated by the complexity of design, selected material, special tooling usage, batch volume, and assembly effort. Performance is highly case-dependent. General metrics include functional performance (e.g. capacity of force, strength, energy, etc.) and complementary performance (e.g. robustness towards service environment, weight, and ergonomics). Assume that group  $G_i$  is one of the feasible groups. The refinement steps are as follows:

- Step 1: enumerate all the possible combinations of components within the group  $G_i$  and delete the ones violating assembly access issues or having typical manufacturing issues (e.g. irremovable support structures)
- Step 2: assume that subgroup  $j$  is one of the combinations derived in Step 1. Possibility of performance improvement or cost reduction is roughly evaluated. This step will need some basic AM knowledge of part-level design freedoms. Typical potential ones include bulky solids, manifolds, heat dissipation components, and complex parts, to name it a few. If it is true, proceed to Step 3; otherwise, go to next subgroup.
- Step 3: redesign of an AM-potential part is definitely not to simply fill it with lattice or optimize its shapes without changing the original boundaries or features. These features especially boundaries are set for conventional manufacturing methods. To jump out of this predefined circle, designers are encouraged to design for function. The output of this step is a new design space [33].

- Step 4: with the input of a new design space, structural optimization methods can be applied. Design parameters are optimized to achieve better performance and other lifecycle objectives as advocated in part-level DfAM [10].
- Step 5: numerical evaluation of each design solution is needed in terms of gains and cost.
- Step 6: repeat Steps 3-5 until each group has reached its best state and the ideal sub-group is saved in each iteration for future comparison.
- Step 7: repeat Steps 2-6 until all groups are exhausted and the best design solution with the optimal performance-to-cost ratio will be the final solution.

Ideally, screening and refinement should be simultaneously conducted because each combination of components evaluated in Level 1 needs to be refined and checked for printability in terms of quality loss and other factors. However, this iteration will be very time-consuming. A feasible but compromised way is to cut this iteration process and pursue a feasible solution with the minimum group count as proposed here. This decoupling of screening and refinement can efficiently shorten development time meanwhile keep high fidelity. To enable such a decoupling method, some other lifecycle concerns such as part retirement in the EoL and change of maintenance scheme should be considered earlier in the screening stage. One possible way is to associate cost and sustainability metrics with material selection, volumetric dimensions, AM processes, etc. after feasibility check. In this sequence, the effort to find the best grouping for AM-PCR can be largely reduced because the proposed new ruleset has already narrowed down the feasible solution space. However, these lifecycle concerns are complex and understudied, and thus not specifically addressed in this paper.

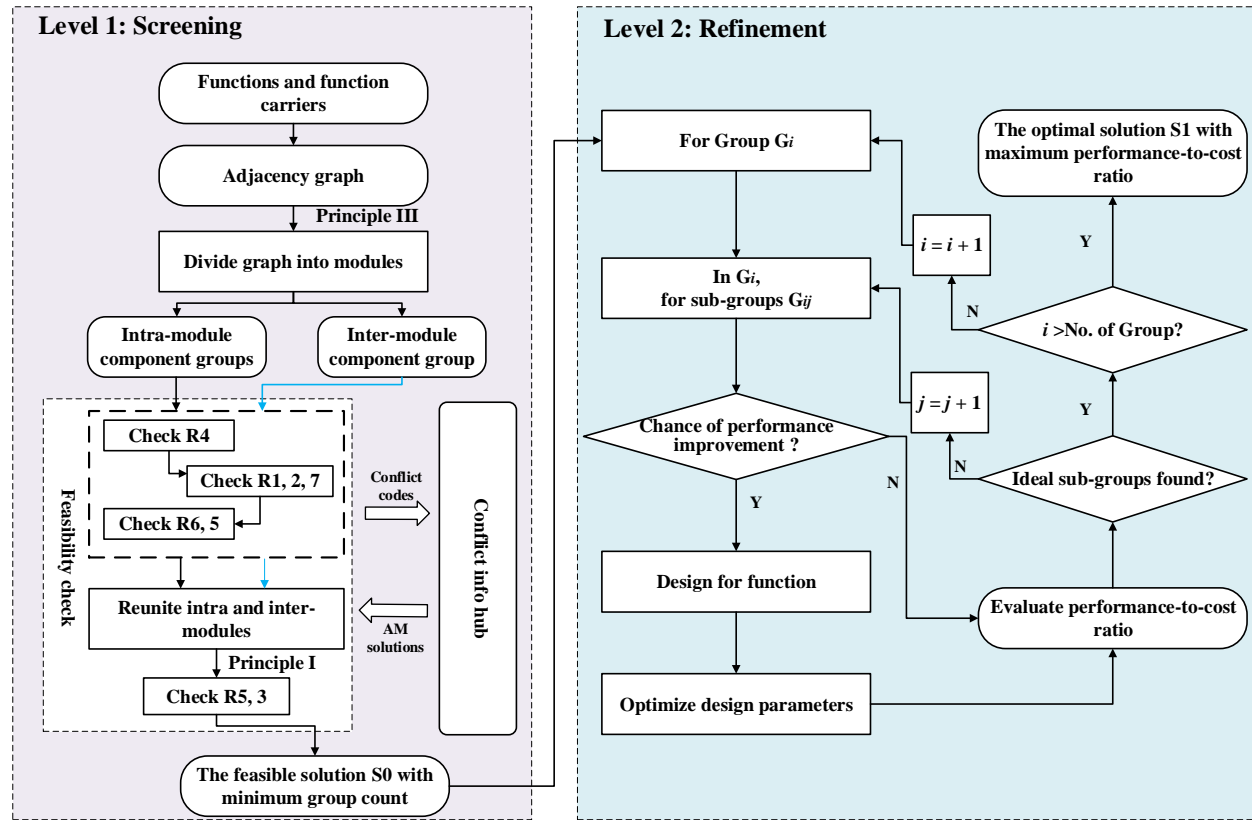


Figure 2 proposed dual-step screening and refinement design framework

## 4.2 Challenges in screening level

In the screening level, there are a few main challenges to be solved including function acquisition, module division, verification of feasibility rules, and conflict-solving design support. These four challenges are briefly discussed as follows.

(1) **Function acquisition:** in current commercial CAD systems, functional information of design is unavailable. This deficit adds much more burden for PCR research especially when the complexity of product is high. Mapping information of function-function carrier is a prerequisite for both understanding the functional proximity and supporting design for function.

(2) **Module division:** conventional module division methods are employed to promote modular design and manufacture. This allows more flexibility to control the effect imposed by the change of design requirements [57], reduces lifecycle cost through decreased number of processes [58], promotes

reconfiguration and product variety, and eases maintenance and retirement [59]. However, AM challenges modular design and it allows more flexibility. Therefore, new study of how to define modules is in need.

(3) **Verification of feasibility rules:** these feasibility rules still belong to heuristics which need manual interpretation. Therefore, it is normally done in an ad-hoc way. These reasoning processes are so difficult to be documented that the whole process needs to be repeated if new technologies have further relaxed the feasibility rules. A more feasible solution is to embed these knowledge into a black-box so that verification of feasibility rules can be automated. Any violation of these rules can be recorded and retrieved.

(4) **Conflict-solving design support:** currently, this area of research is rare. For each specific conflict type, special attention must be paid because each solution varies dramatically from each other. For example, to solve the issue of “relative motion”, compliant mechanism is one possible answer. But what factors should keep in mind are not well-known. Another solution of “relative motion” is to modify the interface clearance, which is machine and process-specific. In brief, a comprehensive design support system is strongly needed.

### 4.3 Challenges in refinement level

Refinement level has large overlaps with part-level DfAM studies. To some extent, they are equivalent. The main challenges in this level include design for function, design parameter optimization, and performance-to-cost ratio. These challenges are briefly elaborated as follows.

(1) **Design for function:** to realize this goal, two design techniques are very critical: function analysis and function-based design synthesis. Function analysis is discussed in Section 4.2 so that it is not repeated here. When functions become explicit, how to synthesize a new function-carrier in the context of AM is rarely studied. Designers are used to following DfMA rules with reluctance to push the boundary of feasible innovation. Possible strategies could be analogy-based design, case-based design, and graph-based design to facilitate computer-aided design synthesis [60]. Analogical design heavily depends on existing artifacts which are either natural or artificial. In accordance with the similarity of functions, the

principles can be analyzed and reused for a new physical entity. One design repository is built by Oregon State University which contains more than 6000 artifacts [61]. Case-based design concentrates on demonstrating the successful examples that can be reused. In AM domain, these examples do not necessarily fulfill the same function as the target, but it can show where designers can have more design freedom, for instance, material composition and topology. One good demo system was developed by Bin Maidin [62]. Generative design synthesis can be regarded as one example of graph-based methods where graph rules are associated with boundary conditions. In generative design, it employs the advancement of computational power and artificial intelligence to generate optimized physical structures. Typical applications include topology optimization and cellular structures [63]. However, how to generate an alternative function carrier which is suitable for PCR is still unknown.

(2) **Design parameters optimization:** as indicated in Figure 2, for each combination, the clustered components are redesigned with respect to all design parameters to maximize performance and lower cost. Main challenges include high-dimensional design parameters, optimization algorithms, manufacturability (e.g. overhanging), and material properties (e.g. anisotropy). Topology optimization issues are well discussed in literature [31]. In terms of how to reduce the dimensions of the problem to be solved, certain design parameters should be determined in the beginning although it may result in sub-optimal solutions. For example, in a lattice optimization problem, topology of a unit cell is normally predefined and the optimization work is only to search for optimal beam size and orientation.

(3) **Performance-to-cost ratio evaluation:** consistent with Altshuller's "law of ideality" [7], a good design should be governed by a ratio of useful functionality to a sum of harmful effects and/or costs. In this paper, we define this ratio as performance-to-cost ratio. In the refinement level, optimization of design parameters should approach towards the objective of maximizing performance-to-cost ratio. However, having lifecycle information ahead of design will be very challenging. Necessary compromise needs to be made while it can lead to a design with a higher ratio. Lifecycle cost study of additively manufactured part is well studied in paper [56], but it does not take development cost into account.



Besides, lifecycle data of commercially used parts have not reached its retirement stage yet. A more comprehensive study to evaluate lifecycle cost of AM-PCR parts is needed.

## 5. Case study

An example of a motorcycle steering assembly (noted as STA in the following discussion) is presented to demonstrate how to apply the proposed feasibility rules and how to do refinement according to the dual-level framework. This case study was first used by the authors in IDETC 2016 [33] with a focus on how to consolidate a selected candidate which is identified on the basis of user experience and the well-known three heuristic questions [1]. In this paper, a more systematic analysis of potential candidates will be conducted, which can be adapted for wider applications. As shown in Figure 3 (a), there exist 12 components (regardless of fasteners) in the STA within which 9 parts are unique. The STA is supposed to fulfill overall functions of steering and support driver, which can be further decomposed to more detailed sub-functions, such as import hand and distribute force. These sub functions have to be further decomposed into leaf-functions which can match up with their physical components individually. Detailed function-function carrier view is depicted in Figure 3 (b) where overall, sub, and leaf functions are colored in orange, green, and blue respectively. Links between functions (circles) are functional relationships including decomposed-by, conditioned-by, and enhanced-by relations [64], which are colored in orange, green, and red respectively. The dotted link represents the mapping relation between function and its function carriers. From the figure, we can see that there exist n-to-1 function-physical entity mappings (e.g. steering handle) and 1-to-n ones (e.g. secure handle V.S. cap & base). In this paper, we assume that redesign does not change function structure other than function-to-function carrier mappings where AM truly makes a difference [40]. All physical information of each component is summarized in Table 4.

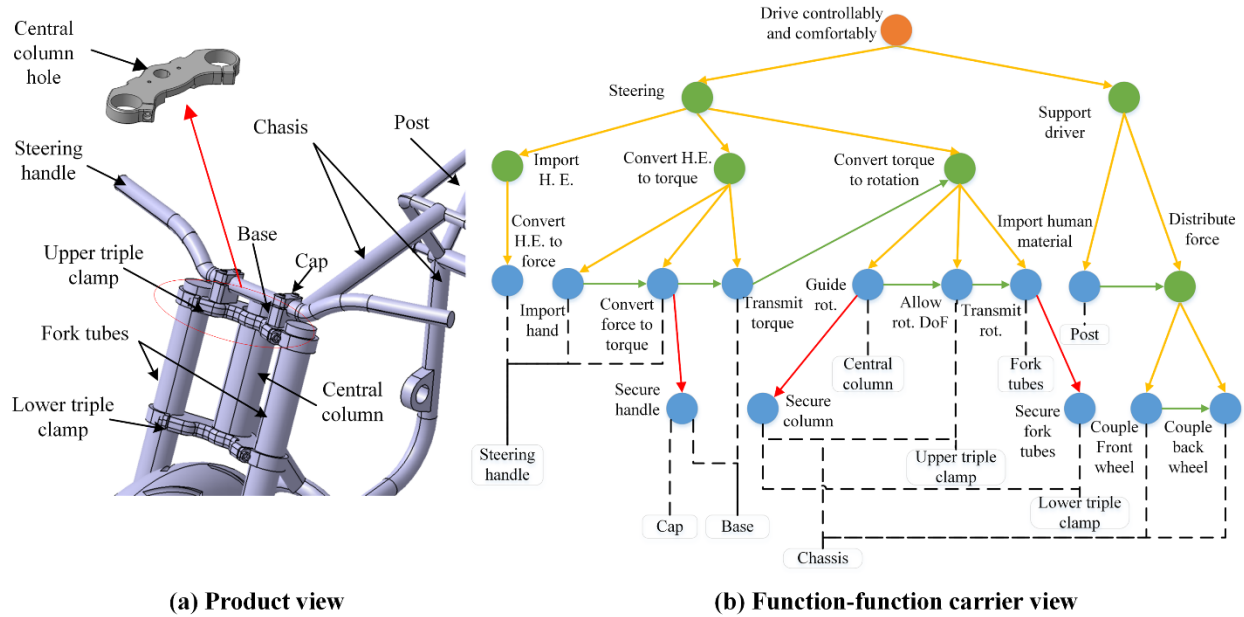


Figure 3 product and function view of a motorcycle steering assembly

Table 4 component physical information

Name	Steering Handle	Cap	Base	Upper triple clamp	Fork tubes	Lower triple clamp	Main frame
#	C1	C2	C3	C4	C5	C6	C7
Volume (L,W,H) (cm)	50*4*3	6*3*3	6*3*5	25*10*9	55*7*7	25*10*9	100*25*50
Material	steel	steel	steel	steel	steel	steel	steel
Maintenance frequency	low	low	low	low	low	low	low
Is standard?	no	no	no	no	yes	no	no

According to the proposed dual-level screening and refinement framework, the first step is to translate function-function carrier tree into an adjacency graph. In reference to Figure 3 (b), connections between components are determined by corresponding functional relations. In this paper, all types of functional relations are treated the same. Special attention is in need for 1-to-n function-function carrier mappings where physical entities to fulfill the same function should be connected. The resultant graph is shown in Figure 4 (a). The second step is to group these components into modules which should consider the functional proximity of components. Since the adjacency graph is simple enough, we can directly know that functional dependency within module M1 (C1, C2, C3) and M2 (C4, C5, C6, C7) is much higher than that of inter-module one (C3, C4). This module division signifies that we should study the feasibility of intra-module components earlier than inter-module ones. The third step is to investigate conformance of

these component pairs within module and across modules simultaneously. Take M2 as an example and the sequence is as follows:

- R4 (high-quality or low-cost standard device): as shown in Table 4, only the two fork tubes are in simple shape and highly standardized; therefore, links (C4, C5) and (C5, C6) should be broken. Conflict type code CF\_StandardD is drawn for these two pairs. The result is shown in Figure 4 (c).
- R1 (relative motion): there exist relative motion within (C7, C4) and (C7, C6). Conflict type code CF\_RelativeM is drawn for these two pairs. The result is shown in Figure 4 (d).
- R2 (material variance): all components are made of steel so that this rule is invalid.
- R7 (maintenance difference): all the presented components are highly durable and rare maintenance is needed. Thus, this rule is ineffective.
- R6 (material availability): all components are made of steel which is already feasible for metal AM processes.
- R5 (size limitation): after all the above steps, all components C4-7 are separate and the largest component is C7. The volume size of current commercial printers may be a problem, but it is promising by using Big Area Additive Manufacturing (BAAM) with a change in material type [65].

Similar steps are taken for M1 and all rules are satisfied. Required by Principle I (minimizing part count), link (C3, C4) is studied and it does conform to all rules, as shown in Figure 4 (e). By now, we have Groups ((C1-4), C5, C6, C7). Consolidation of components C1-4 makes a bigger size; therefore, R5 has to be verified again and the rule is met. In the end, R3 (assembly access) is checked and there is no problem for all groups. The final result of feasibility check is shown in Figure 4 (f). In feasibility check steps, two types of conflict codes are caught: CF\_RelativeM and CF\_StandardD. In the first case, the clearance between the central column and its mating hole is 0.2cm which is acceptable for resolution of currently available printers. Although it is technically feasible, the loss of quality interfaces of the central

column is greater than the gain of minimized assembly cost. The main consideration of the second case is to reduce cost and consolidation does not impose a significant impact. In conclusion, the optimal solution S0 is comprised of 4 groups: (C1, C2, C3, C4), (C7), (C6), and (C5).

In the refinement module, each group of S0 needs to be studied in terms of possibility of performance improvement. Apparently, C5 is cheaper to be fabricated by conventional manufacturing methods so that there is no need of further redesign. For C7, original welding process can be replaced and the whole main frame can be substituted by a more organic design which has a strong sense of fashion. Topology optimization methods [31] can be applied to synthesize such a design concept that fulfills the same functions of “support driver” and “couple front wheel”. Similar design innovation is applicable for C6 because it is so bulky and full of features that are designed for CM. As for Group 1, it definitely has potential improvement of customization and weight reduction which are two typical application scenarios of AM. Customized handle grants better manipulation and adds more values to the product. However, all these analyses are qualitative and performance-to-cost ratio still needs to be evaluated to find the optimal design solution. Performance here can be defined as a function of weight, quality, level of product innovation, and level of customization. Cost here should consider both lifecycle cost and environmental impact (which can be seen as a penalty). Mathematically, there are totally 10 combinations for Group 1 as shown in Table 5, but some can be eliminated because of R3 or cost. Possible pros and cons are summarized as well. For example, the seventh solution is to consolidate components C1-3 and it requires bolts to be inserted from the bottom side of C4, which is inconvenient. In the “decision” column of Table 5, estimated rank of fitness is given on the basis of the authors’ experience. However, final decision of which solution is the best needs taking full consideration of quality, design innovation, and cost.

One possible conceptual design is shown in Figure 5. In this new design, there are totally 5 components: handle, mainframe, bottom triple clamp, and two fork tubes (not shown). The handle is customized and optimized for lightweight purpose. As requested by design for function, the handle is redesigned into two sections while fulfilling the same function of “import hand”. Compared to the old design, the consolidated

handle enables faster assembly and more pleasing appearance. The mainframe can also be customized using generative design methods [66] to provide multiple choices for users. As for the bottom triple clamp, there are many cut-outs to reduce weight as shown in the top view (Figure 5).

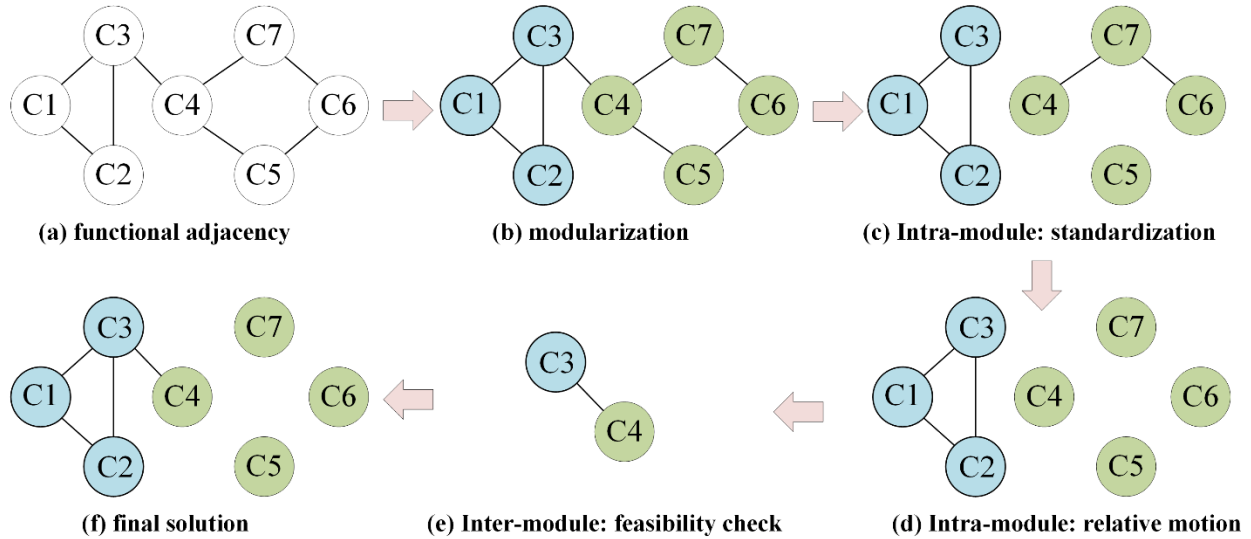


Figure 4 level 1: screening process

Table 5 possible combinations of Group 1

#	Subgroups	Pros	Cons	# of assembly	Decision
1	C1, C2, C3, C4	Both AM and CM* are feasible	Lots of assemble operations	11	5
2	C1, (C2, C3), C4		Violate R3	N/A	X
3	(C1, C2), C3, C4	C3 and C4 can be made by CM		9	6
4	C1, C2, (C3, C4)	Handle quality can be better		7	4
5	(C1,C3), C2, C4		Lots of assemble operations	10	7
6	(C1, C2), (C3, C4)	more compact		6	3
7	(C1, C2, C3), C4		Assembly operation needs to be done from bottom side	5	2
8	C1, (C2, C3, C4)		Violate R3	N/A	X
9	C2, (C1, C3, C4)		No need to have C2	N/A	X
10	(C1, C2, C3, C4)	no assembly need	large overhanging area	0	1

\* CM conventional manufacturing

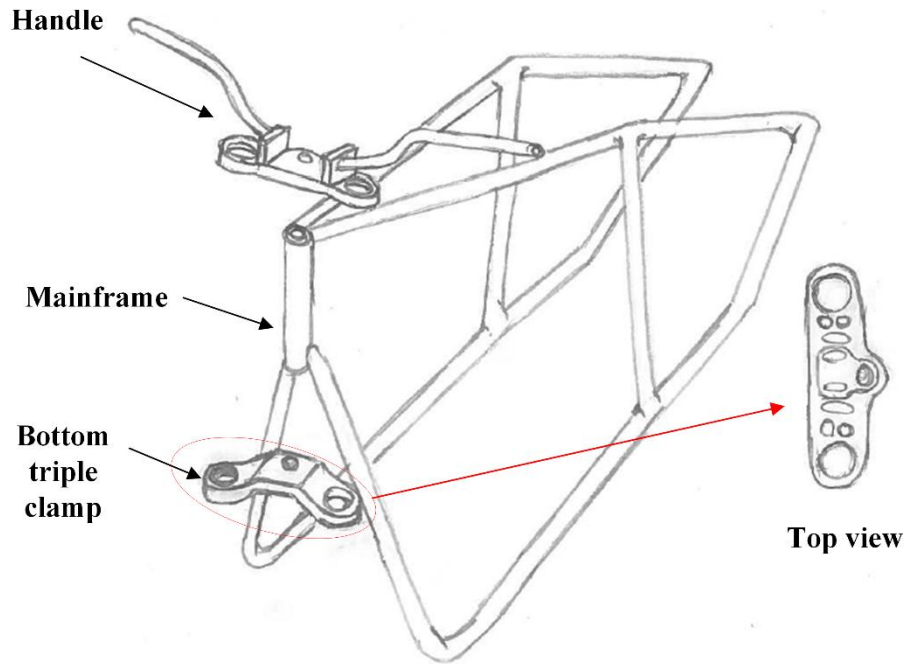


Figure 5 hand draft of a consolidated design solution

## 6. Conclusions and future research

In this paper, we first reviewed the lifecycle constraints and opportunities of conventional part count reduction research (G-PCR). These constraints and opportunities indicate the complexity of PCR problems. Important design rules to support G-PCR are summarized. As AM becomes a possible manufacture method, new challenges and opportunities of AM-PCR are discussed in a point-to-point fashion with respect to G-PCR. In the end, current AM-PCR research is briefly summarized and unsolved problems are discussed. To support AM-PCR, a new set of design rules is proposed to exclude infeasible solutions and support early-stage decision making of consolidation. Application sequence of these rules is also discussed. More importantly, we propose a conflict-solving mechanism which can support evolutionary synthesis of AM-enabled design solutions. These rules are integrated into a dual-level screening and refinement design framework to support potential candidate identification and to find the optimal consolidated design solution with respect to performance and lifecycle cost. In the end, a case study of a motorcycle steering assembly is given. Effectiveness of both the proposed new design rules and the dual-level design framework is proven. However, there are a few limitations should be advised:

(1) In the case study, size limitation is invalid because we did not take machine availability into consideration. If size limitation of height takes effect, for instance, priority of consolidation has to be considered. For example, if (C1, C2, C3, C4) cannot be consolidated, then (C1, C2, C3) has higher priority than inter-module link (C3, C4) because of risk management requirement.

(2) Screening and refinement are conducted in sequence to eliminate design iterations and decision complexity in this paper. However, this design method may not find the theoretical optimal solution. For example, size limitation may partition a large component groups into smaller ones and this result is passed onto the refinement stage. Nevertheless, the size of component sometimes can be reduced by using AM; therefore, the original large group should be reserved. This issue can be improved at the proposed mechanism-solving step. If the designer can realize the potential of size reduction in advance, then the component group remains unchanged.

For future research, the following directions should be investigated:

(1) Feasibility rules should be validated to a wider scope of product and possibility of automating the validation process should also be investigated.

(2) In the case study, module division effort is saved because of its simple adjacency. However, a more efficient approach should be developed for a more complex product.

(3) Conflict code-based conflict-solving mechanism requires a large database to provide solutions to those conflicts and each solution needs to specify possible challenges and constraints.

(4) Other lifecycle concerns should be investigated especially the impacts of AM-PCR on sustainability and cost. It is very likely that the consolidated part changes the type of materials (and its production), way of manufacturing, spare part management, and method of retirement in EoL. A more comprehensive study of these impacts are necessary to update the new ruleset for AM-PCR.

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**Figure caption list**

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**Table caption list**

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Table 1 Pugh Analysis of G-PCR and AM-PCR

		Criteria	Reference (assembly design)	G-PCR	AM-PCR
<b>Lifecycle phases</b>	Design	Reduce function coupling	0	-1	-3
		Structure simplification	0	+1	+3
	Manufacture	Manufacturability	0	-1	+2
		Reduce cost	0	+1	?*
	Assembly	Simplify assembly operation	0	+1	+2
	Service/ use	Improve efficiency	0	+1	+2
		Reduce maintenance effort	0	+1	+1
	EoL	Reusability	0	-1	-2
		Re-manufacturability	0	0	+1**
		Recyclability	0	0	-1***
<b>Global objectives</b>	Performance improvement		0	+1	+3
	Lifecycle cost reduction		0	+1	?
	Reduce ecology impacts		0	+1	?

\* “?” means undetermined.

\*\* Reparation can be done by some AM processes such as Direct Energy Deposition [47].

\*\*\* Recyclability is hampered when multi-material AM is adopted [13].

Table 2 point-to-point comparison of opportunities and challenges of AM-PCR

<b>Rules</b>	<b>AM opportunities</b>	<b>Remaining challenges</b>
r1	individual discipline feasibility (IDF) [48, 49] multidisciplinary optimization (MDO) [50]	high computational burden
	improved performance: hydraulic manifold [9], Airbus duct [10], GE nozzle [11], conformal cooling device [30]	case-specific
r2	universal joints [51], classic mechanisms [37, 38], chains [10], compliant mechanism [52]	still in proof-of-concept stage, poor quality, clearance issue
r3	embedded components [35], printed circuit [53], functionally graded material (FGM) [36]	still in proof-of-concept stage, not all materials are compatible and available
r4	all-in-one printing [54]	process-specific, size limitation, separation issue
	all-in-one design [10, 11]	only stationary parts are consolidated
r5	almost no tooling is needed in printing process [10]	post-processing tools are needed
r6	adaptive slicing [55] or multi-resolution printing can achieve controlled quality	It can only vary the surface roughness along building orientation
	manufacture cost of high or low-quality part is not significantly different; therefore, higher quality standard can be followed	Some high-quality parts especially electronics are still far from production by AM
r7	manufacture cost is no longer a function of geometric complexity	Lifecycle cost model of additively manufactured part is still under development
r8	mass customization is enabled by AM regardless of batch size	Simple-geometry, highly-standardized, or massively-produced parts are cost-efficient
r9	material saving, energy-efficient process [56]	material toxicity, material recyclability of FGM and unused raw material

Table 3 conflict type codes and potential solutions

Rule #	Rule name	Conflict code	Potential solutions	Time cost	Apply sequence (manual)
R1	Relative motion	CF_RelativeM	universal joints [51], classic mechanisms [37, 38], chains [10], compliant mechanism [52]	2	2
R2	Material variance	CF_MaterialVar	embedded components [35], printed circuit [53], functionally graded material (FGM) [36], or change material	2	3
R3	Assembly access	CF_AssemblyX	all-in-one design [10, 11]	$n^* - 1$	7
R4	High-quality electronic/standard device	CF_StandardDev	embedded components [35], printed circuit [53]	1	1
R5	Size limitation	CF_SizeLimit	new AM process or reduced size	~4	6
R6	Material availability	CF_Material0	change material or find new material	1	5
R7	Maintenance frequency difference	CF_MaintenanceDiff	if consolidation can overcome maintenance-related problems	2	4

\* n is the total number of components and time cost varies from n-1 to 1 which depends on sequence of verification.

Table 4 component physical information

<b>Name</b>	<b>Steering Handle</b>	<b>Cap</b>	<b>Base</b>	<b>Upper triple clamp</b>	<b>Fork tubes</b>	<b>Lower triple clamp</b>	<b>Main frame</b>
<b>#</b>	C1	C2	C3	C4	C5	C6	C7
<b>Volume (L,W,H) (cm)</b>	50*4*3	6*3*3	6*3*5	25*10*9	55*7*7	25*10*9	100*25*50
<b>Material</b>	steel	steel	steel	steel	steel	steel	steel
<b>Maintenance frequency</b>	low	low	low	low	low	low	low
<b>Is standard?</b>	no	no	no	no	yes	no	no

Table 5 possible combinations of Group 1

#	Subgroups	Pros	Cons	# of assembly	Decision
1	C1, C2, C3, C4	Both AM and CM* are feasible	Lots of assemble operations	11	5
2	C1, (C2, C3), C4		Violate R3	N/A	X
3	(C1, C2), C3, C4	C3 and C4 can be made by CM		9	6
4	C1, C2, (C3, C4)	Handle quality can be better		7	4
5	(C1,C3), C2, C4		Lots of assemble operations	10	7
6	(C1, C2), (C3, C4)	more compact		6	3
7	(C1, C2, C3), C4		Assembly operation needs to be done from bottom side	5	2
8	C1, (C2, C3, C4)		Violate R3	N/A	X
9	C2, (C1, C3, C4)		No need to have C2	N/A	X
10	(C1, C2, C3, C4)	no assembly need	large overhanging area	0	1

\* CM conventional manufacturing