Chapter 71
Part Consolidation in Design for Additive Manufacturing: A Two-Level Approach Using Complexity Metrics

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Abstract Design for additive manufacturing (DfAM) creates opportunities for improved product design. Part consolidation (PC) is an important design opportunity in DfAM. The existing methodologies for part consolidation in DfAM are mostly based on expert judgment or heuristic rules. In addition, they only suggest the candidates for part consolidation. They do not assess the manufacturability of the consolidated parts. This paper proposes a two-level approach for part consolidation using complexity measures at the system level and part level. At the system level, the centrality score (a complex network measure) is used to identify parts with high potential for consolidation, and at the part level, a geometry-based complexity measure—modified complexity factor (MCF)—is used to assess the manufacturability. This two-step approach is expected to improve efficiency and effectiveness in DfAM since it uses minimal information at the system level and detailed assessment of manufacturability is done only for those parts where AM potential is high. Such an approach can be extremely useful to product designers at the early stages of design. Two case studies are presented to illustrate the effectiveness of the proposed approach.

71.1 Introduction

Design for additive manufacturing (DfAM) recommends different methods and tools that help designers about the capabilities of additive manufacturing (AM) (technological, geometrical, etc.) in the design stage. In general, DfAM capabilities have been classified into two categories: opportunistic and restrictive. In opportunistic DfAM, each design potential will have a value addition and design benefit. Kumke et al. [1] have developed a semantic network of the design potentials and benefits of AM (49 nodes and 290 relations). The top three highly influential nodes in this semantic network include (a) part consolidation, (b) different material in one part

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and (c) reduced number of joints. These important design potentials represent the key drivers of complexity in any system—the parts, the content of the parts and the relationships among parts. In AM, the possibility of part consolidation is widely studied in system level, and some of the existing methods is discussed in the next session.

71.1.1 Existing Approaches to Part Consolidation in DfAM

AM has its unique process capabilities that remove the product complexity restriction because of part consolidation. Some components in the part are no longer required to be separately manufactured and then assembled; instead, they can merge into a single part to be manufactured through a single AM process. Schmelzle et al. [3] have studied the challenges that engineers face when redesigning a multicomponent assembly into a single component and fabricated using laser-based powder bed fusion for metal AM. Yang et al. [4] have proposed a new part consolidation (PC) methodology comprehensively considering function integration and structure optimization. The modular design approach is another way to perform PC. Samyeon et al. [5] have proposed a methodology to consolidate parts by considering the maintenance and product retrieval at the end-of-life stage by extending modular design approach. The modules are identified using the single component complexity index and Markov clustering algorithm. Researchers working on design structure matrix (DSM) have developed several measures and clustering approaches to study modularity in systems. For instance, Suh et al. [2] have used key drivers of complexity in any system like the number of parts, relationships and nature of relationships to develop complexity measures to guide discussions on modularity. From the literature, it is found that the existing PC methodologies are focused only on finding a suitable candidate for part consolidation in the assembly, but the manufacturability of the consolidated design is not discussed. At the same time, those focusing on manufacturability by AM have largely concentrated on geometrical complexity at the part level and not the whole.

Given that the top three design potentials in DfAM point to the key drivers of complexity in any system (number of parts, the content of the parts and the number of relations), this paper argues that there may be opportunity to improve the efficiency and effectiveness of the DfAM process in practice by using objective metrics at both the system (product) level and the part level. The paper proposes the use of complexity network measure (centrality) to identify the potential parts for consolidation from the product level design structure matrix (DSM) and an existing geometry-based approach measure for assessing the manufacturability at the part level.

The centrality score, which measures the connectedness of a node in the network, helps identify the parts with high centrality and the other parts that are directly connected with it. The manufacturability of the consolidated parts is calculated using the modified complexity factor, a measure used for assessing the manufacturability in AM [6].

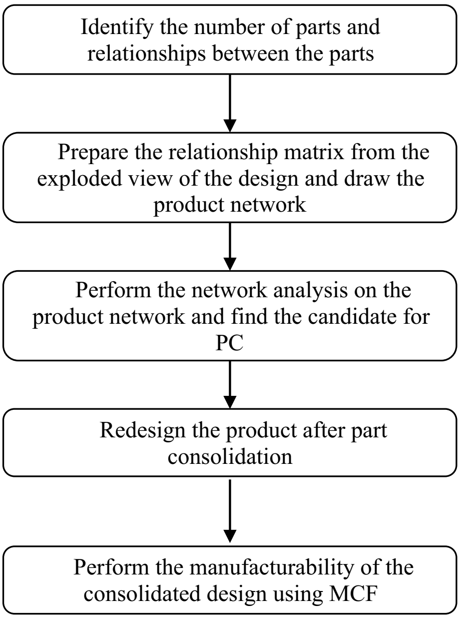
71.2 Two-level Approach

71.2.1 Identification of Possible Candidates for PC

For identifying the possible candidates for PC, the overall methodology is explained in the flowchart as shown in Fig. 71.1.

The suitable candidate for part consolidation is identified by performing complex network analysis on the product architecture or design structure matrix (DSM). The product network is constructed from part interaction matrix created from the exploded view of the assembly in any CAD modeling software. Then the centrality of each component in the product network is calculated, and the component with high centrality score is selected as the candidate for PC. The centrality score is defined by the number of connections incident on each node, and it is used as an estimate of its importance in the network [7]. The centrality score obtained from the network analysis resembles the complexity metric discussed in [2], which is a function of the number of components, the number of interfaces and the adjacency matrix of the system. While consolidating the parts, the functionality of the overall design has to be preserved. So, the decision has to be taken by considering the material compatibility and manufacturability of the consolidated design in AM.

Fig. 71.1 Proposed part consolidation strategy



71.2.2 Manufacturability Using the Modified Complexity Metric

While the consolidation of the parts has been done, now we have to measure the complexity of the design to check the manufacturability. To evaluate the manufacturability of a shape for AM, Conner et al. [6] have developed a metric called modified complexity factor (MCF) which is a modified version of complexity factor mentioned in [8]. The complexity of the design, modified complexity factor (MCF), is calculated by using the geometry-related parameters like surface area, the volume of the part, volume of the bounding box, etc. [6]. The equation for calculating the MCF is shown below.

$$\text{Modified Complexity Factor, MCF} = 5.7 + 10.8C_{\text{pr}} + 18C_{\text{ar}} + 32.7C_{\text{nh}} \tag{71.1}$$

where, part volume ratio,

$$C_{\text{pr}} = 1 - \frac{\text{Volume of part}}{\text{Volume of bounding box}} = 1 - \frac{V_p}{V_b} \tag{71.2}$$

Area ratio,

$$C_{\text{ar}} = 1 - \frac{\text{Surface area of part}}{\text{Surface area of sphere}} = 1 - \frac{A_p}{A_s} \tag{71.3}$$

Hole ratio,

$$C_{\text{nh}} = 1 - \frac{1}{\sqrt{1 + N_h}}, \tag{71.4}$$

where V_p is volume of the part, V_b is the volume of bounding box, A_p is the surface area of the part, A_s is the surface area of the sphere which is considered to be a less complex shape, and N_h is the number of holes. These geometry-related parameters are measured from the mass properties of the 3D CAD model. If the MCF value is more than 44 falls under the high complexity part category, these designs are more suitable for AM according to [6].

71.3 Case Study

To understand the feasibility of the proposed approach, two case studies are carried out. Section 71.3.1 discusses an existing motorcycle steering assembly, which is already discussed in [9], and Sect. 17.3.2 discusses a throttle pedal assembly discussed in [8].

71.3.1 Motor Steering Assembly

Initially, there were seven components in the design, and Fig. 71.2 shows the initial design and components in the design. The total number of parts in the assembly is reduced to four by using the complex product network measure.

The network from the relationship matrix is drawn as shown in Fig. 71.3a, and the centrality score is calculated for each node. Based on the centrality score, the candidate for part consolidation is identified and part count reduced to four from seven. The product network after the consolidation is shown in Fig. 71.3b, and the centrality score of each part is graphically represented in Fig. 71.4.

From Fig. 71.4, upper triple clamp has the highest centrality score, so the upper triple clamp is the most important node in the product network. The next step is to consolidate the possible parts along with the upper triple clamp without eliminating the functionality of the assembly the parts need to be consolidated. So, out of seven components, the lower triple clamp, upper triple clamp and fork tubes can be considered as standard parts and without eliminating the functionality steering handle, cap, the base is combined with the upper triple clamp, and it can be made as a single part. The next step is to check the manufacturability of the consolidated part using Eq. (71.1). The consolidated design is shown in Fig. 71.5. By using the additive

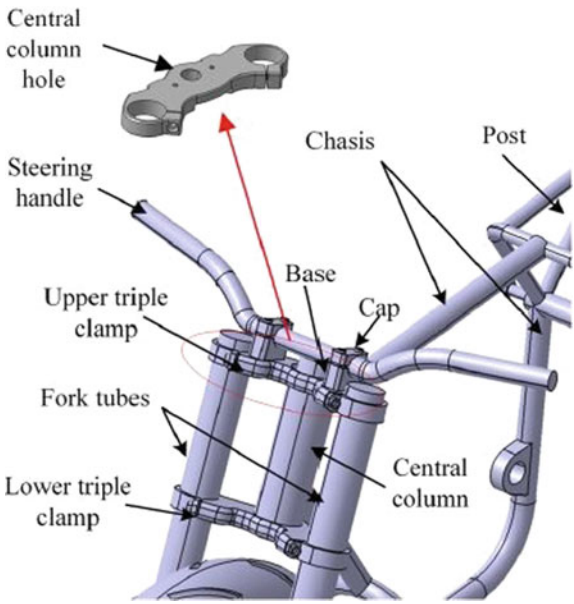


Fig. 71.2 Motorcycle steering assembly [7]

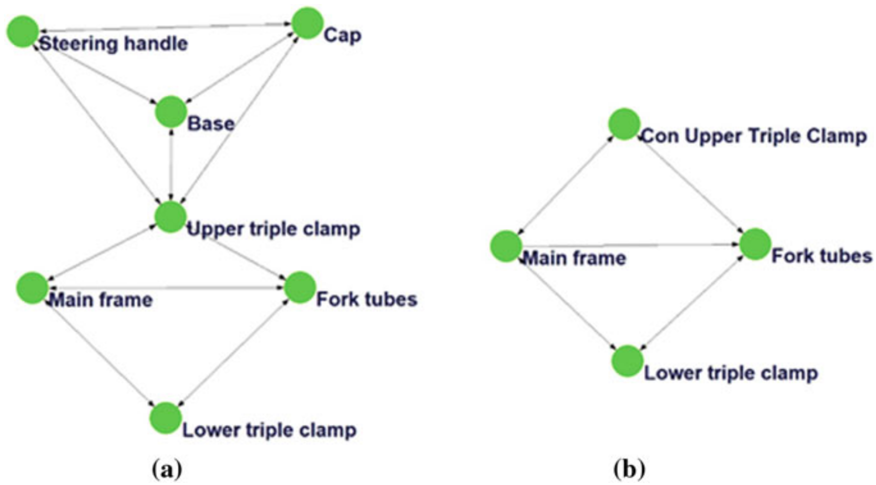


Fig. 71.3 Product network **a** before consolidation **b** after consolidation

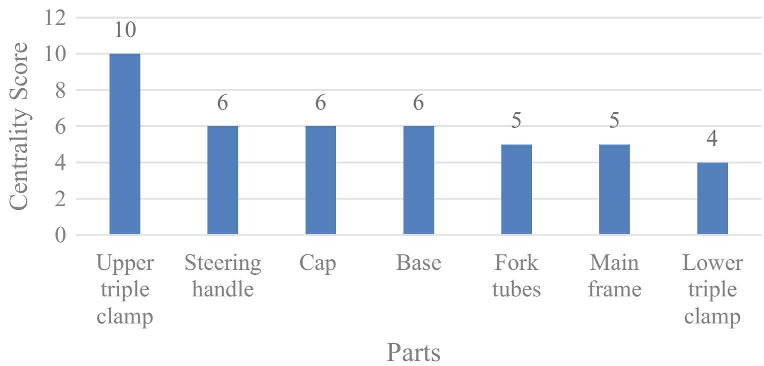


Fig. 71.4 All degree centrality of the motorcycle steering assembly

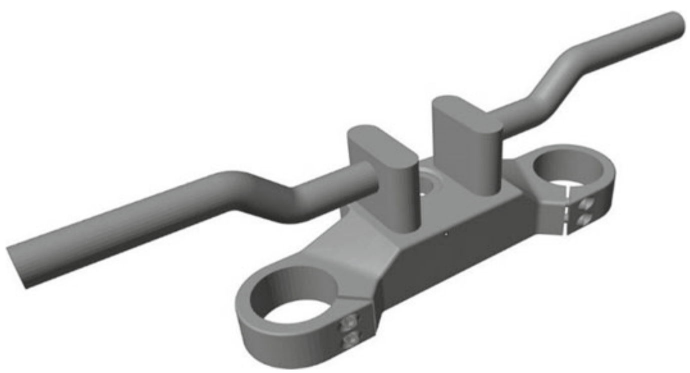


Fig. 71.5 Consolidated upper triple clamp

Table 71.1 Mass properties and parameters for calculating the MCF

Vol of the part (cm^3)	Vol of the bounding box (cm^3)	Surface area of the part (cm^2)	Surface area of the sphere (cm^2)	No of holes	C_{pr}	C_{ar}	C_{nh}	MCF
582.827	4215.809	1139.952	337.424	2	0.8617	0.7040	0.50	44.03

manufacturing-enabled part count reduction (AM-PCR) followed in [9], seven parts are reduced to five.

The details of mass properties and the modified complexity factor of the consolidated design are shown in Table 71.1.

From Table 71.1, the MCF value of the consolidated design is more than 44, so the design is suitable for manufacturing using AM [6].

71.3.2 *Throttle Pedal*

A throttle pedal design is selected to demonstrate the proposed framework and validate the effectiveness of the new method with the Part Consolidation Candidate Detection (PCCD) algorithm used in [8]. The original design is taken from an open-source CAD database [11]. As shown in Fig. 71.6, the throttle pedal consists of 12 parts without counting the washers and fasteners. The product network is created by identifying the physical contact between the parts. From the network, the component with the highest centrality score is identified as the candidate for part consolidation.

Based on the physical relationship between the components, the product network is drawn using the open-source network tool and is shown in Fig. 71.7. The centrality

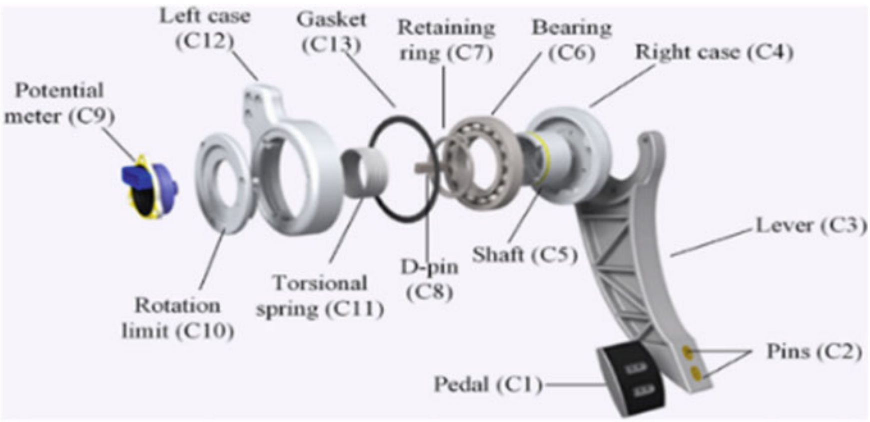


Fig. 71.6 Exploded view of throttle pedal [8]

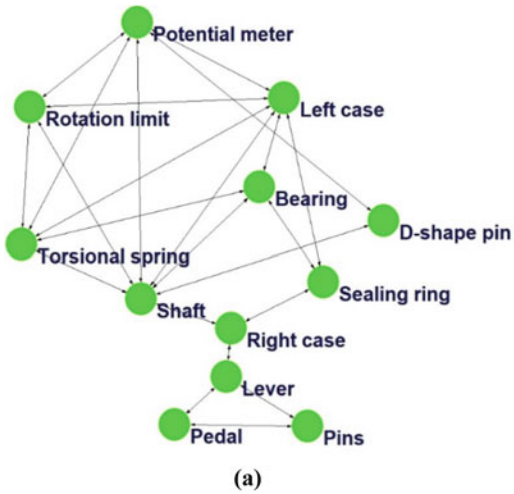


Fig. 71.7 Product network of throttle pedal **a** before consolidation **b** after consolidation

score of each node in the product network is measured and shown in Fig. 71.8.

From Fig. 71.8, the shaft has a high centrality score. Even though the shaft has the highest centrality score in the product network, all the parts around the most center node can be considered for consolidation. Out of nine parts in the assembly, some of the parts are COTS like bearing, torsional spring and potential meter. So, out of the remaining parts, we can consolidate the parts into two groups without eliminating the functionality of the product. In Group 1, the modified pedal consists of the shaft, sealing ring, the right case, lever, pin, pedal and D-shape pin. In Group 2, the rotation limit is consolidated with the left case. The manufacturability of the consolidated design is assessed with the help of MCF using Eq. (71.1), and the details are shown in Table 71.2. The consolidated design is shown in Fig. 71.9.

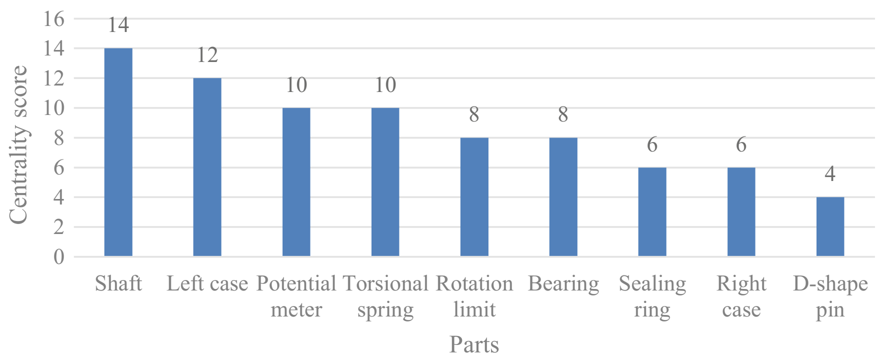


Fig. 71.8 Centrality score of the throttle pedal

Table 71.2 Mass properties and parameters for calculating the MCF

Part name	Vol of the part (cm^3)	Vol of the bounding box (cm^3)	Surface area of the part (cm^2)	Surface area of the sphere (cm^2)	No of holes	C_{pr}	C_{ar}	C_{nh}	MCF
Pedal	147.21	1307.52	631.23	134.83	3	0.89	0.79	0.5	45.79
Left case	37.63	163.55	193.46	54.31	4	0.77	0.67	0.55	44.11

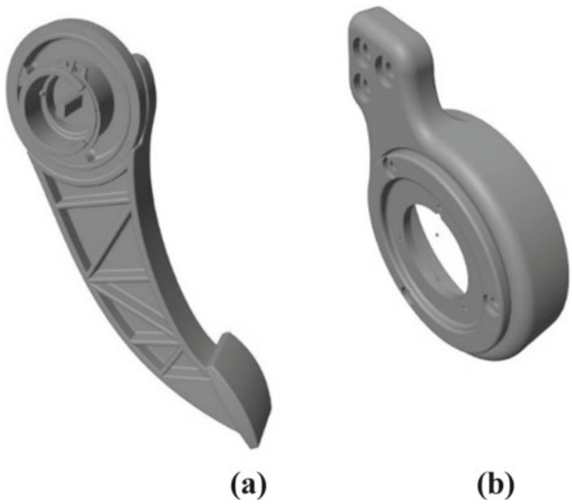


Fig. 71.9 Consolidated design **a** Group 1 and **b** Group 2

The MCF value for both the consolidated designs is more than 44, so these designs are suitable for manufacturing in AM.

71.4 Results and Discussion

The two case studies discussed in the previous section hold well with the earlier studies performed to identify the possible candidate for part consolidation using part consolidation candidate detection (PCCD) algorithm [10] and additive manufacturing-enabled part count reduction (AM-PCR) algorithm [9].

For implementing the PCCD algorithm or AM-PCR, the user has to verify the rule set for each set of component pairs in the assembly. There are seven rules in PCCD and nine rules in AM-PCR. So, the amount of information and time required to perform PC is more as the number of components in the assembly increases. But in this work, we can identify the set of components suitable for PC with fewer information and able to find the possible candidate for PC with comparatively less expertise. Also, in this proposed methodology, the manufacturability of the consolidated design is assessed using the modified complexity factor (MCF). So, if we follow the proposed two-level decision-making strategy, after part consolidation in the first level total number of parts in the assembly will be reduced and needs to check the manufacturability of lesser parts in the second stage. A detailed comparison of the existing algorithms and proposed methodology is shown in Table 71.3. The reduction in the number of parts is improved in the proposed methodology compared to the existing methodologies. So, the new two-level methodology can able to reduce the number of parts and assess the manufacturability of the consolidated parts with less expertise.

Table 71.3 Comparison of different PC methodologies

	PCCD [10]		AM-PCR [9]		Proposed Methodology	
No of parts	Before PC	After PC	Before PC	After PC	Before PC	After PC
Motorcycle steering assembly	–	–	7	5	7	4
Throttle pedal	13	7	–	–	12	5

71.5 Conclusion

An alternate approach for part consolidation using multilevel complexity measures is developed. In this work, we proposed a two-level decision-making procedure to adopt AM for manufacturing the product. In the first level from the product network, parts with high centrality scores are identified and the parts around the high centrality node are consolidated without eliminating the functionality of the product. Then the manufacturability of the consolidated design is assessed with the help of MCF in the second level. Two case studies are presented to prove the feasibility of the proposed framework for part consolidation and assessed the suitability of AM for the consolidated design. The proposed centrality score-based PC will be more effective than the modularity-based PC if the number of parts is more in the system. Further analysis can be done to check the appropriateness of the centrality-based method in future. This work can be further extended to find the suitability of the new methodology for functional integration along with part consolidation, and a view similarity-based measure for manufacturability assessment can be studied in future.

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