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Design for assembly approach for additive manufacturing products: a decision support system for large-size AM products

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ABSTRACT

In a contemporary era, Additive Manufacturing (AM), 3D printing or rapid prototyping has evolved as a distinctive method when compared with the traditional manufacturing. By addressing the topic of Design for Additive Manufacturing (DFAM), it is observed that the basic principles of DFAM and Design for Assembly (DFA) are well established and usually applicable on small-size AM parts. To address this critical manufacturing decision, our research work presents a new decision support system (DSS) for a large-size AM part which is based on compiling the existing DFAM methodologies. Before presenting the new DSS, the previous DFAM approaches are reviewed and investigated the research trends in part decomposition (PD), part consolidation (PC), and topology optimization (TO). The literature is categorized into six distinctive categories and among them the first phase is the information phase. Following this information requisite step, the next phase is parameter assessment phase and so on. The new DSS starts with the clarification of the design goal while in previous approaches this step was usually done at the later stages. Similarly, the remaining steps are efficiently integrated into the framework structure. The developed system is also guiding the post-decomposition assembly process. The developed DSS is validated using the case study of a 6-axis robotic arm. Moreover, a comprehensive concept for using the developed DSS framework is also presented in the research work.

1. Introduction

In Simple words, the designing of parts/components that constitutes the product after its assembly in such a way that its offers the ease of manufacture is known as "Design for Manufacturing" (DFM); while to design a product in such a way that will provide ease of assembly is known as "Design for Assembly" (DFA) and both the term is commonly known as "Design for Manufacturing and Assembly" (DFMA). [1]

The inception of DFMA concept was started with the automatic assembly. The methodology for Design for Automatic Assembly was developed by Boothroyd and his colleagues. The development has opened the gateway for the broader concept i.e. Product design for the ease of Manufacture. Until 1970, the term "Manufacturability" was used instead of "Design for ease of manufacture" and no such quantitative measures were available to assist designers in the manufacturability of parts and its components. The

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deficiency gave an idea to the design engineers regarding the possible manufacturing problems and established a comprehensive guidance for the designing team to not only simplifying the product structure to reduce the manufacturing cost but also impact the assembly operations and cost [2].

In this era of production systems, the aspects such as Design for Manufacturing, Assembly and Disassembly, all three concepts have gained more acceptance and importance during the design phase. The defiance to these concepts causes an abrupt impact on manufacturing operation and material consumption which itself have a direct impact on manufacturing cost and built-up time. In order to resolve and overcome the aforementioned manufacturing issues, the concept of DFA and DFM have been around since 1980's [3]

To comprehend the difficulty in product design and manufacturing phase, DFM is being used as an effective tool from past decades. As per ElMaraghy et al., the sole target of DFM methodology is to reduce manufacturing cost, product complexity and production time.[4] The component's critical features were inspected using DFM by Dereli and Filiz to find the manufacturing feasibility under the given machining processes/parameters.[5] To analyse the product design, bending feasibility and process planning, Ding et al. has used DFM methodology for Tube Bending and developed the computer integrated manufacturing system for automatic inspection [6].

Many researchers have drawn attention towards major challenges of the decade i.e. to design the product in such way that it can easily assembled and disassembled [7]. To understand the assembly and disassembly of a product, the issues related to the part separation, fastening method, part handling and variation of processing material, should be kept in mind. The current basics of DFA were established in 1980s by Boothroyd and was further polished by Swift and Miles in 1990s, which remained intact as they were first conceived [8].

Boothroyd and Dewhurst (BandD) are widely recognized as a founder of DFA field due to their work on automatic and manual assembly methods. To improve overall assembly time, they published the method that how to reduce the part count and explored handling and insertion technique. In 1982, a systematic approach to assess the design and its suitability for manual or automated assembly was proposed by another researcher named Redford. According to his methodology, design assessment could only be possible by assessing the assembly sequence, design efficiency and elimination of redundant parts which were based on criteria i.e. component essentiality, its relevant movement, material for functional purposes and assembly/disassembly possibility [9].

Due to advancement and improvement in rapid prototyping processes, the functional parts can now easily be manufactured directly by Additive Manufacturing (AM). To achieve the entire benefits that are offered by the AM, the new methods, guidelines and requirement have to be developed to grab the evolving inclination in the additive manufacturing and by achieving so the domain of "Design for X" is advanced to "Design for Additive Manufacturing (DFAM)" [3].

The concept of AM was coined in 1980's with the development of stereolithographic machine. However, most of the researchers believe that the additive manufacturing is the appropriate methodology among the all available manufacturing technologies [10]. Some researcher coupled the DFM concept with the AM and proposed the combine machining with the additive manufacturing. Similarly while addressing the problems associated with the AM, researchers considered the complexity related to the shape, material, orientation and functional [11]. The notable advantage of additive manufacturing over conventional machining processes is that it can produce highly customised parts economically without using the product-specific tool [12].

The scope of our research is to precisely integrate the existing knowledge of DFA and DFAM and transformed into the methodological framework to continuous assist the designer in each design stage. In particular, the available design information is highly scattered in nature and this disintegration highlight the inapplicability of existing design framework and tools to develop the AM parts. To address the DFAM, the scope extends towards the Part Decomposition (PD), Part consolidation (PC) and Topology optimization. Many researchers has applied DFMA methodology on small-size and mass produced products. To fill the gap, a Decision support System (DSS) for Large-Size (LS) assembly product has been developed by modifying the existing DFA guidelines, rules and framework, and provide a exemplary model for using the system rationally.

2. Literature Review

2.1 Method Related to Large-Size Product

During the last few decades, numerous design methodologies were developed by the researchers to not only optimize the design but also reduce the final cost of a product. Particularly, the sole purpose of those methodologies is to facilities the assembly operation, assembly cost and time, minimizing the part or variability, handling and fitting tools. In general, the large-size assembly product is highly customized and relatively low in production and it becomes challenging when applying DFA methodologies to such product. From a design perspective which involve costly resources and efficient planning, packing or assembly or joining issues, there is currently no efficient methodology or even a framework to address this unique class of product. To resolve the aforementioned issues, Ramirez and co-researchers have combined the BandD DFA and Lucas-Hull approach and applied it to the solar tracker which optimized the design efficiency by 20.4% and saved 22.8% of assembly cost.[13] Lindemann has developed its own Trade-off methodology matrix to screen out the part/product size at initial assessment stage. The core objective of matrix's assessment is to rank the collected parts and high-ranked part is then considered as a critical part. According to the researcher, the build orientation is significantly limits by the build chamber/ size of AM machines [14].

2.2 Design Method Related to Additive Manufacturing

To create objects in a layer by layer manner, Additive Manufacturing (AM) is now widely being used in manufacturing sector which has enabled to fabricate complex geometries and assemblies, without assembly process. This evolved manufacturing technique have a profound impact on a modern production industry and moving around two opposite objectives:[15]

1- Decreasing: Cost and Time

2- Increasing: Quality and Flexibility

In this ongoing manufacturing evolution, the Design for Additive Manufacturing (DFAM) concept have got the attention of many researchers. It is defined as "a design methods or tools based on the AM technologies, have a capacity to optimize the cost of product, its manufacturability and other life-cycle attributes of a product". In the literature, two discrete categories of DFAM methods were classified and discussed, which are as follow [16].

1- DFAM for Design-making or generating design alternatives

2- DFAM for Design assessment

The coming sections and, particularly our research work, mainly addresses the design-making strategies whose main focus will be on redesigning an existing product prototype. In additive manufacturing, a redesigning is a concept in which an original part/product/prototype changes into another shape while making it compatible for printing with AM technologies.

2.2.1 Part consolidation

A re-design method or strategy (as shown in Fig. 1) to fabricate the discrete multiple parts in such a way that it reduces the number of fabricated components/parts and eliminate the need of joining them into a consolidated single part, is known as Part Consolidation [17]. The concept is often use as a common design strategy by the design engineers in Design for assembly (DFA), Design for Disassembly (DFD) and DFAM. Number of publication based on PC have thoroughly discussed the re-designed structure of aircraft duct case, in which the engineering designers had reduced the 16 parts to the one consolidated single duct [18].

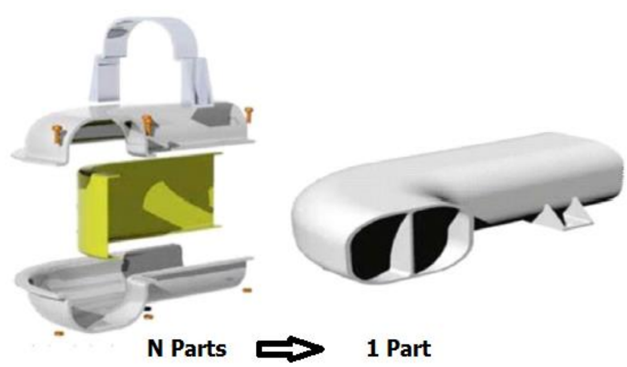

Fig. 1. Part consolidation [17]

2.2.2 Part decomposition

A re-design method or strategy (as shown in Fig. 2) to split a product into few or numerous pieces that leads to increase in number of parts and reduce the height of overall product and amount of support structure, is known as Part Decomposition (PD). According to Sara and Oh et al., the entire strategy to redesign a part is a complete opposite concept to that of part consolidation. The PD concept emphasizes on minimizing the process time including build-up and reducing the assembly processes [19]. In a recent study, Oh and co-researchers have studied 37 publications on PD concept under 5 major motives such as printability, productivity, and others and further categorized PD into decomposition, build-up and assembly issues. PD strategy has not been much highlighted as compared to the PC. According to the researcher's perceptive, part decomposition widely incorporates build and assembly related problems. This is because after decomposition, the number of parts and assembly surface or shape affect the orientation determination, packing/build process, connection/joining type and assembly sequencing (assembly issue).

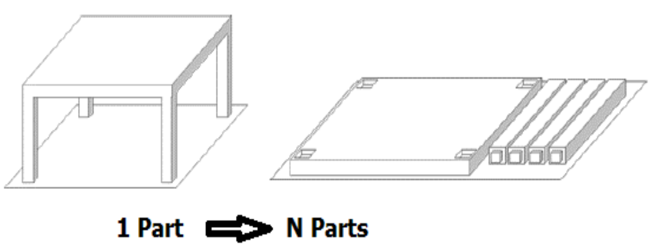

Fig. 2. Part decomposition [16]

2.2.3 Topology optimization

A re-design method or strategy (as shown in Fig. 3) with an objective to optimize the load condition and constrain for a given under-considered part/component is known as topology optimization. The result of redesigning lead towards the material reduction as well as optimized geometry structure which usually have a complex shape. The strategy is known as a part conversation. In high class aerospace industry, topology optimization is one of the most powerful redesigning tool for the designers and mechanical engineers. The methodology is also being applied to the automotive industry [20]. In a most recent work, Berrocal and Fernandez have manufactured the "Lever component and Housing part" by using Laser Beam Melting (LBM) technology with a goal of structural and topology optimization [21].

Fig. 3. Topology optimization [21]

3. Research Trends

Many researchers, as mentioned previously, have been working on multi-issue AM topics since decades and developed the methodologies that can help designer at preliminary stage, manufacturing stage or post-AM processing and to improvise the accurate, concise and better AM decision making. Based on a motive behind the research work, the reviewed literature is categorized into the six distinctive categories which are as under: Design Goal, Part Classification, Technical Feasibility, Functional Feasibility, Degree of Novelty, Economics Feasibility and Process Selection.

The table 1 (page no 7) shows the 23 publications (as a sample size) which are arranged under the six categories based on the motive behind our study. The percentage of different research topics considered in the literature is shown in Fig. 4. Based on sample-size it is got to known that the technical feasibility is discussed most by 95%, followed by part complexity (including shape and size) 86%, design goals 82%, degree of Novelty and economic aspects 73% each, process selection 69% while the functional feasibility is the least discussed research area.

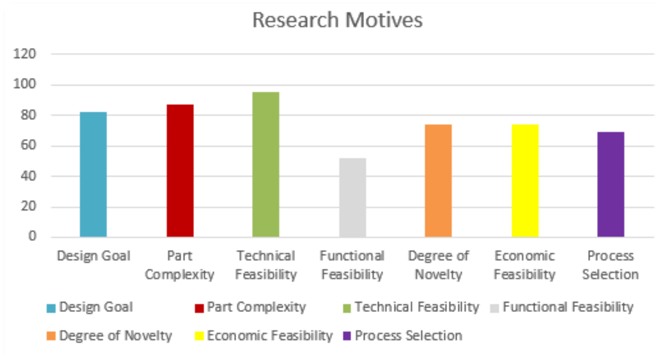

Fig. 4. Research motives

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Figure 5 is showing the in-depth detail of subcategories of each research motive. Three sub-categories come under the design goal i.e. part decomposition which is discussed most by 39%, part consolidation is a second popular topic in the current literature with 30% and least discussed topic is topology optimization (also known as light-weight part) with 21%.

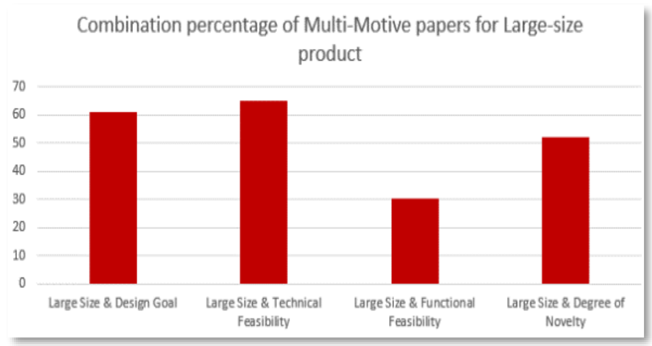

Fig. 5. Multi-motives

Similarly, based on a sample-size, research trend showing that the 17% researchers don't have either design goal they just worked with the other AM aspects and characteristics. It is clear in figure that the most discussed topic in the literature is the AM productivity (including the process time, material cost, and product quality) with the 87% research field area. In our research work, degree of novelty is placed in the re-design category (as shown in the table 1) because in previous research work most of the researchers are considered that only new design offers novelty. While in reality re-design and new design, both offered degree of novelty.

AM economic aspect and re-design are discussed 73% in the literature. The least discussed sub-motives are the Interchangeability aspects (category: Technical feasibility) and relative movement (category: Functional feasibility) i.e. 4% and 17%, respectively.

It is noted that the researcher has now begun to consider multi-objective motive in their research work. As per the research trend, the objective i.e. Large-Size part (as one of the base concept) in combination with other motive, is the least discussed area. The Fig. 6 shows the multi-topic which are dealing with combination i.e. large-size and technical feasibility is discussed 65% while large-size and design goal is discussed 62%, large-size and degree of novelty 52% and large-size and functional feasibility is discussed 30%.

4. Research Methodology

To design new framework that adequately considers AM processes, a thorough understanding of existing design guidelines, knowledge about AM processes and manufacturing capabilities is necessary. Researchers and engineering designers have established their own models or methods that all stand by the overarching theme of DFA, DFM and DFAM. Similarly, researchers have set their own guidelines for the designers to follow during the various design stages regarding part count reduction, minimizing assembly operation, weight reduction, easy to make and component optimization.

The primary focus of our research work is to merge and modify the existing Design for Assembly (DFA) methodologies and rules and put forward a comprehensive decision support system for LARGE-SIZE products. The goal is to assist those who are interested in re-designing methods, packing problem, design for assembly and assembly sequencing. To this end, as already discussed that the data about part classification especially for large size product, functional and technical feasibilities and for the others aspects, are highly scattered in nature. In our methodology, we first gather/consider the relevant information, this is to be called an **information phase**, which is needed for AM (especially for large size) before starting with the production. Once done with the information requisite, there are numerous approaches to redesign the parts. After the finalization of first phase, the next phase is **parameter assessment** which will help/assist the experts in screening out the possible design guidelines and limitations. The findings were used to establish a foundation for developing the decision support system.

4.1 Information Phase

1. As Part Classification

a. Does it be considered a large-sized?

b. Does it be considered a long-life?

c. Is it geometrically complex?

d. Does it have/made-of different material from the rest?

2. Functional Feasibility

a. Does part/component(s) have a relative movement?

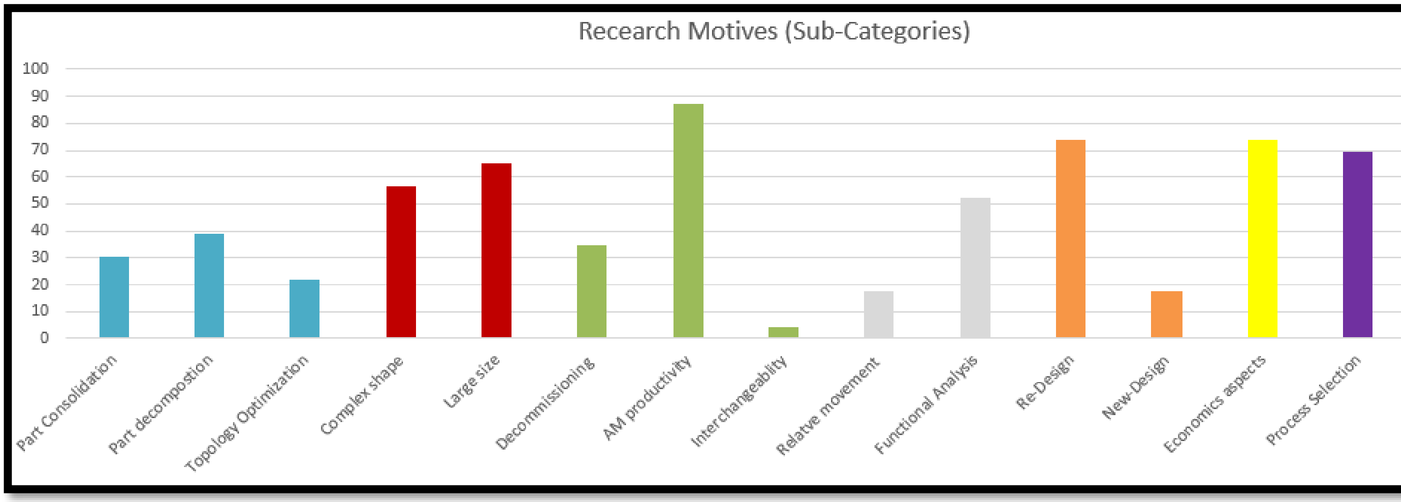

Fig. 6. Research motives (sub-categories)

b. Is this part (under-considered) necessary for correct functioning of product as a whole?

c. Does changing/improvement of design of under-considered part effect product performance?

d. What type of connection method is required (or is any required)? (Example: Riveting, Fasteners or Other)

3. Technical analysis for Pre-AM processing

a. For maintenance: is the part necessary to remove?

b. Is it interchangeable?

c. Is it easy to disassemble the part/component(s)?

d. Is it a base part i.e. where the rest are assembled?

e. Does it need to be separate from other parts?

f. Does it require de-commissioning of whole assembly?

g. Does it require large assembly time?

4. Logistics and Tooling aspects

a. Is any special transportation required?

b. Does it require special tool for assembly or subsequent assembly?

5. Fabrication and Economics aspects

a. Does it have influence on AM productivity (Build time)?

b. Does it has direct impact on manufacturing cost of a product?

6. Degree of Novelty

a. Does it require a new design or Redesign (either assembly or Single part)?

4.2 Parameters Assessment Phase

Information that deals with the part size, complexity, life and material variability are categorized under part classification. Assessing the part attributes can be a time consuming, as in many cases in-depth detail about part candidature is required for processing. Therefore, the mentioned section tries to reduce the efforts for information collection at a preliminary design stage. For AM pre-process planning requirement, various publications are reviewed and have derived the below-mentioned rule template. (Table 2)

The functionality section involves the information that addresses the mechanical and functional aspects and design of joints. For functional feasibility, various publications have been reviewed and a summary of process parameters is provided in Table 3.

Table 1

Research Publications

Reference	Design Goal			Part Complexity		Technical Feasibility			Functional Feasibility		Degree of Novelty		Economic Feasibility	Process Selection
	Part consolidation	Part decomposition	Light-weight part	Complex shape	Large-sized part	Decommissioning aspects	AM productivity	Interchange-ability aspect	Relative movement	Functional analysis	Redesign	New design		
[22]		✓		✓	✓	✓	✓			✓	✓		✓	✓
[13]	✓			✓	✓	✓				✓	✓		✓	
[21]			✓	✓			✓		✓	✓	✓			✓
[23]	✓		✓	✓	✓		✓			✓	✓		✓	✓
[19]		✓			✓	✓	✓				✓		✓	✓
[24]	✓	✓			✓		✓				✓	✓	✓	✓
[25]		✓		✓	✓	✓	✓			✓	✓			
[26]		✓		✓	✓	✓	✓				✓		✓	✓
[27]		✓		✓	✓		✓				✓	✓	✓	✓
[28]	✓			✓			✓		✓	✓	✓	✓	✓	✓
[29]				✓			✓				✓		✓	✓
[30]								✓		✓				
[14]			✓	✓	✓		✓		✓	✓	✓	✓	✓	✓
[17]			✓	✓						✓	✓		✓	
[31]						✓	✓						✓	✓
[32]					✓	✓	✓				✓			
[33]		✓			✓		✓						✓	✓
[34]	✓			✓			✓			✓	✓		✓	
[35]							✓						✓	✓
[36]	✓				✓		✓		✓	✓				✓
[37]		✓		✓	✓		✓							✓
[38]	✓				✓		✓			✓	✓		✓	

The physical realization of assemblies in term of interchangeable into one another, decomposition, ease for disassembly and assembly time are categorized under technical aspects. The attributes for the disassembly and interchangeability, the key rules and technical characteristics are listed in the table 4. To make it more adaptable for large size AM product, logistics and tooling constraints are incorporated section 4 (described on page no 6). Logistics factors usually considered for big parts where the component can be added and transported together. This may reduce the on-field assembly time.

The information that addresses the material fabrication cost (support volume and part volume) and processing time (build time) are categorized under fabrication and economic aspects section. Due to the expanding knowledge in the manufacturing techniques, it has now become challenging for engineers and designers to select technically and economically viable manufacturing process as it considers wide range factors such that applicability, product performance, material selection, and manufacturing cost etc. (Rule: cost and time effective build orientation).

Finally, the information that deals with the part designing aspects is placed under the degree of novelty section. (Rule: Define by designer)

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5. Proposed Decision Support System for Large Size AM Product

To improve the decision-making efficiency, the designers need each and every aspects of the AM process in the mind. The proposed system provides more accurate path to follow during part generation. The comprehensive decision support system is shown in Fig. 7. It consists of 6 key elements which are implemented in the sequence as per the requirement.

- Conceptual design goal clarification
- Requirement clarification
- Concept evaluation and feasibility analysis
- Design validation
- Fabrication and economics feasibility aspects
- Post-AM assembly process

Table 2

Rule Template for AM Pre-Planning Requirement

Attribute	Value
Large Size Part	Larger Than Build Envelope (Depending on availability of machine equipment) 250*250*300 (Some researcher)
Long Life Part	Part Aging /Cycle (5-15 yr)
Geometrically Complex	Undercuts Cavities/Voids Hollow spaces Sharp Contours Complex lattices Structure Intricate Internal Structure Overhang (which either require support structure – 45' degree or more)
Material	Either different from rest of part

Table 3

Effects of functional Parameters

Attributes	Functional Parameter	Rules	Key parameters	Comments
Relative Movement	Transmitting Controlling Constraining the movement	Functionality-based Decomposition Feature-based Decomposition Free-form decomposition	- High Stress	- Solid Fill
			- Low Stress	- Maybe solid Fill - Lattices (Light Weight)
			- Contours with small/sharp corners	- Solid Fill due to Stress Concentration
Connection Type	Depends on Design Consideration and Improvement	Discrete Fastener Adhesive bonding Interlocking base Connection methods	-	-

Table 4

Technical Aspects for AM Pre-Process Planning

Attributes	Technical characteristics	Key Rules	
		Top- down	Bottom-Up
Removing for Maintenance Disassembly and other Etc.	DFA – Concept	Level-set based partitioning 1- BSP 2- Heuristic Algo	Feature-based free form partitioning
Interchangeability	Data-Driven Approach	-	-

6. Case Study

A case study of RBX1 6-axis Robotic arm has been carried out so that to implement our proposed DSS. The RBX1 is a multi-purpose robot having a multiple industrial application. Based on the objective i.e. improving the design, assembly/disassembly problem, ease of maintenance and other derived aspects, the system will be validated by using RBX1 robotic arm. The studied robotic arm is composed of more than 50 parts and sub-components, which are assembled by the fasteners as shown in the figure 8. An original robotic arm is made of ABS material. The robotic arm is based on the eight major assembly sections, which are as: Base plate, Base/Waist (where all modules/parts are assembled), Shoulder, Upper arm, Elbow, Forearm, Wrist and Gripper.

6.1 Case Study – 1 (Part Decomposition)

With an AM, this part is redesigned using part decomposition concept by using the proposed DSS in this research. The problem in under-considered part is that the part is too large and difficult to fabricate in a single-go. As seen in figure 8, the part was failed during the fabrication stage as it was lost the build strength due to the material inefficiency and size complexity. So, after assessing the problem, the user enters into the next phase of the decision system i.e. "conceptual design phase". As we know, the robotic arm is comprises on a number of separate parts/components, the user is directed to the "concept evaluation and feasibility concept" module which is composed on a "CAD model calculation and functional analysis". After the requirements list, the next step is to build a CAD model to calculate the computational load condition, structural response or performance of product. For such a complex geometry of part, FEA model is usually applied to analyse the stress and displacement distribution.

Fig. 8. RBX1 robotic arm.

Fig. 9. Part failure

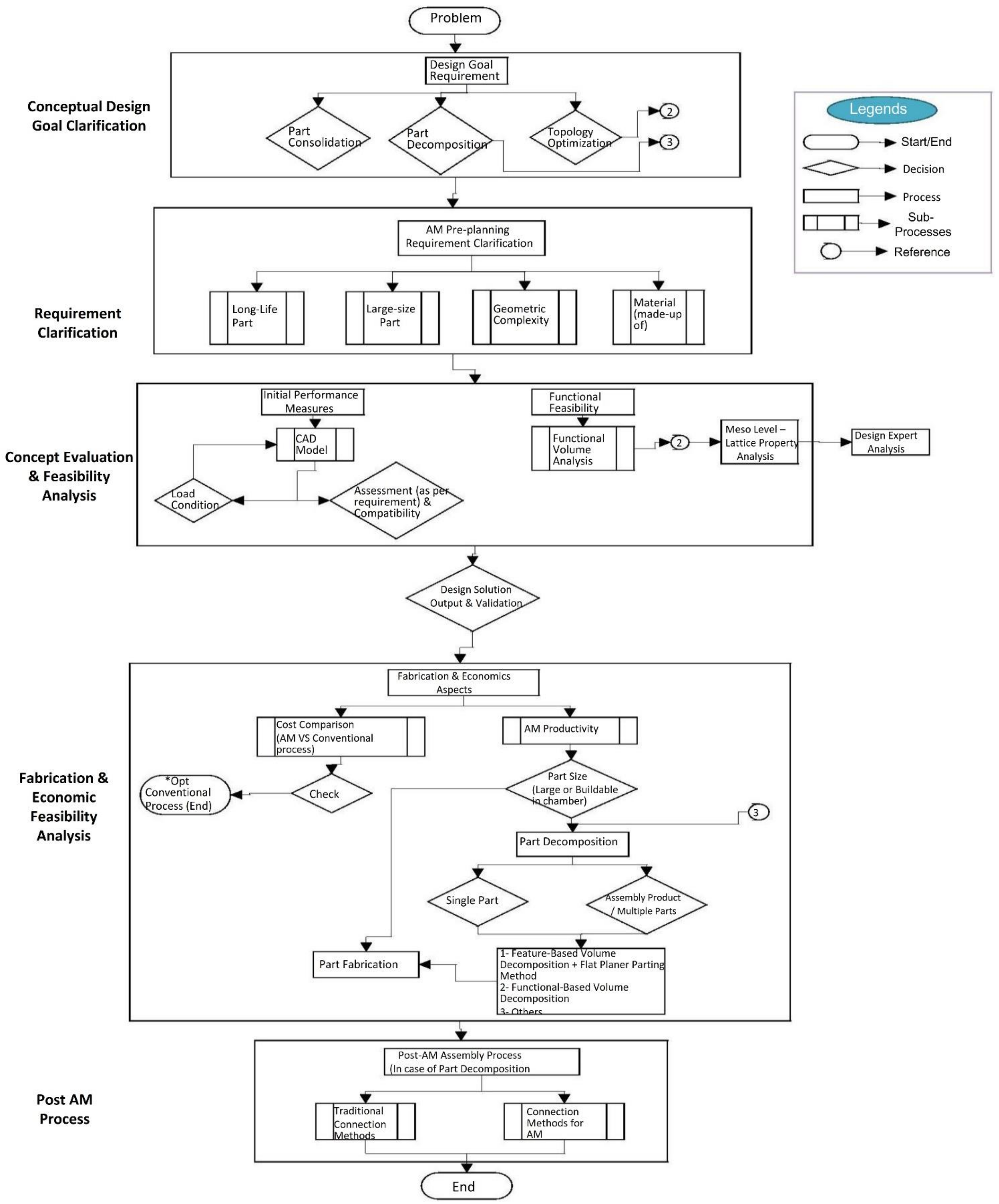

Fig. 7. Proposed Decision Support System for Large-Size AM Objects

To create design conformity, the next phase of the system is provided with the specific design rules and CAD functions. At this stage, the user is also advised to carry out the functional analysis which is only possible after defining the functional surface(s). The functional surfaces are defined in fig. 10. The functional requirements (FRs) of these surfaces is to provide a support to the neighbour parts. To reduce the load at the surfaces, functional volumes (functional surface area) is always packed/filled with the dense/compact material. Similarly, the surface/volume where the stress is high will be filled with the dense material while the lattice structure approach can be used for the functional surfaces/volume where stress is low. Likewise, while fabricating a part, a solid material should be used for a surface having sharp corners or contours.

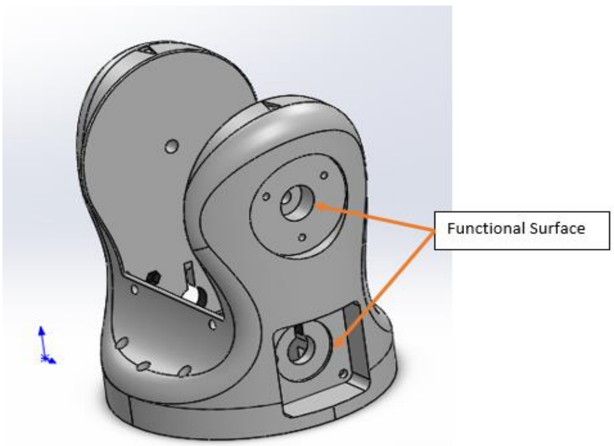

Fig. 10. Functional surface

The result of this phase incepted a new product. After the design validation process, the next phase is deals with the fabrication and economics aspects. In fabrication module, the part size is assessed and comply with the decomposition rules to fabricate the required part. While in the economic stage, user can compare manufacturing cost of a product. (Fig. 11)

6.2 Case Study – 2 (Part Consolidation)

An original robotic arm's forearm and elbow made of ABS material is shown in fig. 12. With an AM, these parts is redesigned using part consolidation concept by following the similar steps as of case study-1. The elbow is composed of two parts which clamp/assemble together to form a single part. (Fig. 12) Due to multiple parts, it requires large built time which is in contradiction with DFA objectives. So, to minimize the built-time and part count, part consolidation concept is applied on the mentioned parts.

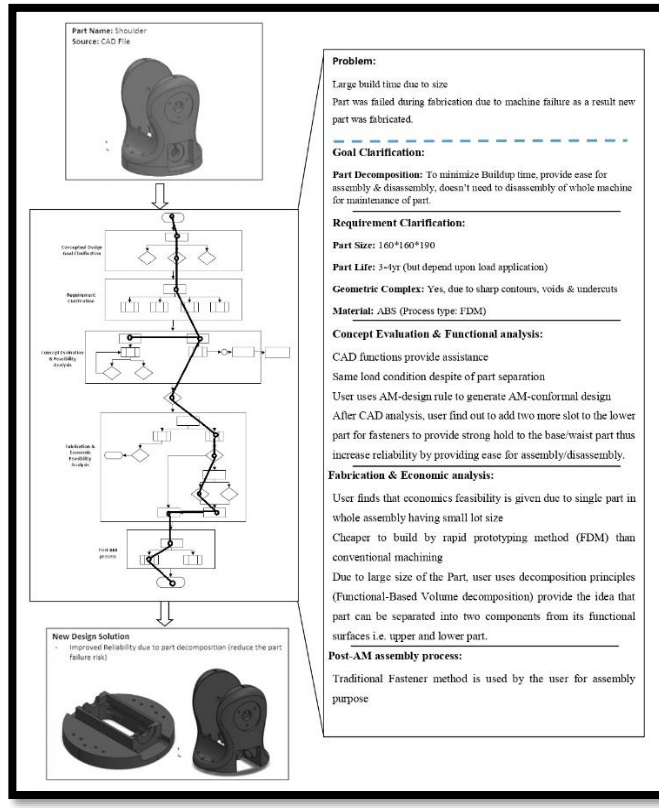

Fig. 11. Example: implementation of proposed DSS (part decomposition).

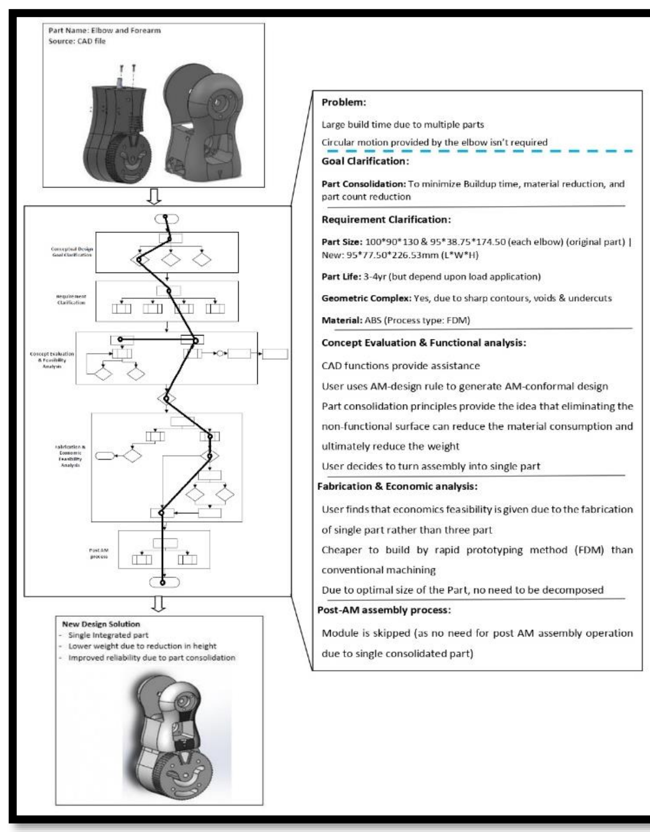

Fig. 12. Example: implementation of proposed DSS (part consolidation)

7. Discussion and Conclusion

This research presents a new and simplified approach towards design for assembly, which is based on existing knowledge and research work. The proposed decision support system is mainly addressing the critical additive manufacturing decisions and DFAM framework by providing a structured guidelines on AM-planning, functional and technical parameters. The developed decision support system is mainly designed to provide an integrative decision-making for tackling the large-size part fabrication. The primary goal of the decision system is to address the challenges i.e. when and how to use additive manufacturing while designing and fabrication of part/product.

Similarly, our DSS also draws the attention toward the whole AM product i.e. design, assembly and connection procedures. Similarly, an equally important objective of the decision system is to provide the guidance to the designers to make the correct decision during the design process. The system not only addresses the Part Consolidation but also the Part Decomposition and Topology Optimization. By thorough implementation of the decision system, a significant number of design changes and built orientations can be identified that would enable a better throughput in term of assembly time and cost saving.

In the case studies, the developed DSS is used twice on an existing product. Robotic arm is redesigned by using the proposed DSS. The size of part is too large and it took almost 27hours to build. As described, the part failed during the fabrication stage due to size complexity and material strength. With the AM process, this part was re-designed with the part decomposition method by using the proposed DSS framework. Because of assembly and functional requirements, the original part was decomposed into two parts which allows ease in assembly process, less material waste, easy to disassemble for maintenance having the same performance. Moreover, it consumes less time in term of fabrication.

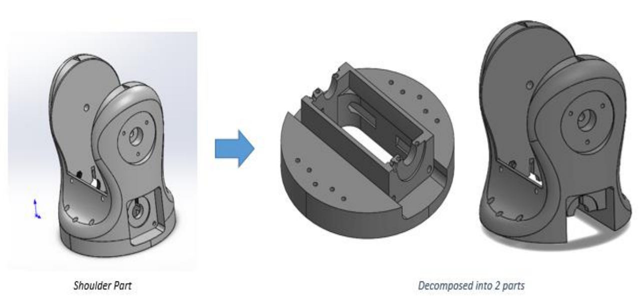

Fig. 13. Part decomposition

Similarly, parts such as elbow and forearm are redesigned by opting part consolidation method via proposed DSS framework. Because of assembly requirements, 3 parts (elbow-2 parts and forearm-1 part) are fabricated separately and assembled. The drawbacks of this original design is that it take excessive assembly operation, more part count, material cost and large build time due to multiple parts. By evaluating the functionality and other features, these parts are redesigned into single consolidated part by excluding non-functional surface of elbow parts.

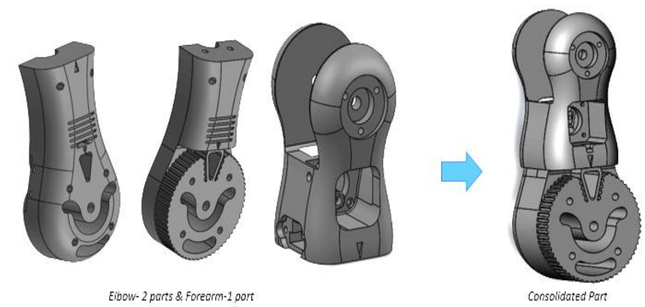

Fig. 14. Part consolidation

8. Limitation and Future Direction

It is obvious that the extensive validation of our DSS framework is required as one or two examples are not enough to proof the quality of framework or its content. Currently, being implemented as computer-based simulation, the proposed framework identifies the possible design alternatives or improvement to the existing product (Robotic arm – example as discussed). For the future research, more case studies related to the large-size part should be performed to check the applicability of the proposed decision support system. Moreover, for future perspective, to address the DFA comprehensively for a product having multiple parts, the production planning issue must be included in the decision support framework.

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