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An Assembly-Level Design for Additive Manufacturing Methodology

Hugo Rodrigue¹, Mickaël Rivette¹

(1) : École Polytechnique de Montréal
2500 chemin de Polytechnique, Montreal, Canada
E-mail : {hugo.rodrigue,mickael.rivette}@polymtl.ca

Abstract: Design for Assembly and Design for Manufacturing methodologies aim at making products easier to fabricate and assemble based upon the limitations of current processes, however due to the capacities of Rapid Manufacturing processes these limitations no longer apply and new possibilities aren't taken into account. This paper describes a design methodology for Rapid Manufacturing through which the user can consolidate and optimize a product using the capacities of Rapid Manufacturing processes. The proposed methodology is then applied to a mechanical assembly.

Key words: DFAM, Rapid Prototyping, Product Design, Layered Manufacturing, Assembly Conception

1- Introduction

Rapid Manufacturing (RM) is defined as the direct production of finished goods through additive fabrication processes that eliminate tooling [W1]. These processes use layer-wise manufacturing and which makes it possible to fabricate complex internal and external features that aren't possible with traditional tool-based manufacturing. Furthermore, the manufacturing cost isn't function of this complexity, but rather of global criteria like volume and build direction [AA1]. The elimination of tooling in the manufacturing process means that design methodologies based around the limitations of tooling are no longer valid and that "the possibilities for design are limited only by the design tools and one's imagination" [W2]. New capacities for RM are also being developed, such as the possibility to build multiple parts with relative motion in a single step [AB1]. Thus, RM allows for new design freedoms and the optimization of products further than previously possible.

The selection of material for RM processes has been demonstrated for many materials such as aluminium, steel, titanium, copper, nickel, silicon carbide composites [EB1], colmonoy-6 [PJ1] as well as many others. In addition it is possible with some RM processes to build multi-material parts. However not all of them are multi-material compatible and research is done on increasing multi-material capabilities

between two specific materials such as nickel and titanium [DB1], tungsten carbide and high speed steel [RR1] and copper and steel [KP1].

However, no design methodologies have been developed for RM even if there will be changes required in the way designers and engineers practice design. An example of this shift in paradigm is provided in [R2]. This article demonstrates how engineers at Bell Helicopter were having trouble designing a cool air duct with RM processes due to their notes for the design of a duct being related to limitations of design processes.

The design process is divided in two major steps, conceptual design and embodiment design. Design methodologies apply to a certain portion of these steps. Embodiment design takes the product from a concept to its final design configuration. The purpose of this design methodology is to be able to incorporate the advantages of RM in the design embodiment phase of the design process by consolidating parts in the assembly design and by optimizing the parts.

2- Related work

2.1 – Methodologies related to RM

In [MR1] a method is presented to assess the possibility of using RM for manufacturing versus traditional methods using artificial intelligence tools. In [RH1] a methodology to determine which components of a multicomponent prototype could be manufactured using RM processes through a graph-based representation of the part's features and fuzzy logic. Another methodology for hybrid multicomponent prototypes is presented in [KM1] using an octree decomposition of the tool followed by an evaluation of the machinability of each octant using a machinability index. These methods help make decisions regarding the fabrication of parts with RM, but they do not help the user take advantage of layered manufacturing during the design process.

In [R1] a design methodology is developed to implement mesostructures, structures with hundreds of thousands of intermediate shape elements forming the structures such as

lattices, into a design through the capabilities of RM. This is done by choosing a cell size and mapping it into the design area following by a shape optimization procedure to determine the diameter of the lattices. While this methodology is applicable to one implementation of RM, it does not help the user determine when to use this type of structure or to use any of the other advantages of RM.

2.2 – Design methodologies

The Lucas DFA Evaluation Method [RC1] is a knowledge-based approach based on a point system to measure the ease of assembly of a product. Using this system it is possible to assess where improvements can be made in the product with regards to assembly, however it doesn't look at improving the product further than saving time on assembly.

The extended Hitachi Assemblability Evaluation Method [OI1] evaluates ease of assembly through a modeling of the assembly process and gives an assemblability score. With this score the user can assess how the assembly process could be eased, but like the Lucas DFA method it doesn't help to improve the product further than saving time on assembly.

The Boothroyd-Dewhurst DFMA Method [BK1] is a method comprising both a DFA and a DFM method. The DFA part provides a method through which the user first analyses the cost, time and ease of assembly. Afterwards the user identifies essential parts and tries to bring the number of parts closer the number of theoretical parts following redesign guidelines. This is followed by the DFM portion of the methodology in which the user is guided to choose an appropriate process for manufacture and to modify the parts based upon the limitations of this process in order to reduce the cost of manufacture. The assembly guidelines of the Boothroyd-Dewhurst method are appropriate for all types of assembly, but the method to determine the theoretical minimum number of parts does not take into account the capabilities of RM. However the DFM method is based around the limitations of tooling and as such aren't appropriate for RM processes.

[S1] does an overview of different part elimination strategies to consolidate designs and ease assembly that is applicable at the conception phase, and is thus also applicable to any type of manufacturing processes.

The TRIZ method [TZ1] helps solve contradictions within a system using four different tools used for different types of problems, some analytic others knowledge-based. These tools usually help eliminate or diminish negative elements in a design or come up with innovative concepts. However this method is more of a complement to other methods used to come up with new concepts rather than a design methodology.

Axiomatic Design [S2] provides a methodology for analyzing the relationship between customer needs, functional requirements, design parameters and process variables. Through design principles, called design axioms, the method helps the user identify designs that lead to high quality products. However this method doesn't consider manufacturing processes and its various advantages, so it aims at obtaining an optimized concept, but doesn't look at the design embodiment phase.

2.3 – Optimization methods

Optimization methods are numerical methods to optimize objective functions of a product within defined constraints. While analytic and knowledge-based methods help bring forth new ideas and bring the user to realize certain possibilities, a numerical portion is necessary in order to optimize certain portion of a product's functionality.

The literature on optimization of structural and mechanical systems is extensive and beyond the scope of this research, therefore the literature that will be presented are a few of the most prominent methods being detailed in [A1], also how to setup such a method is developed in [MB1]. The optimization methods that are presented and used are those that optimize a characteristic, or many, of a part against shape and material distribution although other methods may be applicable to manufacturing with RM processes.

The first of these methods is shape optimization, which [BB1] presents as deforming and modifying the admissible shape, which begins as a defined domain, in order to comply with a given cost function that needs to be optimized. So given design requirements the method will displace boundaries to optimize a characteristic.

The second optimization method that is looked at is topological optimization. This method is detailed in [BS1] and aims at constructing an optimized geometry knowing only the applied loads, the support conditions, the boundaries of the volume of the structure and design restrictions such as location of holes or solid areas.

The last is multidisciplinary design optimization in which there are results in many disciplines for the optimization of the part, whether the design variables are shared or not. These results are then compared and evaluated to obtain an optimal design taking into account more than one discipline.

These methods are particularly suited for RM as they result in optimized geometries that are often complex and need to be adapted for traditional manufacturing processes, but can easily be manufactured using RM processes.

3- Definitions

In order to be able to properly describe all elements of the product while not getting confused between different naming schemes it is important to have definitions that are standards within the industry. The methodology borrows the definitions from the Core Product Model [FF1] developed the National Institute of Standards, which describes a structure for product data creation. The definitions provided in the CPM help structure all the information pertinent to the product throughout all stages of the products life. The definitions from CPM were used for artifacts, features, functions, transfer functions and flows. New definitions were defined to describe elements not described within the CPM. These definitions are parameters, external features and the environment.

Artifact: An Artifact represents a distinct entity in a product, whether that entity is a component, part, subassembly or assembly.

Feature: A Feature is a portion of the artifact's form that has a specific function assigned to it.

Function: A Function represents one aspect of what the artifact is supposed to do. The artifact satisfies customer needs and/or engineering requirements largely through its function. The term function is often used synonymously with the term intended behavior.

Transfer Function: A Transfer Function is a specialized form of Function involving the transfer of an input flow into an output flow. Examples of transfer functions are "transmit" a flow of fluid, current, or messages, etc., or "convert" from one energy flow to another or from a message to an action.

Flow: A Flow is the medium (fluid, energy, message stream, etc.) that serves as the output of one or more transfer functions and the input of one or more other transfer functions. A flow is also identified by its source and destination artifacts.

Characteristic: An attribute of the product that can be measured quantitatively.

Parameter: The quantitative measure of a characteristic.

External feature: An External Feature is a portion of the environment with defined boundaries.

Environment: The Environment is everything that lies outside of the boundaries of the features and external features of the system.

4- Method

In this section the methodology developed for designing parts and assemblies while taking into account the advantages of RM processes is introduced. These advantages include:

- **Shape complexity:** There are no limitations to the possible shapes with RM, such that optimization of material and characteristics is further possible than with traditional manufacturing.
- **Material complexity:** Due to material being processed one point at a time it is possible to vary the material between points and thus create multi-material parts.
- **Cost function:** The cost function of manufacturing is not a function of product complexity, thus complexity can be added at no extra cost.

The methodology begins at the end of the conceptual design phase and begins with a consolidation phase followed by an optimization phase. The methodology is presented as a flow chart in figure 1. Each section of the methodology is further detailed below.

4.1 – Design concept

This is the result of the conceptual design phase.

4.2 – Draft of the assembly

This is a draft of the selected concept. It may have already been done as part of the design concept depending on which methods have been used to come up with the concept.

The draft should have all the necessary parts and connectors for the design to work, but there is no need to have further information.

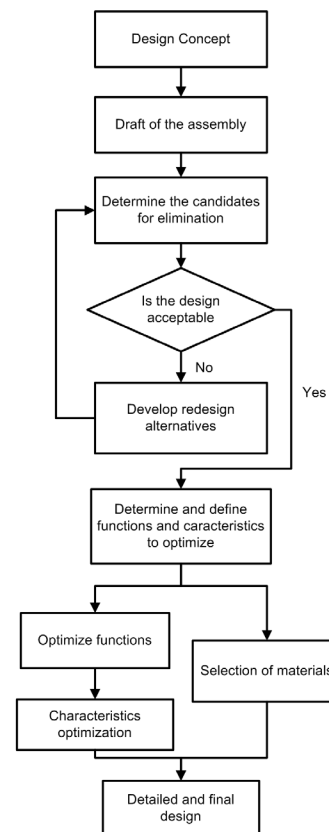


Figure 1: design methodology.

4.2 – Determine the candidates for elimination

The first step is to determine which parts of the assembly can be consolidated by determining which parts aren't theoretical parts. A theoretical part is defined as a part that cannot be eliminated. Using layered manufacturing it is possible to further reduce the number of theoretical parts compared to the candidates for elimination guidelines set in the Boothroyd-Dewhurst method [BK1], however the method is easy to apply and the rules easy to modify to take into account the current capacities of RM as well as future ones.

The system of questions set forth by the Boothroyd-Dewhurst method is used for determining the candidates for elimination and the necessary changes to take into account the possibilities of RM are implemented. When taking into account the multi-material possibility of RM processes it is possible to remove the criterion 'Must the part, for good reasons, be made of a different material' from the candidates for elimination criteria of the Boothroyd-Dewhurst method. Therefore, the criteria for a theoretical part have been modified to reflect these possibilities and are presented in the form of a decision tree in figure 2. In addition, once movable parts become a possibility to be taken into account during the design phase the criteria 'Does the part need to move relatively to all connecting parts' can also be removed such that the only reason for a part to be theoretical is if it fundamentally must be made separate for maintenance or assembly.

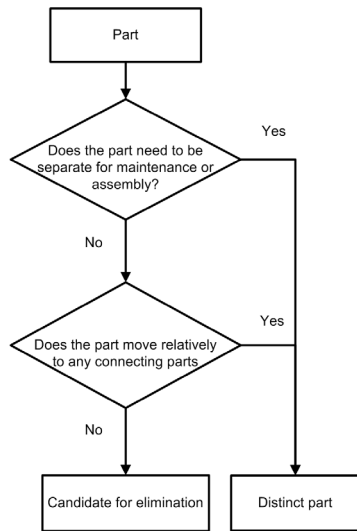


Figure 2: candidates for elimination.

Also, it is important to note that ‘yes’ answers should only be given for fundamental reasons. A shaft must move relatively to its support in order for the assembly to be functional, a bearing doesn’t.

4.4 – Is the design acceptable

For a design to be considered as acceptable all candidates for elimination remaining must have been weighted against redesigned alternatives and considered as the best design. If an answer of yes is given, it is considered that the design has been consolidated as much as possible, however if the answer is no redesign alternatives must be considered.

4.5 – Develop redesign alternatives

Consolidate parts while keeping in mind the following guidelines

- Two or more connecting parts can be consolidated by uniting the interfacing surfaces in order to create a single part.
- Consider exchanging moving parts for equivalent non-moving parts (i.e. bearings for bushings.)
- Fasteners are eliminated if the parts it connects are consolidated, so they can be overlooked.
- When consolidating, verify that by doing so you aren’t making other parts impossible to assemble, if so make it one of the goals of the re-design.

Afterwards re-design the pieces by consolidating the pieces that can be directly consolidated and think of a new design to consolidate the others that doesn’t prevent the assembly of other parts while keeping in mind that it is possible to realize any shape.

4.6 – Determine and define functions and characteristics to optimize

The first step is to determine all functions of the artifact and to determine which ones are simple Functions and which ones are Transfer Functions.

For regular functions define what the function is and what its associated feature is.

For transfer functions determine the artifact from where originates the flow, even if external to the analyzed artifact, and where it exits. Build a directed graph with the origins on the left and the exits on the right and position all artifacts as well as external features that the flow traverses as nodes, and all flow between artifacts as arrows between nodes. Determine which flows have to be minimized and which have to be maximized in order to lead the flow to the desired exit. The flows are numerated for ease of use later in the methodology.

An example of this graph is given below in figure 3. In this example the flow has to be lead from the source to the second exit of flow.

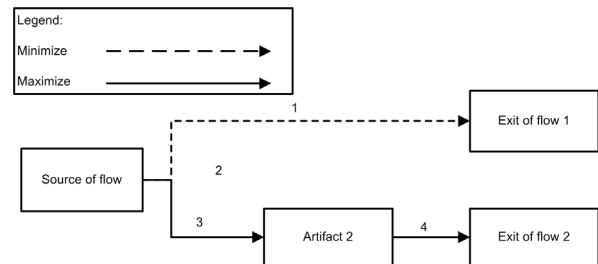


Figure 3: representation of a transfer function.

For regular functions, determine which ones need to be optimized. One can also choose to optimize all functions.

For transfer functions, determine which flow between nodes needs to be optimized. One can also choose to optimize all flows.

For characteristics, the designer needs to determine which characteristics of which artifacts should be optimized. The designer can also choose all artifacts to be optimized.

4.7 – Functions optimization

The method to optimize functions is based upon the process for creative problem solving within the TRIZ methodology in order to help the user determine the important factors to analyze in the optimization. The essence of the method is to approach the problem in a manner where it is easier to find potential solutions to a problem than simply asking how to solve the problem, thus an indirect route is taken. This is done by taking a subversive approach to the problem as it is easier to rationalize by destroying than by building [M1]. The steps in this method are illustrated in figure 4 and the application of the method to each type of function is described below.

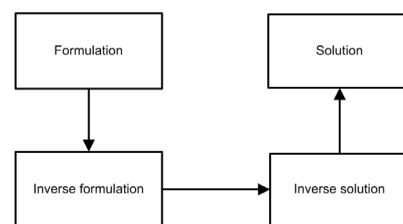


Figure 4: method for the optimization of functions.

4.7.1 –Optimization of regular functions

The method is established as following for a regular function:

Formulation: In this step the failure or underperforming modes to avoid are determined. For example ‘we want to avoid too much friction with the connecting element.’

Inverse formulation: In this step the question how to reach the inverse of the formulation determined previously is posed such as to amplify the problem. So for the provided example the inverse formulation is ‘how do we increase the friction with the connecting element?’

Inverse solution: Solutions to the inverse formulation are found and listed. This also means that the solutions found in this step will worsen the problem. For the example one of the solutions could be: ‘to increase the coefficient of friction of the feature.’

Solution: Potential solutions to the initial formulation are found taking the inverse of the inverse solution. The solution to the example could be ‘reduce the coefficient of friction of the feature.’

4.7.2 – Optimization of transfer functions

The method is established as following for transfer functions:

Formulation: In this step the transfer function is formulated by stating whether the flow is to be minimized or maximized and what is artifact A the flow originates and to which artifact B the flow B goes. For example ‘we want to maximize the transfer flow from artifact A to artifact B.’

Inverse formulation: The inverse of the formulation found previously is posed as a question on how to amplify the problem. In the example the question would be ‘how can we minimize the transfer flow from artifact A to artifact B?’

Inverse solution: As in the regular function the possible solutions to the inverse formulations are found. A possible solution to the example could be ‘decrease the conduction surface area to artifact A to artifact B.’

Solution: This is the inverse of the inverse solution in order to find a solution to the initial formulation. Taking the inverse in the example would result in ‘increase the conduction surface from artifact A to artifact B.’

4.7.3 – Implementation of solutions

Find out how to implement the solutions found in both the optimization of regular functions and transfer functions if they are straightforward and non-conflicting. If there is a conflict between the two functions determine how a compromise could be made, either by local properties or by choosing one over the other.

For external features the implementation of solutions is done on artifacts of the assembly. If the solutions found have more than one way to be applied analyze if there is a solution that would either be better than others for the particular function or if there is a solution that can help with the optimization of other functions.

4.8 – Characteristics optimization

In the previous section ‘Determine and define functions and characteristics to optimize’ the artifacts to optimize along with their characteristics have been defined. To realize the optimization of these characteristics commercial Computer-

Aided Engineering software is used. Two programs were tested within the scope of this research, namely Altair Hyperworks and Ansys Workbench. However many more commercially available software are able to do this type of optimization such as MSC Nastran.

Prior to setting up the optimization the general problem is to be defined, namely by defining the material, the loading conditions and the constraints. Afterwards the variables relating to the optimization are to be defined:

Design variables: The parameters of the system that will be modified during the optimization in order to obtain the optimal solution and their allowable range.

Objective: This is the characteristic of the system to be optimized and the direction of the optimization.

Design space: The volume in which material can be assigned during the optimization.

Non-design space: The volume in which material is assigned and that cannot be removed during the optimization.

Design constraints: Bounds on the characteristics of the system that need to be satisfied for the design to be acceptable.

Afterwards a mesh is applied to the design and non-design space, the mesh should be fine enough such that the numerical solution is a valid representation of an actual solution by not featuring many jagged edges.

Due to the meshing of the parts the solution found with the software may feature many jagged edges which will need to be post-processed in order to obtain a smooth solution.

4.9 – Selection of materials

The first step is to determine the materials the RM machine to be used is able to employ and the possible combinations for multi-material. Afterwards these materials are assigned to the various features and artifacts. The selection of materials is left to the designer, he has to keep in mind the material properties to maximize or minimize found in the functions optimization section while choosing appropriate materials and verifying compatibility for multi-material parts.

4.9 – Selection of materials

This is where the proposed methodology ends as it brings nothing new to this portion of the design process. In this section the sizing of components and engineering drawings of the product are completed.

5- Example

The design methodology is illustrated by applying it to a planetary gear system. The results of the design concept and the draft of the assembly are presented in figure 5 as the starting point for the developed methodology.

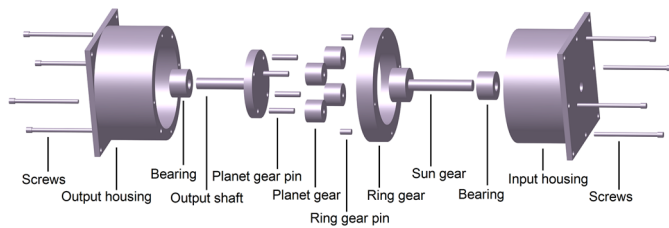


Figure 5: representation of the elements of the assembly.

The functioning of the mechanism is displayed in figure 6 and the gear ratio is function of the radius of the sun gear and the ring gear.

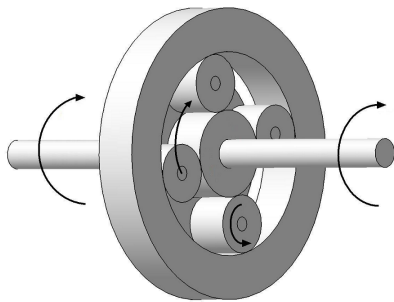


Figure 6: mechanism of a planetary gear system.

The design is intended to have an engine holding the input housing part of the casing and to have a motor held in cantilever on the other side. The primary goals of the design are to minimize the transfer of heat from the engine to the motor and to reduce the overall weight while complying with mechanical loads. The motor weighs 12 kilos and the engine outputs 14 N·m of torque.

5.1 - Determine the candidates for elimination

The criteria to find the candidates for eliminations are applied to all parts of the assembly. However the details of the method are only shown for the sun gear.

The first criterion is whether the part needs to be separate for maintenance or assembly. However this part does not need to be separate for any of these reasons. The answer to the criterion is 'no'. The second criterion is whether the part needs to move relatively to all connecting parts. On one end the sun gear is connected to each of the four planet gears and it is a base principle of planetary gear system that they must have relative movement. On the other side the sun gear is connected to the bearing, however a bearing's task is to separate objects with relative moment and cannot be merged with the bearing in order to maintain the relative movement. Once again an answer of 'no' is given. As the answer is 'no' to both criteria the part is defined as a theoretical part.

5.2 - Is the design acceptable

There are many candidates for elimination left and no design alternatives have been considered so the design isn't considered acceptable.

5.3 - Develop redesign alternatives

The redesign is only shown for the output shaft and planet gear pin group. The consolidation of both pieces can be done without causing any trouble in the rest of the assembly. The new part is shown in figure 8.

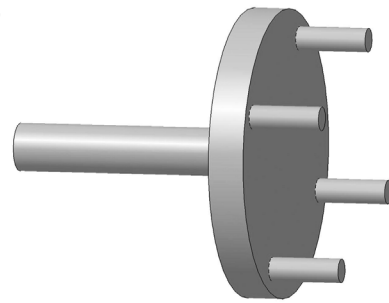


Figure 7: redesigned output shaft.

The result of the casing redesign without details is shown in figure 9. Since all candidates for elimination have been redesigned the design is now considered acceptable and it is possible to move to the next step of the methodology.

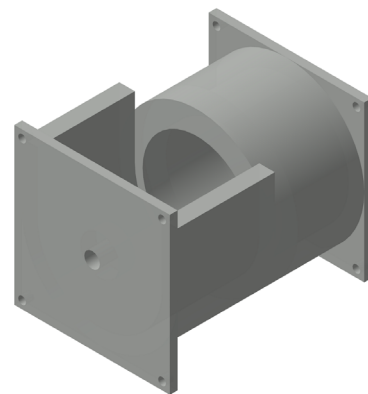


Figure 8: redesigned casing.

5.4 - Determine and defined functions and characteristics to optimize

For regular functions only the planet gears will be looked at as they will properly illustrate the method. The methodology is applicable similarly to the other parts.

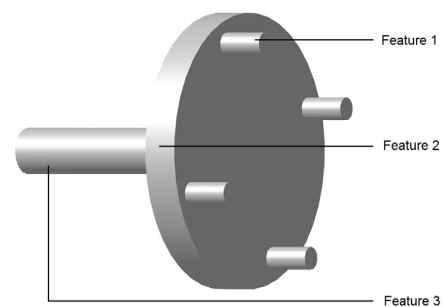


Figure 9: features of the output shaft.

Feature 1 - The function is to receive the torque from the planet gears and allow for the rotation of the planet gears. The feature is the protruding shaft.

Feature 2 - The function is to transfer the torque from section 1 to section 3. The feature is the entire shaft except for feature 1 and 2.

Feature 3 – The function is to transfer the torque from the output shaft to the motor. The feature is the outer part of the end of the shaft that connects with the motor.

The only transfer function to be optimized is the transfer of heat from the engine through the mechanism and the inside of the casing to the motor and the environment. The goal is to minimize the flow of heat from the engine to the motor and to maximize the flow of heat to the environment, as heat must to exit either through environment or the motor.

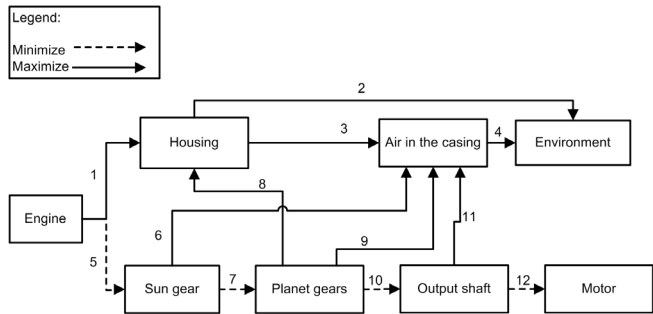


Figure 10: representation of the heat flow in the system.

The flow diagram has been established in figure 11 with the motor being the source, the environment and motor being the exits and heat being the flow. The goal is to minimize the amount of heat transfer to the motor. It is decided to optimize the flow from the sun gear to the air in the casing.

The characteristic to be optimized is the weight of the casing and the only requirement is to keep the structural integrity of the casing during the normal functions of the assembly.

5.5 – Function optimization

With functions being defined previously, a subversive approach is taken in order to find solutions that optimize the functions. The result of both optimizations is displayed in table 1.

5.6 – Implementation of solutions

Output shaft

- Geometry
 - Increase the surface area. There are many

ways to implement this solution so it is chosen to add fins as it also creates more air movement within the casing.

- Ensure the geometry of the shaft can handle all applied loads.
- Surface finish
 - Low roughness at the interface with the planet gears.
 - Rough surface finish at the interface with the engine.
- Material
 - High heat conductivity at the surface of the shaft exposed to the air.
 - Low coefficient of friction at the interface with the planet gears.
 - Material with a high/infinite fatigue life.
 - High coefficient of friction at the interface with the motor.
 - High wear resistance at interface with planet gears.

5.7 – Characteristics optimization

Finite element analysis (FEA) software is used to realize the optimization of characteristics, in the given example Altair Hypermesh was used with the Optistruct module in order to realize a topology optimization.

The first step is to define the support and loading conditions which was done based upon the problem specifications. After these are defined the next step is to define the variables relating to the optimization.

Design variables: In this example the only variable design variable is the volume of the design space.

Objective: As previously defined, it is desired to minimize the volume of the design space.

Design space: The design space is shown in figure 11 as the part in grey.

Regular functions optimization				
Part and feature number	Formulation	Inverse formulation	Inverse solution	Solution
Output shaft 1	Underperform by loss of energy during rotation of the planet gears	How do we increase the loss of energy during the rotation of the planet gears	Rough surface finish	Smooth surface finish
	Failure by wear of the contact surface	How do we increase the wear of the contact surface	Material with high coefficient of friction	Material with low coefficient of friction
Output shaft 2	Failure by fracture or deformation of the shaft	How can we help reach failure by fracture or deformation of the shaft	Material with low wear resistance	Material with high wear resistance
			Material with low fatigue life	Material with high fatigue life
Output shaft 3	Underperform by slip from the motor	How can we achieve slip from the motor	Thinner shaft such that it can't handle the loads	Thicker shaft that can handle loads
			Material with a low coefficient of friction	Material with high coefficient of friction
			Smooth irregular surface finish	Rough regular surface finish
Transfer functions optimization				
Flow number	Formulation	Inverse formulation	Inverse Solution	Solution
5	How do I minimize the heat flow from the engine to the sun gear	How do I maximize the heat flow from the engine to the sun gear	Use a material with high heat conductivity at the interface	Use a material with low heat conductivity at the interface

Table 1: Results of function optimization

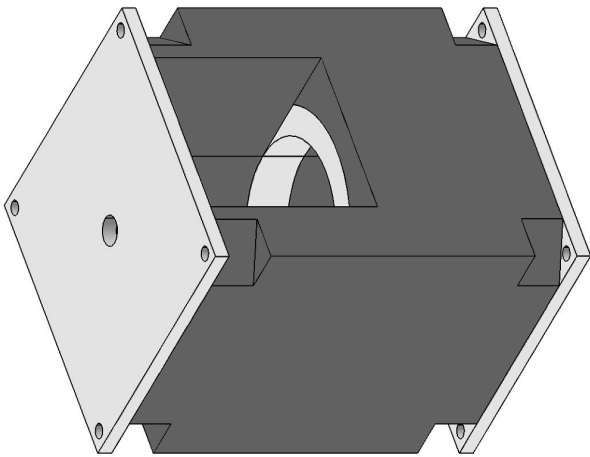


Figure 11: design and non-design areas.

Non-design space: The non-design space is shown in figure 11 as the parts in white.

Design constraints: The design has to be able to support the loads acting upon it. In addition displacement constraints were applied at nodes subject to the largest displacements.

A mesh is applied to the artifact and the optimization is launched with the previously defined variables. The result is displayed in figure 12.

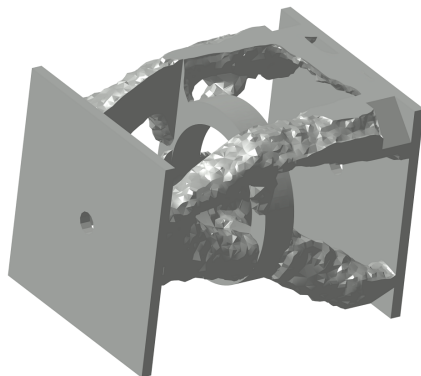


Figure 12: result of the topology optimization.

The solution to the topology optimization gives a very good idea of a lightweight geometry that meets the loading conditions. The method can be applied to any type of part once the loading conditions are known. It is to be noted that there are limitations to the software, especially for multi-material parts.

5.8 – Selection of materials

The choice of material is made by comparing the solutions described in the implementation of solutions with the list of possible materials and multi-materials. An example of the choice of material is shown for the planet gears.

The planet gears require a teeth material with high wear resistance and a low coefficient of friction on the inner surface which would be optimized using Colmonoy-6, however the density is higher than titanium and it is wanted to reduce the overall weight of the system, therefore Colmonoy-6 could be used at both interface and titanium in between.

6- Conclusions

The proposed method guides the user through different steps in order to apply the advantages of RM to many facets of a product as the added complexity comes at no extra cost and enables an optimization of a product's functions.

The methodology defines a framework for optimization of a product through RM's capabilities by defining the relevant information of an artifact and developing a suitable method to push forward the advantages of RM for each element of the artifact. It also combines an algorithmic approach and a numerical method in order to optimize the functions of the product through each of the elements defined previously.

The methodology updates the Boothroyd-Dewhurst criteria for elimination of parts in order to consolidate a product and borrows from the TRIZ method to develop a new algorithmic approach to the optimization of features. FEA software forms an integral part of the methodology as it is used to realize numerical optimization of the shape of an artifact.

A case study was done by applying the methodology to a planetary gear system and satisfactory results were obtained encompassing ameliorations across various aspects of the product. Further testing on other products across a broad range of applications should be done in order to thoroughly test and refine the method.

As applications and possibilities of RM processes are always developing, the next step for RM design methodologies is to integrate a knowledge-based advice system in order to suggest solutions that the designer may not have considered or be aware of. Also numerical optimization methods need to better integrate the multi-material aspect through both the optimization of multi-material parts and through the exchange of data between systems.

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