Multi-objective Optimization-driven Design: Generative Design Approach for Manufacturing of a Train Bogie

Amirmohammad Daareyni[1], Antoine Queguineur[1,2], Hossein Mokhtarian[1], Reza Asadi[1], Iñigo Flores Ituarte[1]

[1] Faculty of Engineering and Natural Sciences, Tampere University, Korkeakoulunkatu 6, 33014 Tampere, Finland
[2] Ecole Centrale Nantes, GeM-UMsR CNRS 6183, 1 rue de la Noé, 44321 Nantes, France

`amirmohammad.daareyni@tuni.fi>`

Abstract. In recent years, advances in additive manufacturing (AM) technologies, particularly in Direct Energy Deposition (DED) as Wire Arc Additive Manufacturing (WAAM) and Laser Wire Directed Energy Deposition (LW-DED), have enabled engineers to produce large complex structures. Consequently, these developments drive a paradigm shift in how we conceptualize and manufacture complex components, pushing the limits of what is possible in engineering and design. As a result, there is a growing need for optimized structures considering the material constraints and advantages. This study uses a multi-objective optimization-driven engineering design approach to optimize the shape and materials of a train bogie as a case study. From the material perspective, different materials were selected to benefit from the high-strength steel (HSL) and low-carbon steel (LCS) and achieve weight reduction while considering other structural constraints. We generated multiple prospective designs using the generative design feature from Autodesk Fusion 360. Subsequently, safety factors are collected from these models using AbaqusCAE and the fatigue data with fe-safe. Moreover, a multi-objective optimization approach is applied to find the best possible design based on the resulting safety factor, weight, fatigue life, and maximum displacement of the proposed part. Finally, the collected results are compared, and a set of optimum designs is presented based on different criteria detailed in the study.

Keywords: Engineering design, Generative design, Multi-objective optimization, Additive Manufacturing.

1 Introduction

Engineering design can be characterized as a collection of decision-making procedures and tasks. These are utilized to establish the structure of a product, component, system, or process based on the functionalities specified by the customer [1]. The objective of engineering design extends beyond just fulfilling design requirements; it also aims to optimize performance, cost, reliability, and manufacturability [2]. Modern design tools, such as generative design, play a key role in the evolution of manufacturing, especially in AM processes. These tools encompass a range of software applications and technologies that enable engineers and designers to create innovative designs optimized for manufacturing efficiency and performance. Generative design takes optimization a step further by automatically using algorithms to explore a wide range of design solutions. Design constraints and objectives are input by the software, which then generates a variety of potential solutions. Barbieri et al. compare two Additive Manufacturing design methods using topology optimization and generative design tools, aiming to assess the traditional approach's evolution and the integration potential and limitations with CAD systems [3]. Watson and colleagues introduce a generative design approach focused on optimizing space-frame systems to achieve minimal volume and compliance, while also accounting for stress and buckling constraints [4]. This study utilizes the generative design feature available in Fusion360 as well as stress and fatigue life simulation in AbaqusCAE and fe-safe to redesign a train bogie, considering defined boundary and loading conditions, various materials, structural limitations, and manufacturing techniques, such as AM and die casting.

AM offers significant freedom in the fabrication of various part shape and materials [5]. The control and comprehension of material properties are crucial for the integration of these technologies into industrial applications [6]. Generative designs utilize the advantages of AM to create unique/unconventional shapes from generative designs, which are typically unachievable via conventional manufacturing methods such as machining, casting, or assembling at feasible costs. The design of train bogies is pivotal for the functionality, durability, and safety of railcars, constituting a fundamental aspect of their operation. In this study, generative design feature in Fusion 360 were used to find several possible designs for bogies. As generative design can evaluate just one objective at the same time (either minimizing mass or maximizing stiffness), this study aims to add a multi-objective feature to find the most optimized design within defined criteria. A fatigue analysis completes this study to enhance the durability of the design. Therefore, the primary objective of this study can be considered to be employing various engineering tools to generate and evaluate a range of proposed designs to identify the most optimal solution according to different criteria, including safety factor, weight, and fatigue lifetime which proof to be competing optimization objectives.

2 Methods

2.1 Generative design

A generative design process can be considered as an exploration of various design possibilities. During this process, designers or engineers specify their design objectives, parameters such as performance or spatial requirements, materials, production techniques, and budget limits into a generative design software. Then, the software explores all the possible permutations of a solution, quickly generating design alternatives. With each iteration, the software evaluates and learns, identifying effective solutions and discarding those that fall short [7]. In recent years, generative approaches have been used more and more in mechanical design. Several CAD software such as Fusion360, Ansys NX, and Altair Inspire offer generative design. In a study conducted by Buonamici et al. [8], they sought to achieve a practical and efficient representation of the design workflow provided by Autodesk Generative Design (AGD), which is hosted within Fusion360. This study employed AGD to address a static structural optimization problem, and subsequently executed the entire design phase by making use of the tools provided by the AGD suite. The proposed case study in their research aimed to investigate the capabilities of the AGD through the redesign of a robot's gripper arm, as suggested on the GrabCAD website. In this study, Fusion360 generative design feature is utilized to find the most optimum solution for a train bogie under stationary structural analysis. In order to use generative design feature in Fusion360, first the operator requires defining the part dimensions, preserved area, obstacle area, loads and supports, design objectives, materials, and manufacturing methods. Dimensions used for this redesign problem are borrowed from GrabCAD platform and it represent a general train bogie [9]. Preserved area is defined as the area which must be included in the final design. This area includes the supports, loading surfaces, and every other part which must meet a certain criterion or have a precise dimension or shape, such as bearing supports. Obstacle area can be defined as empty spaces which must be avoided during the generative design process. As a mandatory option, a starting shape also can be defined for the design. The preserved and obstacle area, the starting shape defined for the case study of this paper , and Dimensions are shown in Figure 1 (a) and (b) respectively.

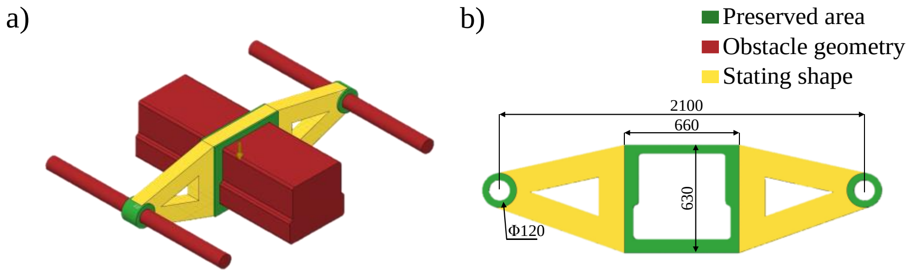

Fig. 1. Bogie redesign problem definition. a) preserved area, obstacle area, and starting shape defined in Fusion360. b) bogie dimensions.

Regarding the loads, support, and boundary conditions, the acting forces are calculated according to the requirements listed in EN 13749 standard [10] using equations (1) and (2) for lateral (F_y) and vertical forces (F_z), respectively. The forces acting on the bogie are calculated according to the requirements listed in EN 13749 standard [10] using equations (1) and (2) for lateral (F_y) and vertical forces (F_z), respectively.

$$F_{y1} = F_{y2} = \frac{F_y}{2} = 10^4 + \frac{(m_v + c_1)g}{12} \qquad (1)$$

$$F_{z1} = F_{z2} = \frac{F_z}{2} = \frac{1.4g(m_v + c_1 - 2m^+)}{4} \qquad (2)$$

Where m_v, m^+, c_1, and g are the vehicle weight, the bogie weight, the passengers' weight, and acceleration due to gravity respectively. F_{z1} and F_{z2} stand for the vertical forces in each frame. Since there are two bogie frames under each carriage (in total 4 under each wagon), the total vertical force is divided evenly between them. In this analysis, the weight of the wagon is assumed to be 50,000 kg, and passengers' weight is assumed to be equal to 10,000 kg in total, and the weight of the bogie itself is assumed to be 500 kg. According to these assumptions, the total lateral force and vertical force are selected to be 60 kN and 205 kN respectively. The supports for this bogie system are located at the right and left ends, where the bogie is attached to the axles.

To conduct a generative study in Fusion360, design objectives, materials, and manufacturing methods need to be explored and exploited. This objective can be either minimizing the mass or maximizing the stiffness. In this paper, two studies have been conducted in which the primary objective is chosen to be maximizing the stiffness with a mass target of 500 kg and minimizing the mass respectively. Another defined design objective is achieving a minimum factor of safety, set at 2.5. To explore a range of designs utilizing various materials and manufacturing methods, this study incorporates four different steel class and four distinct manufacturing techniques. The selection of these four materials is based on two main criteria. Firstly, they encompass a broad spectrum of mechanical properties, ranging from low strength to high strength. Secondly, they are readily available as built-in materials within both the Fusion360 and fe-safe materials libraries. **Table 1** presents the mechanical properties for these materials. These include unrestricted manufacturing, AM, and die casting.

Table 1. Materials used in Fusion360.

Material name	Young's Modulus (GPa)	Poisson's Ratio	Density (kg/m^3)	UTS (MPa)	Yield strength (MPa)
Steel AISI 1006	207	0.33	7872	318	248
Steel AISI 1020	207	0.33	7870	392	254
Steel AISI 4130	207	0.33	7850	895	778
Steel AISI 5210	207	0.33	7810	2011	1922

2.2 Finite Element Analysis, fatigue life, and optimization problem

Finite Element Analysis (FEA) is used to predict and analyze the structural integrity of a mechanical part under various loading conditions. FEA can optimize the proposed design, enhancing safety and reliability. In the present study, a set of static analysis based on linear elastic material theory were carried out using AbaqusCAE and Fusion360 simulation section on the proposed designs extracted from Fusion360. A similar load case and materials are considered both in simulations and generative design. Furthermore, minimum Safety factor (Sf) is also calculated for each design based on results obtained from AbaqusCAE. Sf is calculated based on equation (3) [11].

$$Sf = (Yield\ Strength/Max.von\ Mises\ stress)_i - 1 \tag{3}$$

where the subscript i represents the different designs proposed by Fusion360. It is worth noting that if the resulting Sf is equal to 0, the maximum von Mises stress and yield strength are equal, indicating that the structure will be able to withstand loads and boundary conditions. An Sf less than 0 represents an under-engineered design and would result in a non-feasible solution, while in the case of an Sf greater than 0, the design is over-engineered. Regarding fatigue life analysis, EN 13749 specifies that the fatigue tests should be conducted with three types of loads: static loads, quasistatic loads, and dynamic loads:

$$F_{z1} = F_{z2} = \frac{F_z}{2} \tag{4}$$

$$F_{z1qs} = F_{z2qs} = \pm\alpha\, F_z/2 \tag{5}$$

$$F_{z1d} = F_{z2d} = \pm\beta\, F_z/2 \tag{6}$$

$$F_{y1qs} = F_{y2qs} = \pm 0{,}063(F_z + m^+ g) \tag{7}$$

$$F_{y1d} = F_{y2d} = \pm 0{,}063(F_z + m^+ g) \tag{8}$$

Where in these equations, F_{zi}, F_{ziqs}, and F_{zid} (i=1,2) represent the vertical static, quasistatic, and dynamic loads, respectively. Additionally, F_{yiqs}, F_{yid} (i=1,2) denote the lateral quasistatic, and dynamic loads, respectively. Vertical forces are affected by rolling and bouncing, resulting in quasi-static and dynamic variations respectively. These variations are represented by coefficients α and β, respectively. Generally, these coefficient values are 0,1 for α and 0,2 for β. In this study, fatigue life simulations were conducted using the Goodman theory integrated into fe-safe software.

In order to find the optimal design meeting a set of goals and targets, a multi-objective optimization process has been conducted. To simplify this procedure, the scalarization multi-objective optimization method is applied [12]. This method aims to generate a single solution from a multi-objective function while using a set of predefined weights [13]. The equation (9) represents the optimization problem formulation two objectives:

$$f(x) = w_1.j_1 + (1 - w_1).j_2 \tag{9}$$

Where j_1, j_2, and w_1 stand for the first objective, second objective, and weight respectively. Weight factors can aid in assessing the importance of each factor.

3 Results and discussion

Figure 2(a) shows some example design with different manufacturing methods. A set of 32 possible design based on the conditions described in the previous section is generated in Fusion360. The most recommended design for each study (e.g., study 1 with primary objective of maximizing stiffness and study 2 with primary objective of minimizing mass) are shown in Figure 2 (b). These designs are chosen based on the recommendation value reported by Fusion360. Figure 3 show the results for exploration and exploitation of the bogie design considering different manufacturing methods and materials. The exploration phase in Figure 3 (a) involved 32 generative design simulations, from where a narrow window of material and design alternatives was later exploited with 80 additional simulations. Figure 3 (b) represents this narrower window for exploitation.

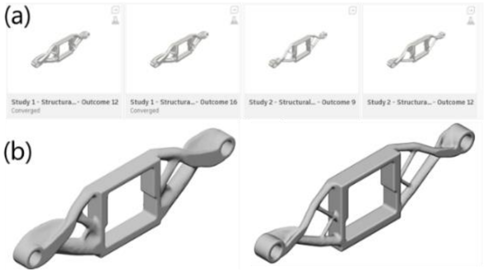

Fig. 2. Example of generative designs derived from Fusion360.

To build the data set for the optimization problem, 10 generative design processes have been done with 80 proposed designs in total. For the exploitation phase, we modified the primary design objectives (mass and maximum SF) and materials to discover designs like those enclosed within the exploitation area. To find less over engineered designs ($Sf > 1$) in the exploitation phase, materials are chosen to be Steel AISI 1006 and Steel AISI 1020 and mass target is chosen to be between 300 and 450kg. The results derived from these designs are subsequently employed to conduct a multi-objective optimization.

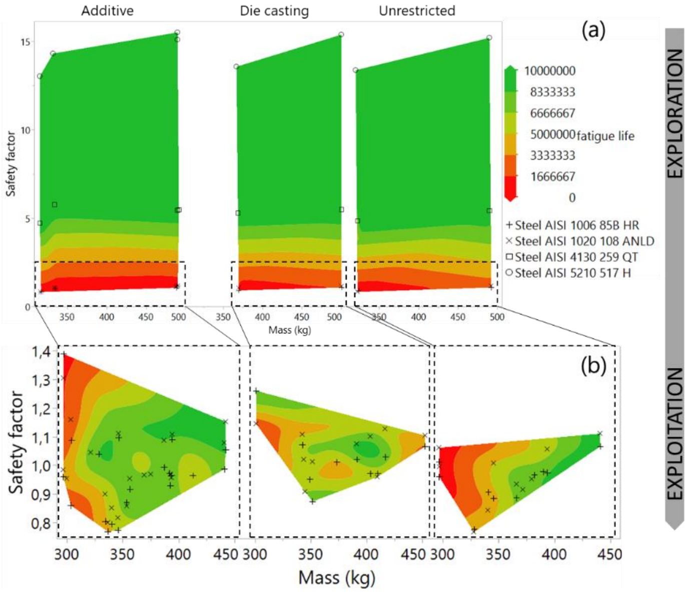

Fig. 3. Fatigue life estimation derived from Fe-safe based on Sf and mass for each design. rectangles represent the design space for the exploration phase.

Table 2 shows the scenarios utilized in this study, along with the resulting design characteristics for each scenario. It is observed that the minimum attainable mass is approximately 297kg. However, this design is deemed unacceptable due to its low estimated fatigue life. In contrast, the resulting design from the second scenario meets all requirements and variables within reasonable bounds, rendering it acceptable. Similarly, the design proposed for the third set of objectives in this multi-objective optimization problem is also deemed acceptable, although it exhibits a higher maximum displacement (U_{max}) compared to other proposed designs. conversely, the designs proposed in the fourth and fifth scenarios are heavier than other proposed alternatives.

Table 2. Results obtained for different optimization scenarios.

No.	j_1	j_2	w_1	Fatigue life	Sf	Mass (kg)	U_{max} (mm)	Manu. & Mat.
#1	Min (m)	Max (Sf)	0.5	1.5E4	1.38	297.06	0.76	AM & AISI 1006
#2	Min (m)	Min (U_{max})	0.5	2.1E6	0.97	369.16	0.41	AM & AISI 1020
#3	Min (m)	Max (f)	0.5	1E7	1.26	300.96	0.91	Die casting & AISI 1006
#4	Min (U_{max})	Max (f)	0.5	1E7	1.11	440.62	0.34	Unrestricted & AISI 1020
#5	Min (U_{max})	Max (Sf)	0.3	1E7	1.15	441.89	0.39	Die casting & AISI 1006

4 Conclusion

In this study, an extensive examination of exploratory designs has been conducted, considering factors such as mass, safety factor, fatigue life, and maximum displacement, aimed at identifying the optimal design for a train bogie. Through the implementation of a generative design approach, supplemented by statistical simulation and fatigue life analysis, a comprehensive dataset encompassing all feasible designs was generated. Subsequently, this dataset was employed to formulate an optimization problem, facilitating the identification of optimal design. Additionally, an exploitation process, informed by the outcomes of the initial exploration, was carried out to refine and identify more suitable designs. Following the optimization process, the most optimal designs were identified according to different optimization scenarios. The study acknowledges several limitations, including the lack of validation of simulation results through real-world experiments, which remains a primary objective for future investigations. Additionally, comparisons between different generative design methods and between results derived from generative design and those obtained using other methods such as topology optimization are slated for further examination in subsequent studies. In future research, there is an intention to advance the methodology by developing a generative design approach specifically tailored to optimize fatigue life. Additionally, leveraging AI and surrogate models to generate more designs in the exploitation space will be explored as a means to enhance the study's findings and expand its scope.

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