

WEIGHT OPTIMIZATION USING DESIGN TOPOLOGY AND MULTI-MATERIALS FOR AM APPLICATION IN MULTHEM PROJECT

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Summary. Mechanical products such as EV Batteries and Electrical Motors have housings confined to their boundary spaces. Existing industrial products use metal like aluminium as a full-covered casing or housing material, and this is costly in terms of performance overall as weight is a major affecting factor. With the use of metal-polymer 3D printing technologies, designs can be optimized for weight, and thus, the performance. In MULTHEM project, a new approach in Additive Manufacturing (AM) has been researched for designing such housings to reduce weight and to improve thermal management by using design optimization and new developed multi-materials composed of Reinforced Carbon Fiber Composites (RCFC) and aluminium combinations. This is virtually applied on housings of use-cases (an EV battery and an electric motor) in a modelling and simulation environment. The Finite Element Analysis (FEA) and Topology Optimization with multi-materials (metal-polymer) has been simulated on the housings. The heat dissipation in these components to the environment has also been taken into account in the design optimization where a balance is required between heat transfer and mass reduction through the material thickness. Limitations in design topology optimization process occur with less material thicknesses in the housings where no further reduction in mass is possible as constraints from 3D printing processes are applicable. Results show significant

reductions in housings mass up to 50% compared to original metal designs. This further enhances the capabilities in Design for Additive Manufacturing (DfAM).

1 INTRODUCTION

With the ongoing transformation of the world from fossil fuels towards many greener options, the product design sector is also bent to abide by such ambitions, i.e., by designing products which tend to be lighter and consumes less energy for high performance. Metal being a prominent material choice in product design in almost every transport sector type whether it be aviation or locomotive etc., trend is gathering pace to replace metal with advanced composite materials which nearly match the properties of metal alloys like aluminium ones. The multi-material combination of metal and polymer is the new perspective in the design world [1, 2]. Components such as motors and electric vehicle (EV) batteries have their casings made of common aluminium material [3,4]. However, this has been changing with time in order to achieve high performance and efficiencies from designs. For instance, in aviation sector, lighter materials especially composites are achieving more composition by weight with time than the heavier metal parts in the construction of commercial aircrafts [5] (Figure 1).

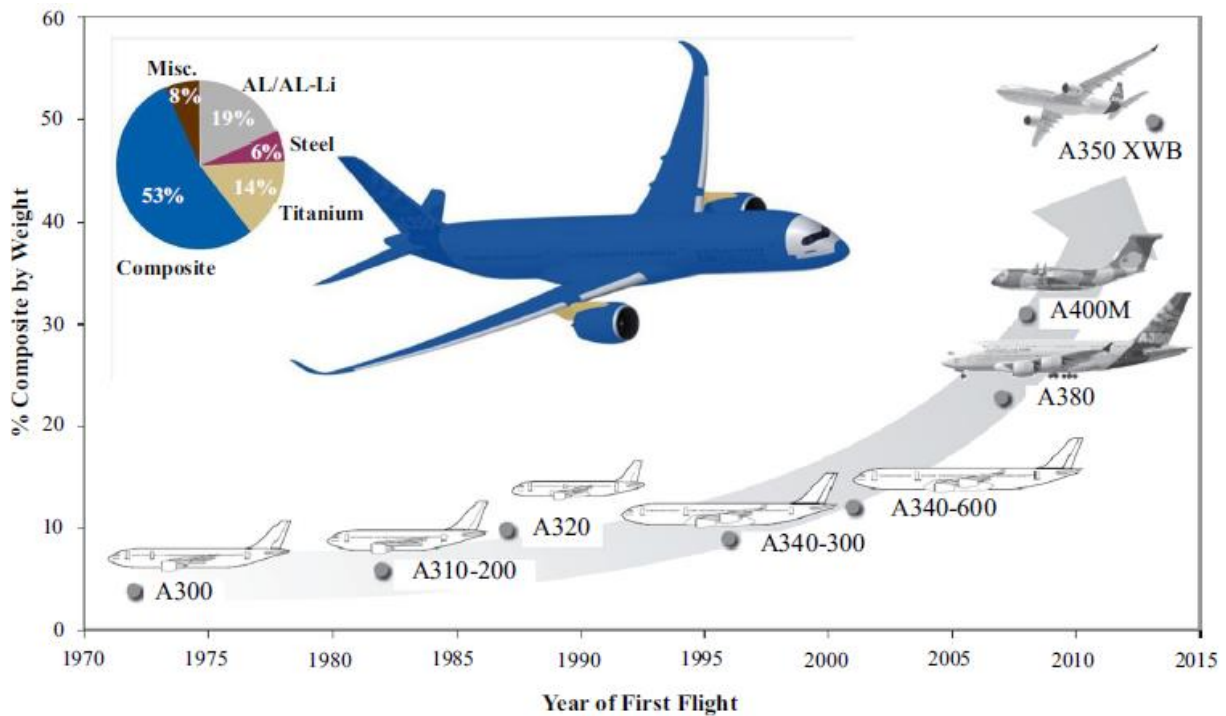


Figure 1: Trends in the use of composite materials in commercial aircrafts Airbus and Boeing [5]

2 BACKGROUND OF MULTHEM PROJECT

The multi-material design aspect is further accelerated by the advent of 3D printing technology. Complex organic parts with optimized geometries and multi-materials composition are gaining momentum in order to shed dependency on metal (e.g., aluminium). Additionally, multi-materials offer more light weight solutions in order to achieve high performance, high

efficiencies and low costs in fuel consumption, e.g., extending range especially in case of EV applications etc. With this aim in sight, MULTHEM project ^[1] (<https://multhem.eu>) explores to reduce metal material, and therefore, mass in real world applications such as EV battery casing and electric drones motor housings. MULTHEM is an EU Horizon Europe funded project with a grant value of around 4 million euros distributed among nine partners from eight countries in EU and UK ^[1,11].

MULTHEM stands for ‘Multi Material Additive Manufacturing for Lightweight and Thermal Management’. It takes the advantage of additive manufacturing (AM) which offers flexibility in complex design manufacturing, combination of light materials such as aluminium and carbon fiber (CF) composites and topology optimization technique. Combining both the characteristics of aluminium and CFC, this project aims to achieve good mechanical performance, good thermal performance and lightweight solutions for the use-cases involved, as summarized in Figure 2. In recent years, most of the development in CF-reinforced polymers for AM has involved the inclusion of particulates of short-Carbon Fiber (s-CF), while continuous-Carbon Fiber (C-CF) printing remains a relatively novel area of research ^[6]. The use of C-CF brings the highest mechanical reinforcement from the two types of composites. While on the flip side, the metal domain is aluminum alloys due to their low density (2.6 to 2.8 g/cm³) and high thermal conductivities (88 to 251 W/m.K). Aluminium alloys are difficult materials to be developed by AM technologies due to its high energy reflectivity. Laser Powder Bed Fusion (L-PBF) technologies with high-energy source are well established for the processing of aluminium alloys ^[7,8]. However, the processing of aluminium alloys by other AM processes like Direct Energy Deposition (DED) ^[9] also known as Laser Metal Deposition (LMD) needs to be further developed by both processes DED-wire and DED-powder ^[10]. In MULTHEM project, Al5356 is being developed by DED-wire process, and AlSi7Mg is being researched by DED-powder. High quality materials without presence of big pores, lack-of-fusion defects nor cracks are being obtained.

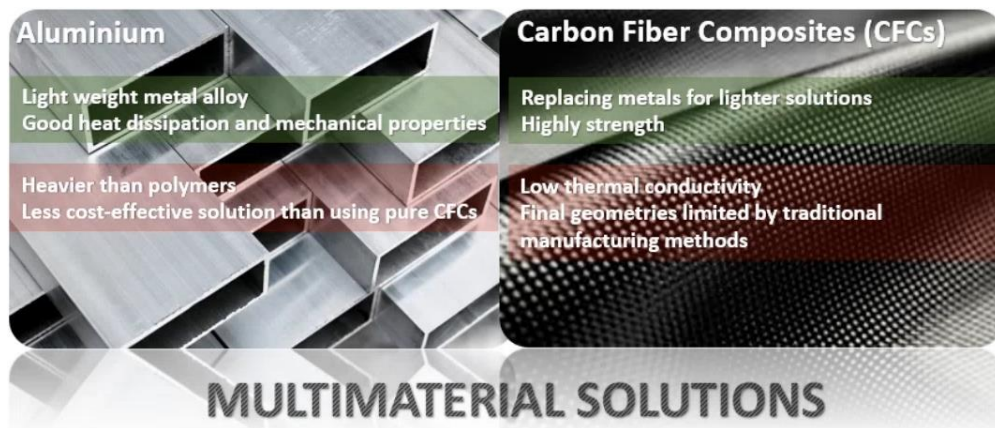


Figure 2: Individual characteristics of aluminium and carbon fiber composites ^[1]

3 USE-CASES IN MULTHEM PROJECT

The MULTHEM project works around real-world use-cases in EV and aviation sectors.

These include an electric drone motor housing, an electric vehicle battery casing and an aircraft radio altimeter casing. Each of the use cases come with their own sets of KPIs (Key Performance Index) in this project. These are summarized in Figure 3. The common KPI listed among the use-cases is ‘mass reduction’ which ultimately contributes to mechanical, thermal, overall product performance and costing etc. *The work on radio altimeter use-case has yet not started in the project and its details are omitted in this paper.*

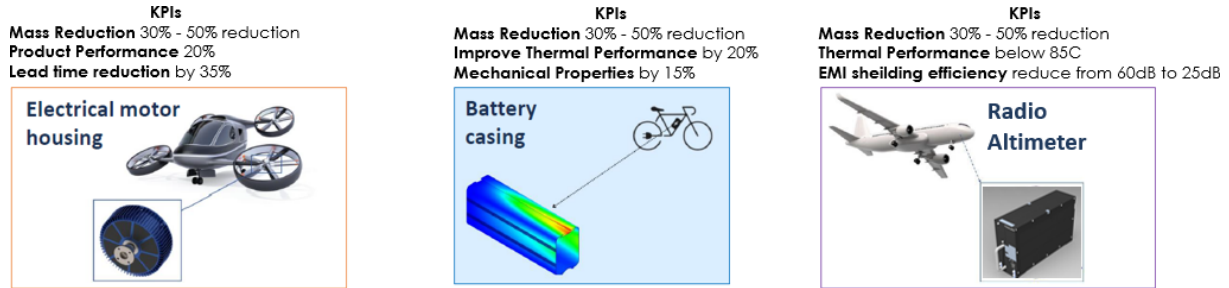


Figure 3: Use-cases in the MULTHEM project with individual KPIs ^[1]

5 METHODOLOGY IN MULTHEM PROJECT

Design optimization with multi-materials for mass reduction is the main driving factor in this project. Typical product design methodology is adopted with data inputs from materials, additive manufacturing and joining technologies. The methodology followed for this study is explained in next points:

- **AM Processing and Material Characterization:** Both aluminium grades and carbon fiber composite 3D printing materials are being developed through shortlisted AM processes which are then tested for characterization in structural and thermal domains. Multi-material combinations with short and continuous carbon fiber reinforced PEKK and PA6 materials (sCF or cCF PEKK and PA6) and AlSi₁₀Mg, AlSi₇Mg and Al5356 alloys are being investigated.
- **Joining Multi-Material (welding technologies):** Both 3D printed metal (Al) and CFC materials need to be joined together in individual use-cases' designs. Laser Beam Welding, Electron Beam Welding (EBW) and Robotic Friction Stir Welding (R-FSW) are the innovative welding technologies being used.
- **Simulation Analysis:** The use of finite element method simulations is intended to optimize the designs of use-cases using topology optimization and multi-material assignation. The steps involved are: i) incorporate input data from characterized materials, ii) selected 3D printing processes and their constraints and parameters (minimum line width or layer thickness), iii) remodeling of original designs, multi-system design analysis under multi-loading conditions like thermal and structural, and iv) finally coupled with topology optimization. This makes the simulation step as an externally influenced iterative procedure. ANSYS software was used for simulation analyses.

- **Weight Reduction:** This is a sub-step of simulation analysis where weight in the use-cases designs is reduced by geometrical feature analysis for simplification, assigning lightweight multi-materials and topology optimization (volume or lattice based).

6 MULTI-MATERIAL DESIGN OPTIMIZATION OF USE-CASES

6.1 EV Battery Casing

The MULTHEM iterative mass optimization methodology was applied to EV battery casing use-case with multiple FEA as illustrated in Figure 4. A results summary of simulation analysis using different combinations of multi-materials for this use-case is briefed in Table 1 (where ‘TD’ is a FEA result parameter representing maximum total deformation in model). A few starting iterations were setup trials to observe the correct behavior of the model. Iterations 2 to 4 were tested with sCF-PA6 and AlSi₁₀Mg materials with different single or dual angular tractions of carbon fiber filaments (based on multi-FEA outcomes) in the thickness of the model side walls, such as from vertical 15°, 10°/15° or 11.14° to find the best angle for resisting model deformation. Iteration 5 was tried with additional metal removal (0.5 mm from features near CF and metal interfaces) to further observe mass reduction; however, the results showed a possibility increase in mass reduction though along with a penalty of increased model deformation. It was found that the methodology adopted meet the mass reduction KPI of 50% for this use-case. The combination of ‘cCF-PA6’ with AlSi₁₀Mg offers minimum deformation so far. However, results for ‘cCF-PEKK’ results are yet to be explored. Cost will be another factor to influence the material choice since PEKK is an expensive material for this use-case.

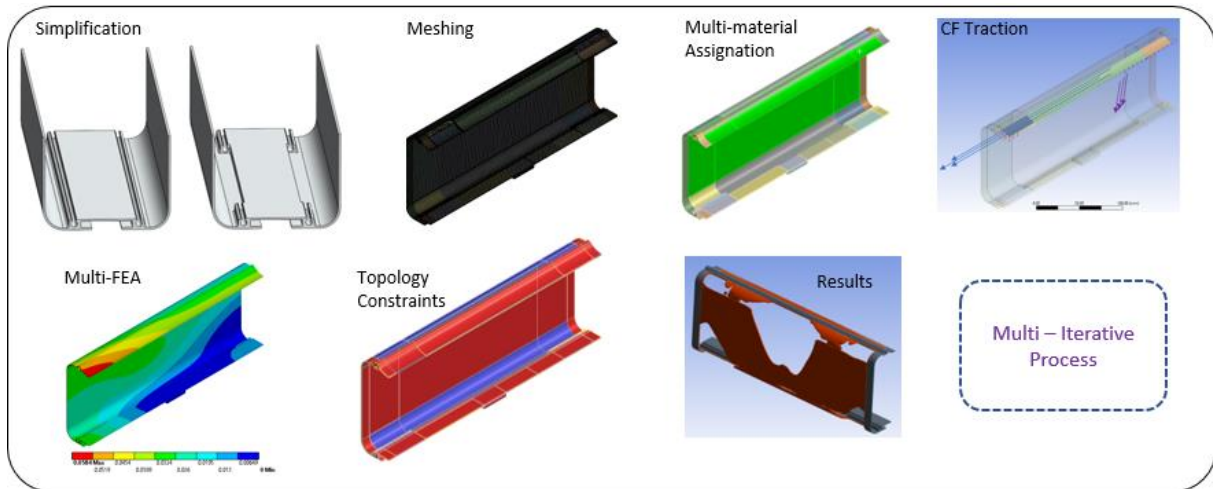


Figure 4: Simulation based design optimization process of EV battery casing use-case using multi-materials

Table 1: Iterative mass optimisation analysis of EV battery casing use-case using multi-materials

Iteration	Material (composite + AlSi ₁₀ Mg)	Initial Mass (kg)	Optimized Mass (kg)	Reduction (%)	TD (mm)
1	sCF-PA6 (Setup trial)	0.631	-	-	-
2	sCF-PA6 15° traction	0.631	0.27536	56.36	0.058406
3	sCF-PA6 10° / 15° traction	0.631	0.27536	56.36	0.058463
4	sCF-PA6 11.14° traction	0.631	0.27536	56.36	0.058402
5	sCF-PA6 (further metal removal)	0.631	0.24478	61.21	0.069147
6	sCF-PEKK	0.631	0.28366	55.05	0.07391
7	cCF-PA6	0.631	0.2843	54.94	0.04562
8	cCF-PEKK	0.631	TBC	TBC	TBC

6.2 Electric Motor Housing

Similar MULTHEM methodology for mass reduction is being applied to the electrical motor housing use-case. Initial stages included original metal housing design analysis under given structural and thermal loads coupled with topology optimization (Figure 5). This was intended to observe the model behavior such as deformation, stresses, heat dissipation and possibility of mass reduction. The mass reductions in the baseline designs were observed to be 27.7% in model without fins versus a 30% reduction set target, and 37.94% in model with fins compared to a 30 – 50% set target, respectively. Adding fins in the model improved the thermal performance, on the contrary, the aggressiveness of topology optimization method was increased to reach the desired set target range. Both structural and thermal stability criteria were given equal weighting during the optimization process.

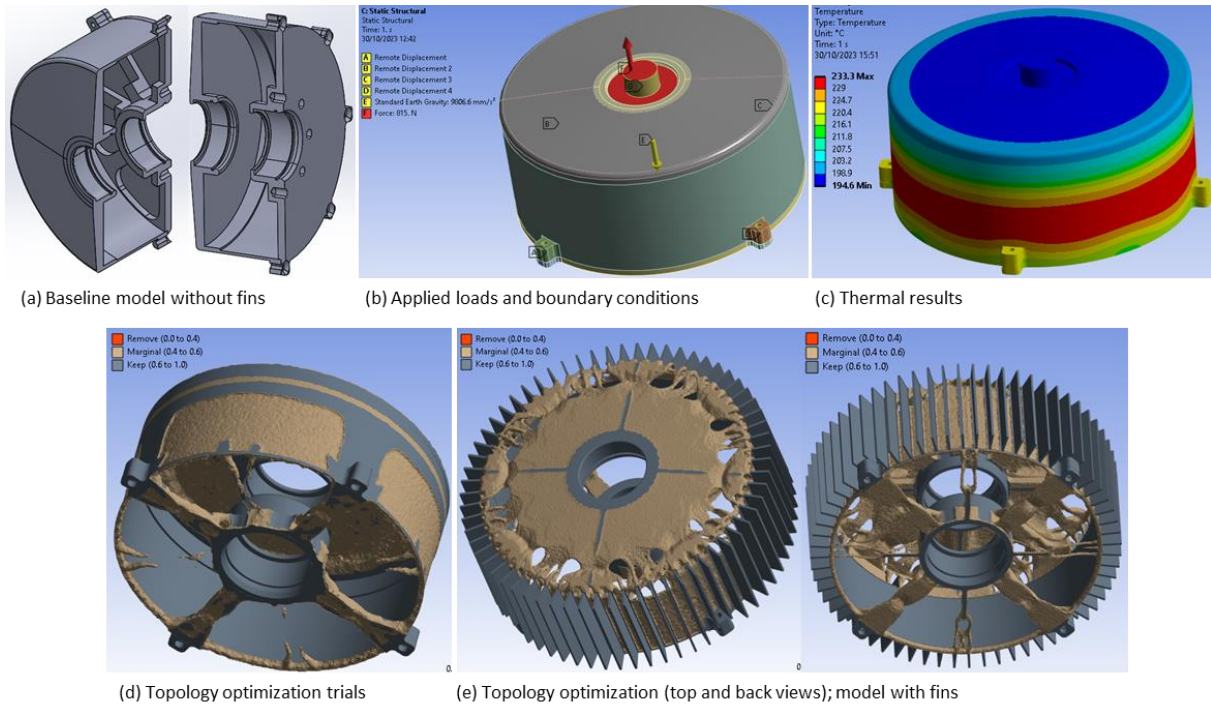


Figure 5: Steps explored for FEA and topology optimization analysis of motor housing baseline model (with and without fins)

Currently, at this stage of MULTHEM project, design exploration for the assignation of multi-materials is under investigation. This depends on material data, selected 3D printing process and the joining methods. Characterization and joining tests are being performed on the 3D printed multi-material samples under the operating loading conditions. Simulation trials are also being performed with different combination of CFCs and Al multi-materials based on given operating loading conditions similar to first trials (Figure 5). For instance, Figure 6 briefly describes the decision steps and also shows an intention to include CFCs spokes (at top and back parts in the design, highlighted in blue) integrated with the main AlSi₁₀Mg metal housing as part of the first multi-material simulation trials being conducted.

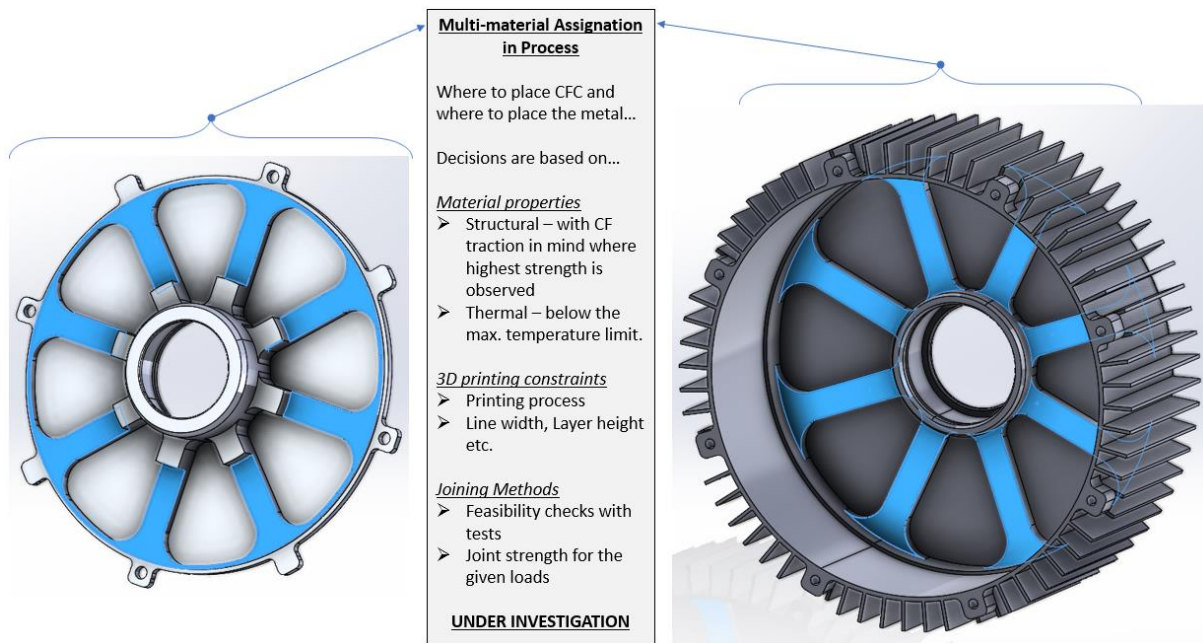


Figure 6: Steps to consider in assigning multi-materials to the motor housing use-case (for instance, spokes made of CFC on aluminium housing, highlighted in blue)

7 CONCLUSIONS

- The MULTHEM project aims to optimize the casings' designs of the use-cases involved by mass reduction, using 3D printed metal (Al) and CFC multi-material combinations and topology optimization technique. The emphasize is on the weight as it is one of the main affecting factors contributing to global emissions and induces component performance caps.
- MULTHEM aims to combine useful characteristics of both the aluminium and CFC materials molded together with the advantages of additive manufacturing in product design. Aluminium a good strength provider while also a good heat dissipator while CFC, a lightweight material with equal or more strength than aluminium; though less thermally conductive.
- Existing metal housings of real-world use-cases can be optimized for up to 50% mass reduction or more using multi-materials and by adopting mass reduction techniques presented without affecting design stability and thermal performance by keeping weights balanced.
- As an iterative process, considerations should be made while assigning multi-material to the designs, take into account the 3D printing process constraints and parameters for both metal and composite (layer thickness and line width). Low values limit the mass reduction process, and thus, balance is required between design optimization and manufacturing). Finally, the strength of the joint interface between multi-materials must be considered as essential to validate the process.

The outcome of MULTHEM project is basically a framework for multi-material additive

manufacturing process which could be adopted for enhancing mass reduction in existing metal-based designs. Therefore, this project is being contributed towards simultaneous progressing and strengthening of the capabilities of design for additive manufacturing (DfAM) field within the additive manufacturing industry.

8 FUTURE WORK

The use-cases in the MULTHEM project will be designed, simulated, manufactured and test-prototyped with multi-materials harnessing the advantages of 3D printing technology. Multi-material assignation in the designs in line with the development of new metal and polymer materials by different AM processes and joining techniques are the main activities which are under focus. Number of prototypes will be developed and tested under real world operating conditions for the designs to get validated. Exploitation strategies about the new designs of use-cases are also under development to get the maximum possible impact of MULTHEM project.

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