Case Study

Bike Crank Design Optimization – Towards Sustainable Product Design

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Summary

In pursuit of realizing a responsible production (*United Nations Sustainable Development Goal No.12*) of goods, sustainability considerations are becoming indispensable in an engineer's decision-making process throughout the product development. This case study presents a sustainable product design methodology, using a bike crank as an example. It is centered around Ansys Granta EduPack and Ansys Discovery, allowing for a concurrent consideration of material candidates (strategic material selection) and designs (FEA-simulation), respectively. Furthermore, it demonstrates means of structurally optimizing designs using topology optimization with the aim of reducing the amount of material required for a bike crank design. Beyond the structural analysis, a streamlined life-cycle-assessment is conducted to elucidate the ecological and economic impact of different material and design choices. In a final trade-off analysis, light is shed on key performance indices to make informed and responsible decisions and discusses additional consideration for critically assessing and improving material and design choices.

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1. Introduction

1.1 Background

A bike crank is the part in a bicycle that connects the pedal with the bottom bracket and spindle and is usually made from an aluminum alloy. There are multiple designs depending on the integration and fixture of the chain rings and spindle with the crank arms. The parts of such a crank set are often casted, forged or CNC machined depending on the business case (cost), batch size, and design complexity.
The objective of this case study is to explore the most sustainable bike crank design, considering the material and the component design concurrently and assess their environmental impact bases upon the energy and CO_2 footprint in all phases of the product's life cycle. Including the environmental impact assessment at the end of the design cycle addresses goal 12 of the SDGs [1] aimed at responsible consumption and production. Furthermore, the use of software also indirectly contributes to goal 4, serving to enhance the quality of education, which positively impacts learning [2]. The case study demonstrates a sustainable product design methodology, facilitated through software, which is aimed at supporting a conscious and targeted decision-making process for engineers and designers.

1.2 Methodology

Figure 1 illustrates the approach used in this case study to solve a multi-faceted product design problem, which includes the following steps:

1. Ideation: Define the problem and its function, objective, and constraints.
2. Strategic material selection: Employ the Ashby methodology embedded in Ansys Granta EduPack.
3. Structural Analysis/Optimization: Perform a topology optimization (TO) using Ansys Discovery.
4. Streamlined life-cycle-assessment (sLCA): Utilize the Eco Audit tool within Ansys Granta EduPack based on materials and design choices made in Steps 2 and 3.
5. Trade-off analysis: Elucidate and critically assess the mechanical, ecological and economic key performance indices (KPIs) for different bike crank designs and discuss additional considerations that could affect the decision-making process during the product design stages.

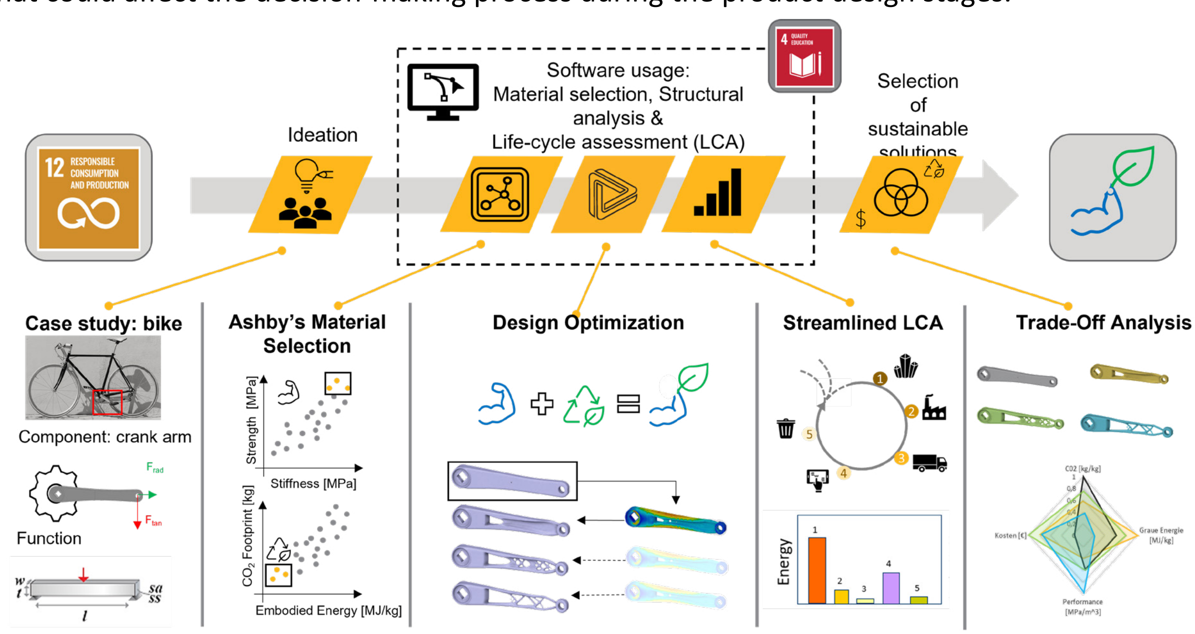

Figure 1: Overview of the holistic workflow to solve the bike crank design problem under ecological, performance, and economic considerations. Icons from this figure will be used throughout as a guide

The workflow illustrated in Figure 1 manifests itself in a product design strategy towards responsible production by considering material and design concurrently, while including an LCA and trade-off analysis as an integral part of the process (see Figure 2). The proposed Sustainable Product Design Methodology (SPDM) is comprised of a strategic material selection based on Ashby's methodology, using Granta EduPack, and the subsequent iterative structural analysis and optimization in the multi-physics simulation software Ansys Discovery. The interconnected nature of material and design choices on the ecological footprint is finally being further assessed using the Eco Audit tool in Granta EduPack, allowing for a more informed decisions and selection of the final design (incl. material and geometry).

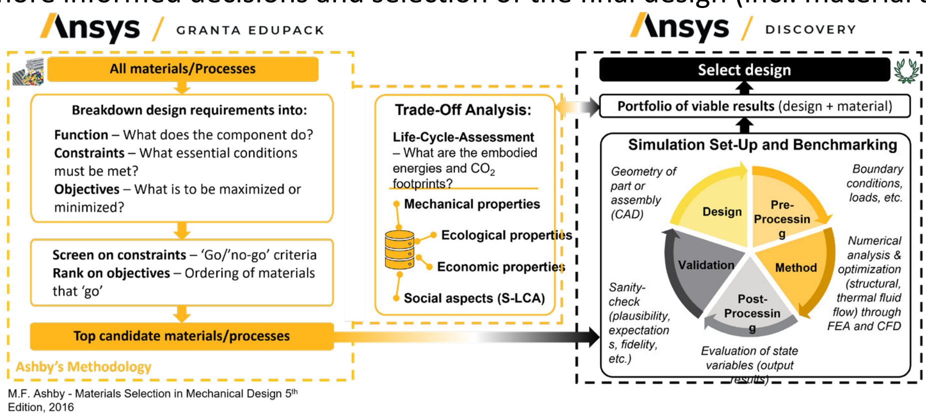

Figure 2: Sustainable product design methodology (SPDM), incorporating Ashby's strategic material selection methodology with the iterative engineering simulation workflow.

If you are new to the above mentioned software tools, the (self-) learning resources summarized in Table 1 are recommended and should serve as an introduction to key functionalities and tools employed in this case study.

Table 1: Summary of relevant links to (self-) learning education resources relevant to (i) get started with the software used in this case study and to (ii) be proficient in the specific tools and functionalities used.

Software	Relevant functionalities/tools	Links
Ansys Granta EduPack	General/Getting Started	Basic Systematic Materials Selection Ansys Innovation Course
		Materials Selection with Ashby Charts Ansys Innovation Course
	Eco Audit Tool	Introducing the Eco Audit Tool in Ansys Granta EduPack Tutorial
		The Granta EduPack Eco Audit Tool Technical Paper
Ansys Discovery	General/Getting Started	3D Design Ansys Innovation Courses
	Topology Optimization	Topology Optimization in Ansys Discovery Innovation Course

1.3 Problem Statement

The aim of this study is to find (i) suitable material substitutes for conventional aluminum alloy bike cranks as well as (ii) optimized designs that requires less material. In pursuit of a sustainable product design solution, the former centers on a strategic material selection by Ashby with the premise to maximize the specific stiffness while minimizing the ecological footprint alongside all the associated design requirements. The latter objective of the study aims to explore means of reducing the material usage by optimizing the bike crank design while maintaining the same stiffness and strength (safety factor = yield strength of the material divided by the maximum stress) as the original design. This constitutes a structural analysis, employing the finite element method which is considering design and material candidates concurrently. Subsequently, a sLCA shall elucidate the effect of different designs and materials on the overall ecological and economic impact. Lastly, a trade-off analysis compares and contrasts KPIs and discusses additional consideration towards a responsible production.

2. Strategic Material Selection

2.1 Reference Material

At the start a material selection project, it often helps to do a search about the materials that are commonly used for the product subject to investigation. This can be done within Ansys Granta EduPack, using the "Search" functionality. In this case study the advanced Level 3 database focused on sustainability will be used. By searching for "bike frame" in this database, one can conclude that Al7075, O (Figure 3) is a commonly used material and can be set as a "reference" material for this case study. Considering commonly used materials can also give an idea about general material families we should be considering for this product. For the case of a bike crank it seems to be sensible to exclude polymers and ceramics from the selection. This can be done, by defining a "subset of materials".

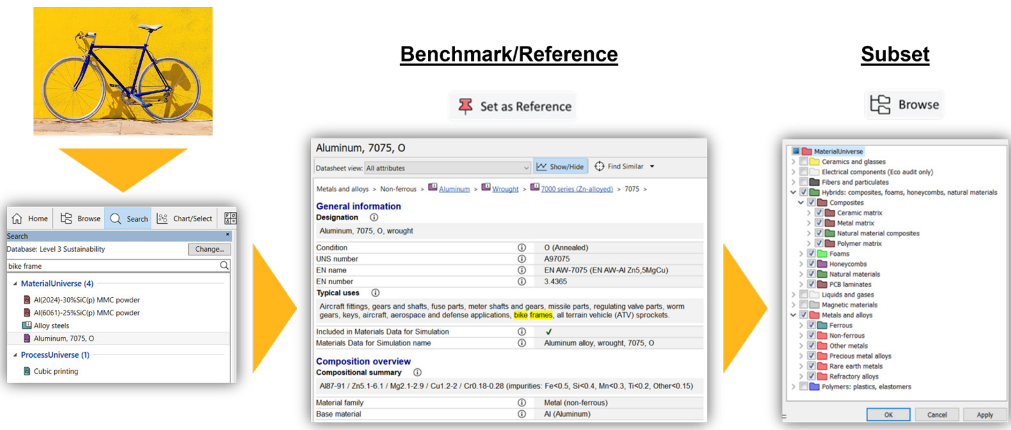

Figure 3: Search results in Ansys Granta EduPack for materials used for bike frames.

2.2 Ashby Methodology

Before setting any further selection criteria, it helps to define up a systematic way for the material selection process. Ashby *et al.* defines [3] this process by identifying the function, objectives, and constraints for the design (see Table 2). It is, therefore, crucial to determine which mechanical properties are key to the performance of a bike crank as a first step. As depicted in Figure 1, the bike crank's function can be simplified as a beam in bending, which is determined by the material's flexural Young's modulus. In this case study, a light and stiff crank shall be realized, *i.e.* a stiffness-limited design at minimum mass, considering the materials density. These two material properties are also reflected in the objective, aimed at minimizing the embodied energy and CO_2 footprint while maximizing the specific stiffness. This can be done using the "Performance Index Finder" tool as shown in Figure 4b.

Table 2: Ashby's design requirements made up of function, constraints, and objectives for the bike crank.

Function	Constraints	Objective
• Beam in bending • Stiffness-limited design	• Fracture toughness: 10 MPa·m$^{1/2}$ • Excellent durability against water and UV light • Recyclable	• Minimize both mass (lightweighting) and the ecological footprint (embodied energy & CO_2 footprint)[1] $M_1 = \frac{H_M \times \rho}{E_f^{1/2}}$ $M_2 = \frac{CO_2 \times \rho}{E_f^{1/2}}$

1 **Note:** H_m= Embodied energy, primary production; ρ=material density; E_f=flexural modulus; CO_{2M}=CO_2 footprint, primary production

Constraints refer to essential conditions that must be met. In this case fracture toughness as well as durability against fresh water and UV light are being considered (Figure 4a). Furthermore, in pursuit of realizing a more responsible production, only materials that are recyclable shall be considered.

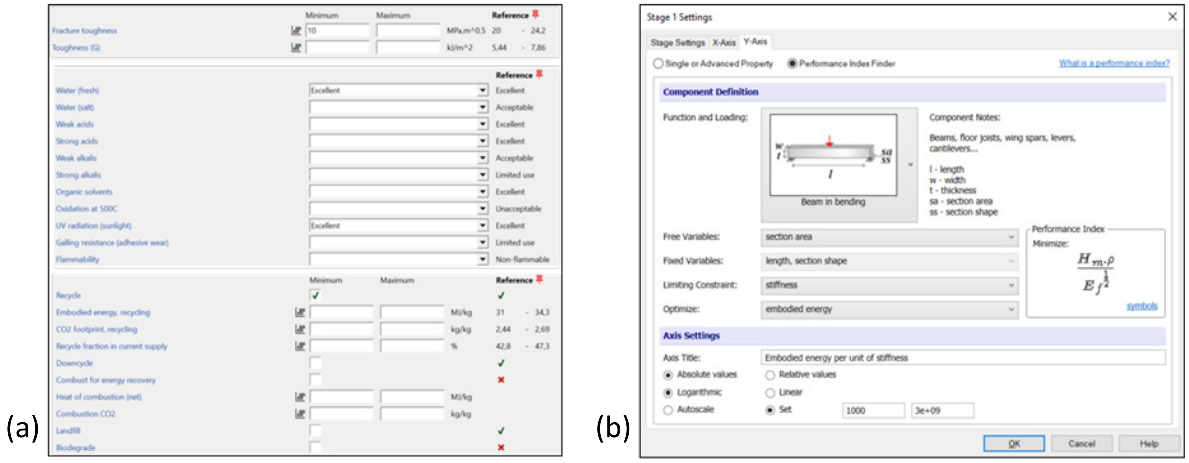

Figure 4: Interface of Ansys Granta EduPack showing (a) the limit stage for setting constraints and (b) the performance index finder for defining the joint material-design objective.

After applying the above-mentioned constraints and objectives, a clearer picture of possible material candidates for the bike crank can be created. These material candidates can now be ranked further on aspects such as price and density (responsible for weight), as shown in Figure 5. While cast iron may be an option for bicycles that are being produced in high quantities at lower cost, the use of titanium enables a reduction in weight which might be critical for competitive sports equipment. However, materials like titanium or alumina particle reinforced aluminum come at the expense of a higher material price and thus part cost. Here, the following material candidates have been chosen for the bike crank:

- Magnesium, commercial purity, ASTM 9980A
- Alumina particle reinforced Aluminum, Duralcan Al-10Al2O3(p) (W6A10A-T6)
- Boron carbide particle reinforced magnesium, Mg-30%B4C(p)
- Titanium, near alpha alloy, Ti-8Al-1Mo-1V, single annealed
- Cast iron, white, low alloy, EN GJN HV350 (former BS 1C)

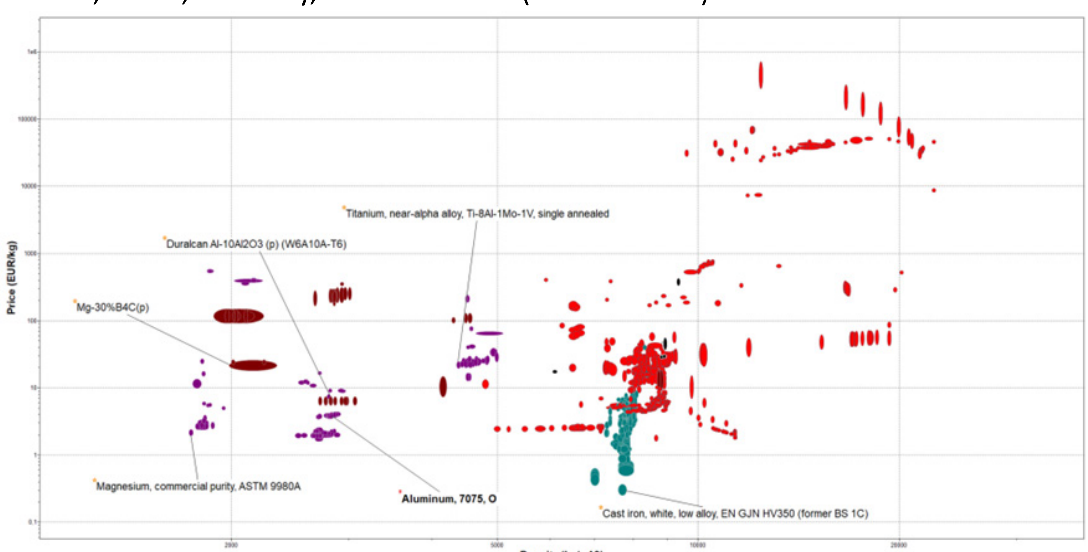

Figure 5: Ranking choice of material candidates based on price and density.

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2.3 Processing Considerations

As materials are tightly connected to manufacturing processes, it is important to consider the possible means of manufacturing for a design alongside their inherent constraints, such as the shapes that can be realized. For this purpose, the links between the *MaterialUniverse* and *ProcessUniverse* as well the Shapes (see Figure 6a) will be utilized in Granta EduPack.

Conventional bike cranks made from wrought aluminum like *Al7075*, are commonly manufactured using a forging process which can produce solid 3D shapes (see Figure 6b). However, when considering design optimization, including topology optimization, complex free-form shapes are generally generated. Thus, one must consider either a process (i) that is suitable for creating hollow 3D shapes or (ii) that accounts for design constraints in a solid 3D shape. The latter refers *e.g.* to cut-outs, under-cuts or cavities, that would hinder the liberation of the part from the tool. Figure 6b-d displays some of the most common and relevant primary processing strategies for the selected materials and 3D shapes, namely (i) Forging, (ii) Die Pressing and Sintering and (iii) Casting.

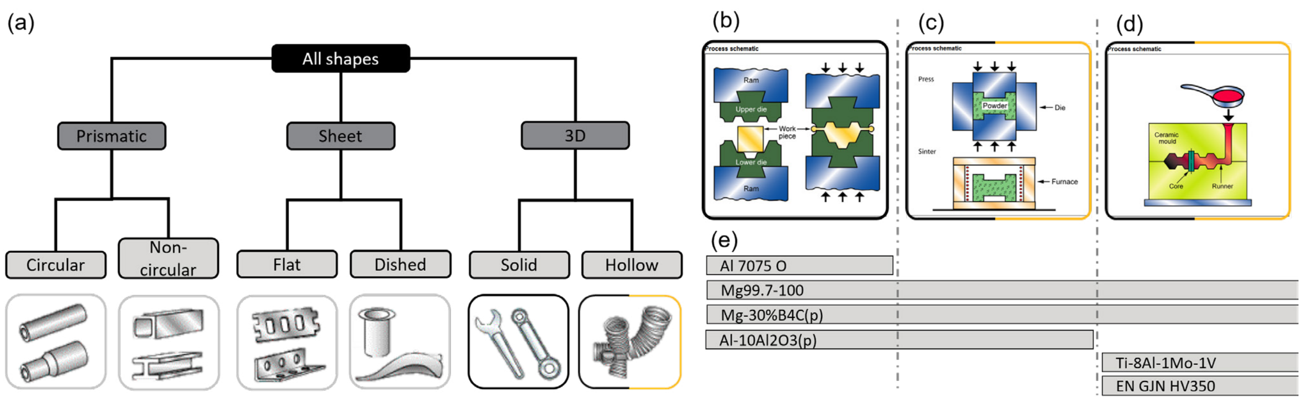

Figure 6: (a) Categorization of manufacturable shapes and link to relevant manufacturing methods for the bike crank, namely (b) forging, (c) die pressing and sintering, and (d) casting. Processes that can produce solid parts are outlined in black and ones that can create hollow parts are highlighted in gold (die pressing can do both). (e) shows which material candidates can be processed with the three chosen processes via a color gradient.

Now that the materials and processes have been identified, we move on to the structural analysis (Step 3).

3. Structural Analysis

3.1 Pre-Processing

To create a product, finding the optimal design is as vital as choosing the optimal material. In this section, the physical design of the bike crank will be optimized to further improve the ecological footprint by reducing material usage while maintaining the structural performance requirements. For this purpose, a structural simulation and subsequent design optimization is conducted, in which the different material candidates are benchmarked against the reference design made of Al7075. This is an iterative process providing scope for optimization before a final design is chosen. Initially, it is important to determine and define the loads and boundary conditions the bike crank will experience. Hereby, the maximum load the crank will experience is of interest. Studies [3, 4] have shown that the effective pedal forces during the pedal cycle at different power outputs and cadences show a max force at 90° (compare Figure 7). Approximating the maximum applied forces by F=ma for a 90kg cyclist we obtain a force of 450N on a single pedal, which is similar to the peak forces at 400 W found in [4] and will thus be used in the subsequent structural analysis.

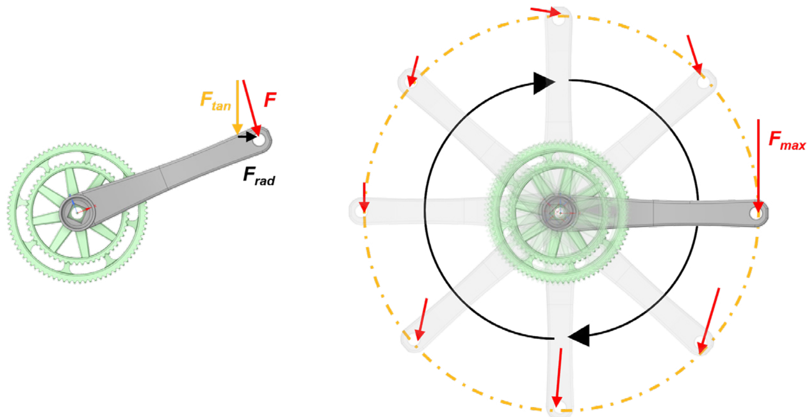

Figure 7: Illustration of the direction and magnitude of the resultant force F and its division into tangential F_{tan} and radial F_{rad} force components. Simplified and approximated resultant force for different stages during a single paddle stroke with maximum force acting perpendicular to the bike crank during its front-most position.

A prerequisite to the structural analysis is a CAD (computer-aided-design) model that can be created or imported using Ansys Discovery. Subsequently the boundary conditions are defined as illustrated in Figure 8, meaning a fixed boundary condition is applied at the fitting for the bottom bracket and a distributed force of 450N is applied in negative z-direction at the pedal fixture using a remote point offset by 42mm in negative y-direction (emulate force applied on the center of the pedal). This initial model of the bike crank, termed 'reference', will subsequently be used as a starting point for further design optimization.

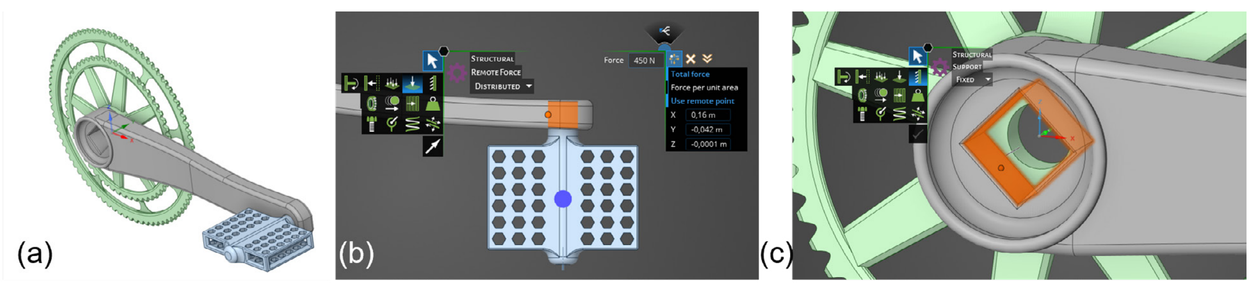

Figure 8: (a) Crank set assembly. (b) Remote force point on pedal is considered for the structural analysis of the bike crank. (c) A fixed boundary condition is applied at the rectangular fitting for the bottom bracket's spindle.

Table 3 summarizes the key state variables for this load case, obtained by utilizing the Explore Mode in Ansys Discovery with an element size of 0.35mm and Figure 9 displays the distribution of the equivalent von Mises stress.

Table 3: Results of the key state variables and parameters of the reference aluminum alloy bike crank design

Component	**Material**	**Factor of Safety**	**Max. Displacement [m]**	**Max. Von Mises Stress [MPa]**	**Mass [kg]**	**Volume [m³]**
Reference	AL7075,O	1.27	$7.33e^{-4}$	86.4	0.12	$4.27e^{-4}$

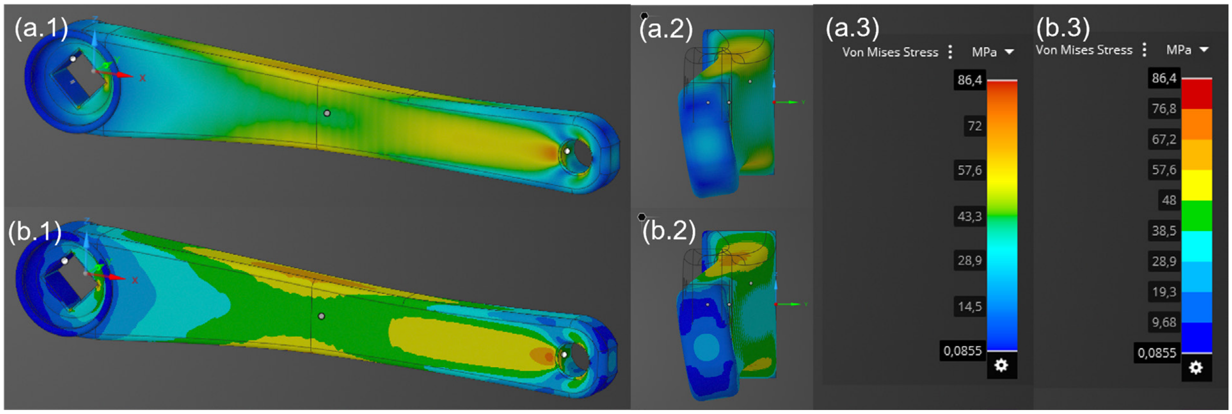

Figure 9: (a) Smooth and (b) gradient Von Mises stress distribution in the reference bike crank arm.

3.2 Design Optimization

Since the aim in this case study is to lower the environmental impact of the product, next a reduction in the amount of material used for the crank while ensuring its required structural performance will be explored. For this purpose, the stiffness and strength of the reference design will constitute the benchmark performance. Hereby, the stiffness of the bike crank constitutes the primary factor (similar to the stiffness-limited material selection criterion in Section 2) and the secondary factor is the safety factor.

A material-reduced design solution can either be found heuristically or mathematically. Generally, material can be reduced in places with the least concentration of stress. The distribution of stress within the design can be analyzed and visualized through Finite Element Analyses in Ansys Discovery (Figure 9). This allows for the introduction of recesses or the elimination of material (see Figure 10). Other popular methods include the use of lattice structures or topology optimization, as shown in Figure 10.

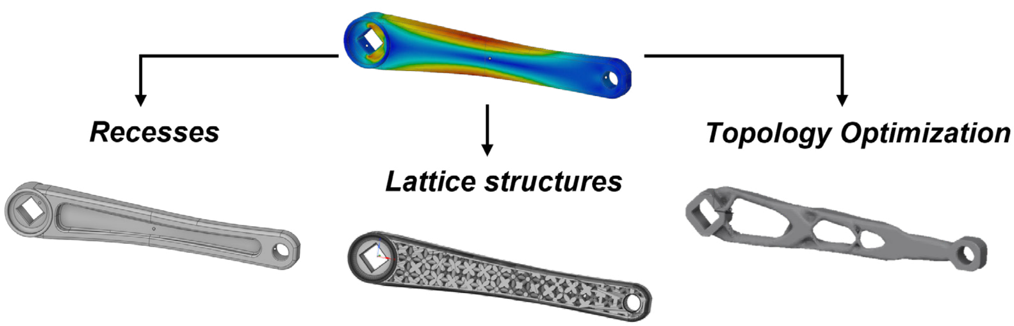

Figure 10: Approaches for optimizing the bike crank design for reduced material usage.

In this case study the Level-Set TO method will be employed, which can be set up from the simulation ribbon in the Explore Mode. By default, the objective function of the TO in Discovery is set to maximize the stiffness (minimize compliance) and remove material by a given percentage or volume. Moreover, a protected depth of 3.77mm is automatically applied to the surfaces at which boundary conditions and loads are applied (see Figure 11). This protected depth can be extended to other geometrical features that shall remain intact (unaffected by optimization) and effectively reduces the design domain (volume in which material can be removed). For this part, the element size for the topology optimization was set to 0.66mm. This is important to consider as topology optimization results are mesh-dependent, yielding different geometries (topologies) and performance values. Moreover, as indicated in Section 2.3, using a die pressing process simple hollow 3D geometries can theoretically be realized, however, more complex (free-form) geometries are likely not easy or possible to manufacture due to shape limitations of the split tool (die). Consequently, a mold-based manufacturing constraint, *i.e.* the "pull direction", was considered in the TO design with Al-10Al2O3(p). Here the pull direction was chosen that is co-axial with the foot pedal and spindle holes.

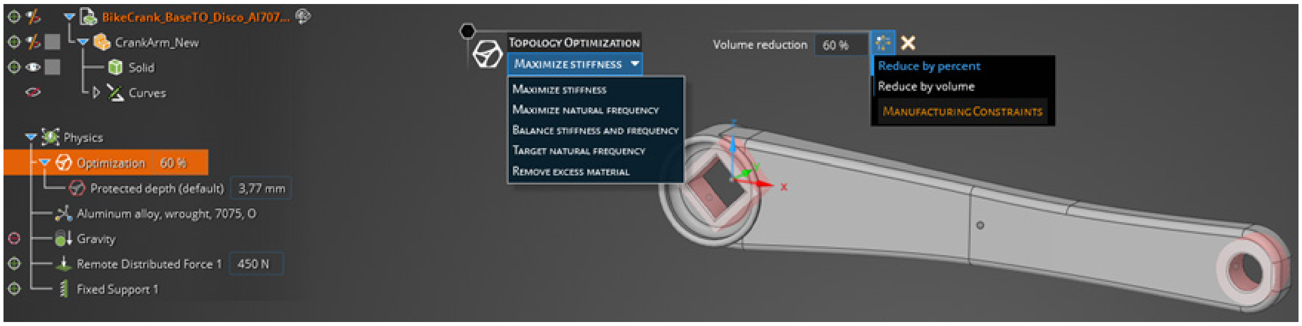

Figure 11: Topology optimization objectives and manufacturing constraints for a given volume reduction, with the boundary conditions defined as 'protected' (domains shown in red remain unaffected by the optimization).

Once an optimal design is generated, it needs to be evaluated with respect to the material used. This is done by comparing each material candidate with the reference material *Al 7075 O*. Hereby, the stiffness was chosen as the primary and the safety factor as the secondary performance indicators that need to be matched by the new material and design selection. By substituting the reference design with the pure magnesium (Mg99.7-100), it becomes evident that there is no scope for material savings. In fact, this design shows a significant drop in stiffness and safety factor (see Figure 12), ruling the material out as viable substitute. When considering the boron carbide particle reinforced counterpart, the safety factor requirements are met, however, the primary objective of matching the stiffness of the reference design is not met, as shown in Table 4. Therefore, it also does not provide scope for material reduction and can be ruled out a potential candidate for the bike crank.

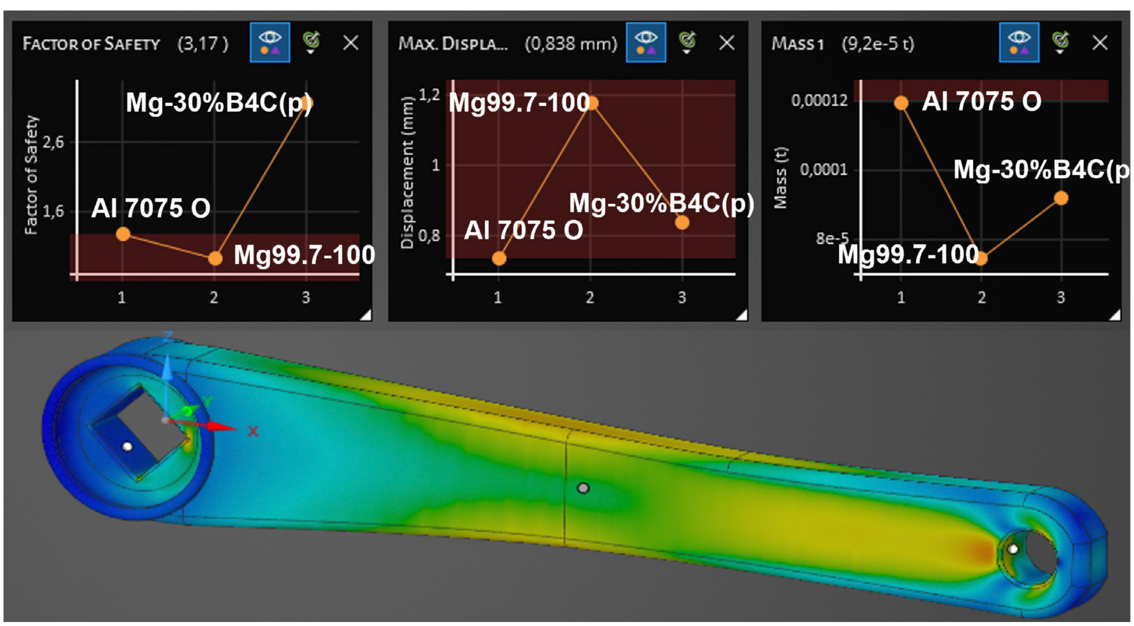

Figure 12: State variables for the reference bike crank geometry made from Al 7075 versus pure magnesium (Mg99.7-100) and boron carbide particle reinforced magnesium (Mg-30%B4C(p)).

As summarized in Table 4, the required material volume can be significantly reduced by employing TO while matching the equivalent performance of the reference design when using alumina particle reinforced aluminum (Duralcan Al-10Al2O3(p)), titanium alloy (Ti-8Al-1Mo-1V) or cast iron (EN GJN HV350). While the former two yield a stiffness-limited design, the latter is limited by its strength and thus even outperforms the reference design in terms of compliance.

Table 4: Results of the key state variables (stiffness, strength, and weight) for different bike crank designs and material choices in comparison to the reference design made from Al7075

Material	Factor of Safety	Max. Displacement [m]	Max. Von Mises Stress [MPa]	Mass [kg]	Volume Reduction [%]
Reference Design					
AL7075,O	1.27	$7.33e^{-4}$	86.4	0.12	$4.27e^{-4}$
Reference Design with Material Substitutes					
Mg99.7-100	0.94	$1.18e^{-3}$	87.3	0.0743	0
Mg-30%B4C(p)	3.17	$8.38e^{-4}$	88.8	0.092	0
Optimized Stiffness-Limited Design (equal max. displacement as Reference Design)					
Al-10Al2O3(p)	3.37	$7.34e^{-4}$	81.3	0.104	12.9
Ti-8Al-1Mo-1V	5.72	$7.33e^{-4}$	147	0.0729	60.6
Optimized Strength-Limited Design (equal safety factor as Reference Design)					
EN GJN HV350	1.26	$5.96e^{-4}$	259	0.111	66.1

Note: The colors denote a ***exceeding***, ***matching*** *or* ***insufficient or lower*** *stiffness, strength and part weight compared to the reference design.*

Figure 13 illustrates the performance of the optimized bike crank design in comparison to the reference design (RD) qualitatively and visualizes the equivalent stress distribution in the final topologies.
As outlined in Table 4, most material volume can be saved when utilizing the cast iron, however, this option also yields the heaviest design. The lightest and safest design on the other hand can be realized using the titanium alloy. The reinforced aluminum alloy displays weight-saving opportunities for the same stiffness while also improving the safety factor in comparison to the RD.

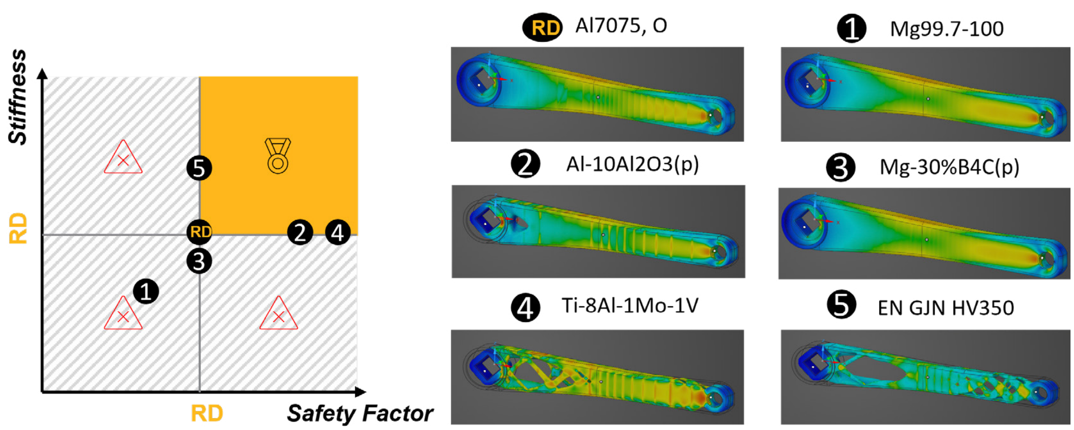

Figure 13: Bike crank performance of the reference design (RD) versus the (optimized) design counterparts/ alternatives. Designs that exist in the upper right-hand quadrant of our comparison chart of stiffness vs. safety factor are considered acceptable.

3.3 Post-Processing

After a TO solution has been obtained, it is first necessary to generate a faceted geometry (see Figure 14). While a validation simulation could be conducted on the faceted geometry, it is often favorable to convert it into a solid geometry which can be more easily integrated into existing part assemblies. For this purpose, it is recommended to employ the various post-processing tools for facts before converting to a solid to ensure the geometry is free of errors. Subsequently, it might be necessary to utilize the repair functionalities to either generate a watertight surface, *i.e.* solidify a surface geometry, or to generally clean up a solid body.

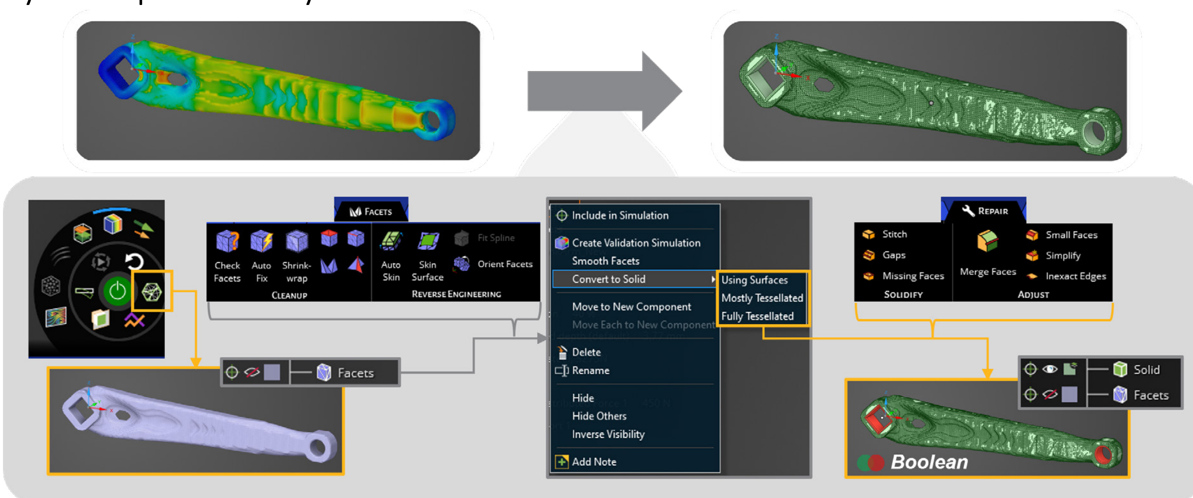

Figure 14: Post-processing (reverse-engineering) workflow from a topology optimization solution to a solid geometry.

It is good practice to keep a CAD of the 'protected depth geometries' stored alongside the main model to conduct a final Boolean operation that ensures tessellated surfaces are substituted by (single) well-defined counterparts that ease the application of the original boundary conditions for validation simulations. In Figure 14, focus was put on the conversion to solids via tessellation, however, a reverse-engineering via the Sub-D tool (subdivision surfaces) may also be considered.

As summarized in Table 4 three materials met the performance requirements in terms of stiffness and strength compared to the reference design while reducing its material volume. The final designs obtained by TO are displayed in Figure 15.

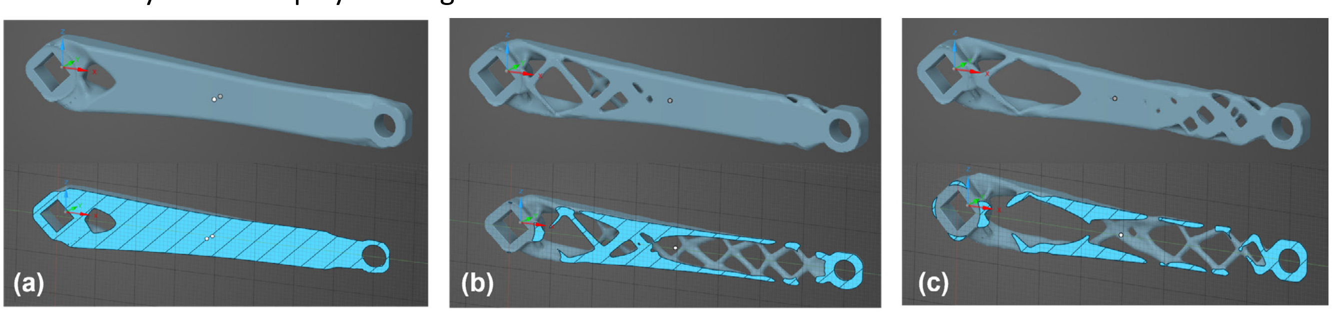

Figure 15: Optimized (solid) CAD designs of the bike crank made from (a) Al-10Al2O3(p) and considering the pull direction as manufacturing constraint, (b) Ti-8Al-1Mo-1V and (c) EN GJN HV350.Section-cut views are included in the bottom row for better visualization.

Now that the structural design that considers both the material candidates and topology optimization has been identified, we move on to Step 4 in our workflow.

4. Streamlined Life-Cycle-Assessment (sLCA)

4.1 Considerations

For the sLCA or life-cycle-inventory (LCI), the Enhanced *Eco Audit* tool tool of Granta EduPack will be employed. It is designed in collaboration with industry to deliver results with sufficient precision to guide decision making in the early design stage. It considers four life phases: material production, product manufacture, product use and end of life. The inventory focuses on energy as a resource and CO_2 for emissions as well as the cost associated with the product. The results highlight the economic and environmental factors for each life phase and are displayed in a chart as well as a more detailed report (see Figure 17 & Figure 18). This helps identify which of the main life phases has the biggest impact.

The sLCA conducted in this case study utilizes the increased environmental data within the Level 3 Sustainability database in Granta EduPack and takes the following consideration for the life phases into account:

- **Material & Extraction** – The embodied energy and CO_2 footprint associated with the primary production of the different raw materials is considered as well as the amount of material required
- **Production & End of Life** – A total of 300 bike cranks are considered for production with a primary and finishing process. A primary shaping process takes an unshaped material (as ingot, powder, pellets, granules, or resin) and gives it shape. As outlined in section 2.3, solid shapes of aluminum alloys are primarily produced using forging process such as cold/hot (closed) die forging while casting processes such as ceramic mold casting would be suitable to realize the complex solid free-form shapes intended for the bike cranks made of titanium alloys and cast iron. On top of both those primary processes considered for the sLCA, a polymer powder coating will be considered as a finishing of the metallic cranks (see Figure 16). For simplicity the same surface area of 0.1m2 is assumed. In line with the material selection constraints defined in section 2.2, the crank shall be recycled after the end of life. This is the best way to extract value from waste and return materials to the supply-stream, preserving material stock. In this context, two scenarios will be compared, the first and second life of the product in which a recycling amount of 50% of the virgin material content is considered:
  - Scenario 1: 100% virgin material and 50% of material gets recycled.
  - Scenario 2: 50% recycled content and 25% of material gets recycled.

  Alternatively, one could consider or compare a scenario in which a re-conditioning or re-manufacturing approach is pursued to restore used products or recover components to as-new condition. However, it must be noted that establishing a market and maintaining a supply chain of recondition products is not easy, and issues of warranty and responsibility for malfunction are deterrents.
- **Transport & Use** – Here the manufacturing site of the bike cranks is situated in Zurich (Switzerland). The small-series bike crank sets of 150 pieces are transported via a 'light commercial vehicle' to its destination in Paris (France). For the transport a packing of 0.05m × 0.2m × 0.15m (H × W × D) is assumed for a pair of bike cranks (see Figure 16). Lastly, a product life of 10 years is assumed in this case study.

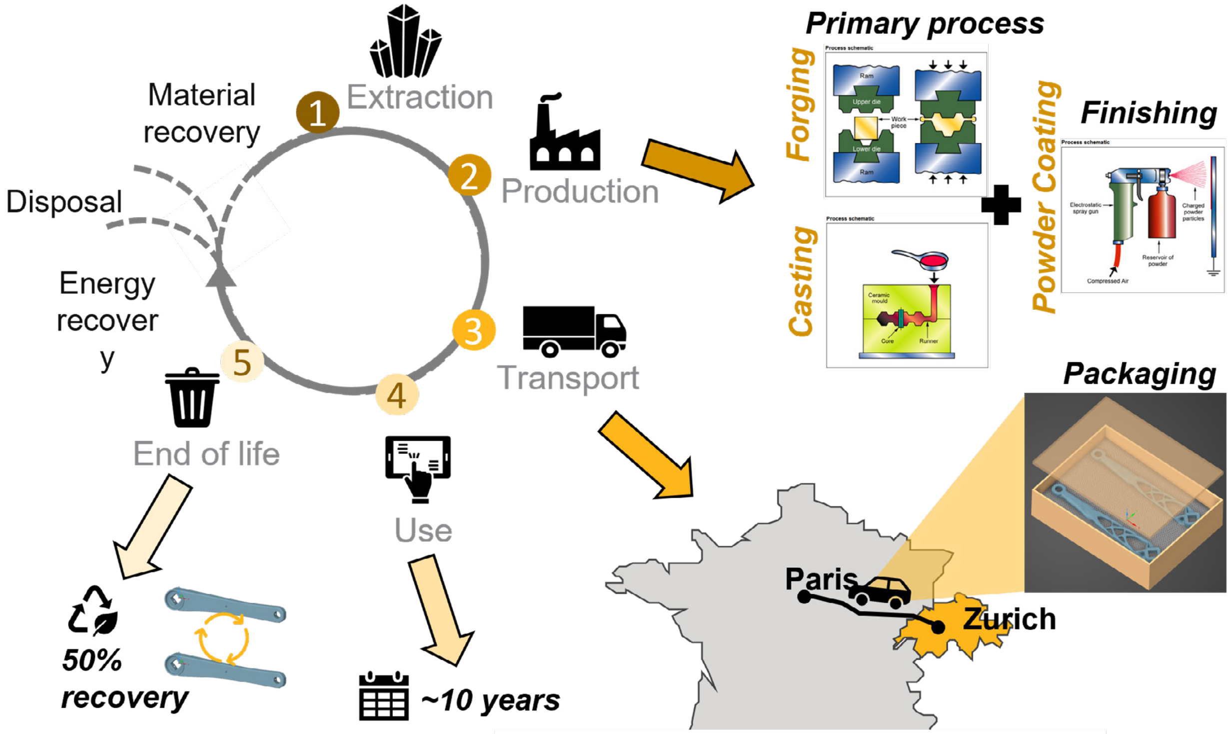

Figure 16: (a) Schematic of the steps in the sLCA and (b) packaging and transport from Zurich (manufacturing site) to Paris in a light goods vehicle.

4.2 Analysis – Advanced Eco Audit

For this case study we are comparing the *Eco Audit* results of the original design using the reference material, with the optimized designs (alternative material candidates), as shown in Figure 17. Therefore, details such as the bill of materials, the weight of the component, the recycled content and manufacturing process used as well as the end-of-life scenario (*i.e.* recycling or landfill) must be specified. Here, the only options that are changing for the different designs are the choice of material, as well as their corresponding weight, which is dependent on the material density and the dimensions of the different designs.

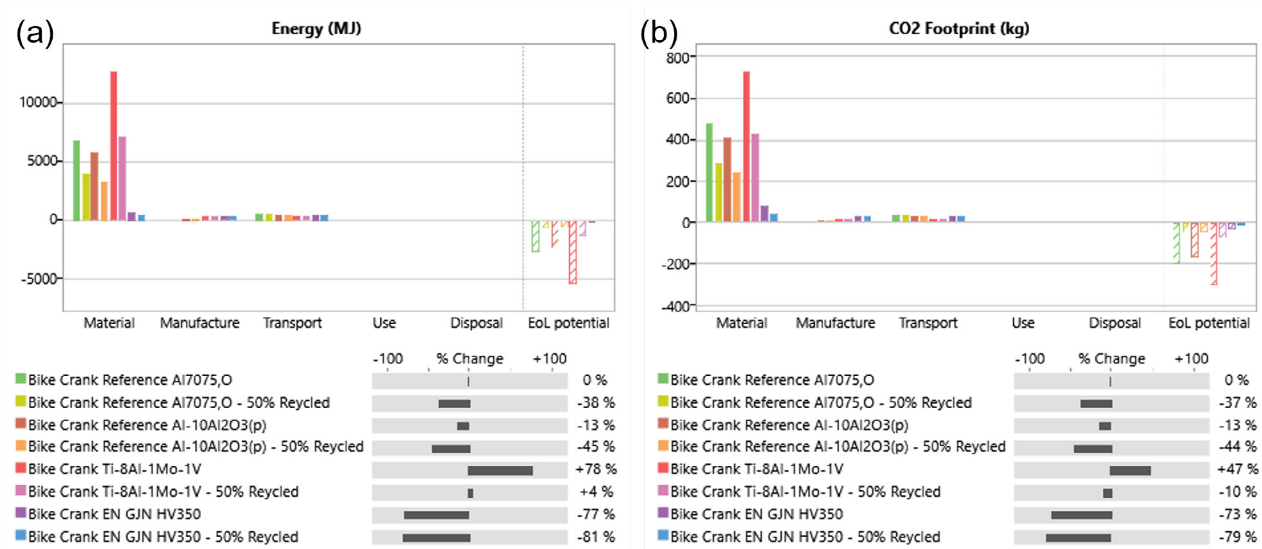

Figure 17: Advanced Eco Audit summary chart for the (a) embodied energy and (b) CO_2 footprint.

Figure 17 shows that the materials phase affects the ecological impact most. Here, the titanium alloy displays a much higher energy usage and CO_2 footprint compared to cast iron and the reinforced magnesium; however, the sLCA also shows a higher "end-of-life potential" (EoL potential) in the titanium alloy. The "EoL potential' represents the end-of-life savings or 'credits' that can be realized in future life cycles by using the recovered material or components. Both the cast iron and the reinforced magnesium are lower in energy and CO_2 footprint as compared to the titanium alloy, however their potential to gain credits in a second life phase is much lower. A detailed summary of the energy LCA for the bike crank designs is provided in Table 5.

Table 5: Eco Audit Summary for bike crank designs made of 100% and 50% virgin material, of which 50% is recovered through recycling (*i.e.* 50% and 25% of the total material used).

Design	**Energy [MJ]**	**Energy EoL Potential [MJ]**	**CO_2 Footprint [kg]**	**CO_2 Footprint EoL Potential [kg]**	**Cost [Euro]**
Designs with 100% Virgin Material					
AL7075, O	7,520	-2,810	529	-195	1,830
Al-10Al_2O_3(p)	6,530	-2,390	462	-166	1,670
Ti-8Al-1Mo-1V	1,340	-5,530	779	-301	2,530
EN GJN HV350	1,700	-269	144	-31	2,100
Designs with 50% Virgin Material					
AL7075, O	4,700	-704	334	-48.6	1,750
Al-10Al_2O_3(p)	4,410	-597	295	-41.6	1,610
Ti-8Al-1Mo-1V	7,860	-1,380	478	-75.3	2,410
EN GJN HV350	1,430	-67.2	112	-7.75	2,100

While the material itself offers the greatest potential for improvements from an ecological standpoint, the manufacturing process takes the greatest weight from an economic standpoint (see Figure 18). Important to note is that while cast iron is very cheap as a material feedstock it is associated with the greatest manufacturing cost. Overall, it can be concluded that a bike crank made from reinforced magnesium constitutes the cheapest, while a counterpart made from the titanium alloy constitutes the most expensive option (compare Table 5).

With the sLCA complete, it is time to discuss trade-offs (Step 5).

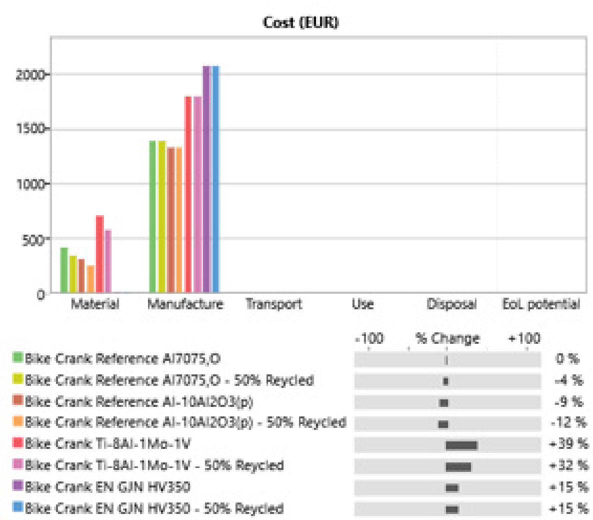

Figure 18: Advanced Eco Audit summary chart for the product cost.

5. Trade-Off Analysis

The most important key performance index (KPI) is the structural performance of the part which guarantees the core functionality of the part. Beyond that, there a multiple factor affecting *e.g.* the overall quality and cost of the part. It is important to recognize that those decisions are generally tightly connected to a business case and are thus exposed to the conflicting priorities of time, quality, and cost (see Figure 19(a)). These can be referred to the 'traditional' product development pillars. In pursuit of meeting the SDGs, these 'economic' factors represent only one pillar that is complemented by environmental and social aspects (see Figure 19(b)); some of which will be compared for the bike example in Section 5.2.

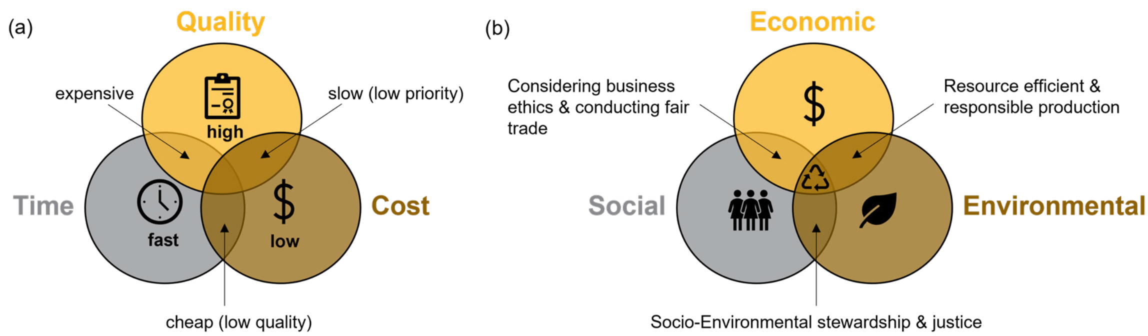

Figure 19: Conflicting priorities or pillars in (a) traditional (economic) and (b) sustainable (adapted from [5]) product development.

5.1 Key Performance Indices (KPIs)

Figure 20 summarizes the mechanical as well as ecological and economic KPIs, as determined through Ansys Discovery and Ansys Granta EduPack, respectively. Here, the structural performance is compared between the reference design made from *Al7075, O* with the topology optimized designs made from other material candidates (compare Table 4). The ecological and economic scores are based upon Scenario 1 of the sLCA (compare Section 4). If all 5 factors were to be considered equally (same weighting), it can be concluded that cast iron achieves the highest score, followed by particle reinforced aluminum, the titanium alloy and lastly the reference design. As outlined above, many additional factors come into play when choosing the right design and often businesses prioritize certain factors more than others. If a business was to choose a 'Performance-Line' or 'Budget-Line' to enrich their bike crank portfolio they may be more inclined to choose an optimized design made from titanium alloy or a simpler design made from aluminum alloy, respectively.

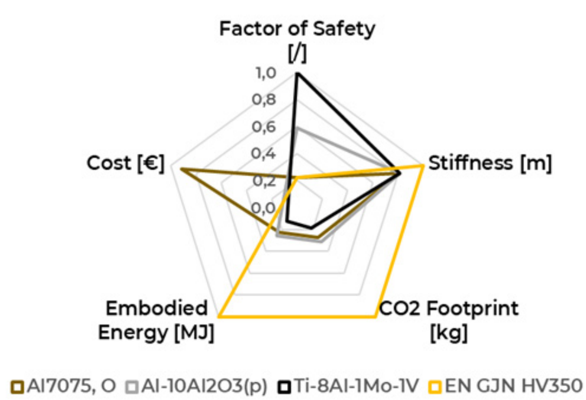

Figure 20. Radar plot visualizing the trade-off between mechanical, economic, and ecological KPIs. Note that the KPIs are normalized from best (1) to worst (0).

5.2 Additional Aspects for Consideration

Beyond the KPIs of interest for this case study, there is a multitude of additional factors that are linked to those pillars/spheres shown in Figure 19(b) that should be considered; the following bullets points provide some examples:

- Manufacturing Method:
  - Does the firm already have specific manufacturing capabilities or would new investments for hardware be required to create the new designs?
  - What is the target batch size and is the throughput for the manufacturing process achievable?
- Supply Chain:
  - Can the material be supplied short or long term and what is the general annual production?
  - Where will the material be sourced from and what would be the transport cost and associated environmental and social impacts?
  - Are there any supply chain risks associated and does the material contain critical elements?
- Market/Sales:
  - What is the target group for the product (*i.e.* low cost mass market or vice versa), *i.e.* what should be the maximum product costs and possible profit margin?
  - What are the distribution channels?

By employing the Comparison Table functionality in Ansys Granta EduPack some additional guidance can be provided on some of the abovementioned questions (see Figure 21). With the information provided in this table, the material candidates can easily be compared on aspects like critical materials, processing, recycling, and geo-economic data:

- **Critical materials risk** – An aspect to highlight from the table is that cast iron's lack of critical elements and minimal abundance risk, thus posing the lowest supply risks. While this may not be of relevance for a small batch size like the one considered in this case study, it might have implication for scaling up production. Regarding the geopolitical risk associated with sourcing, it is also comparable to the reference material and environmental country and conflict material risk level are also lower compared to the aluminum alloy *Al7075*, which is categorized as 'Caution'.
- **Processing properties** – Considering the repairability of the bike crank, the use of a material like the titanium alloy may be favorable, as it can be welded. Generally, both the titanium and aluminum alloy offer a good range of potential manufacturing options.
- **Primary production energy** – Besides the embodied energy and CO_2 footprint, it might also be worth considering (under an ecological perspective) that the titanium alloy and cast iron require significantly less water compared to Al7075. While water is a renewable resource, it only remains renewable at the rate the eco-system allows. Thus, the production with aluminum alloy may put the supply under more pressure.
- **Recycling and end of Life** – The main factor to mention here is related to the two LCA scenarios discussed in Section 4, namely the recycling fraction in the current supply. From Figure 21, it can be inferred that Scenario 2 is unrealistic for *Al-10Al2O3*(p); while a larger percentage of recycled and downcycled material of the three other candidates (Mg-30%B4C(p), Ti-8Al-1Mo-1V, EN GIN HV350) is currently available in total worldwide supply as compared to the reference material.
- **Geo-economic data** – When it comes to the general depletion of the resources, it is worth highlighting that aluminum is more abundant in the earth's crust compared to the other alloys under consideration; however, if magnesium and iron are sourced from seawater, a lower depletion is expected. Furthermore, looking at the reserves, the known quantity of usable iron that can be extracted profitably at today's price using today's technology is significantly higher than that of aluminum.

Lastly, it is worth highlighting that social aspects are becoming increasingly important when considering materials and constitutes an integral part to sustainable product design. For this purpose, investigations into social LCA tools are gaining traction [7]. A social LCA aims to improve the social conditions as well as the socio-economic KPIs linked to the product life phases by identifying focal points. These can be present between stakeholders and linked to aspects mentioned above (*i.e.* materials, manufacture, distribution and use), ranging from human well-being, through working conditions/rights, equal opportunities to business ethics or fair trade.

	Aluminum, 7075, O	Duralcan Al-10Al2O3 (p) (W6A10A-T6)	Mg-30%B4C(p)	Titanium, near-alpha alloy, Ti-8Al-1Mo-1V, single annealed	Cast iron, white, low alloy, EN GJN HV350 (former BS 1C)
Computed Properties					
Embodied energy per unit of stiffness	61500	-6 % ↓	+40 % ↑	+272 % ↑	-80 % ↓
CO2 footprint per unit of stiffness	4350	-5 % ↓	+31 % ↑	+203 % ↑	-70 % ↓
Restricted substances risk indicators					
RoHS 2 (EU) compliant grades?	✓	✓	✓	✓	✓
EU REACH Candidate List indicator (0-1, 1 = high risk)	0	0	0	0	0
SIN List indicator (0-1, 1 = high risk)	0	0	0	0	0
Critical materials risk					
★ Contains >5wt% critical elements?	Yes	Yes	Yes	Yes	No ↑
★ Abundance risk level	Medium			Medium	Low ↓
★ Sourcing and geopolitical risk level	High			Low ↓	High
★ Environmental country risk level	Very high			Medium ↓	High ↓
Price volatility risk level	Low			Low	Medium ↑
★ Conflict material risk level	Caution			None ↓	None ↓
Processing properties					
Metal casting	Unsuitable	Limited use ↑	Limited use ↑	Limited use ↑	Acceptable ↑
Metal cold forming	Acceptable	Limited use ↓	Limited use ↓	Acceptable	Unsuitable ↓
Metal hot forming	Excellent	Limited use ↓	Limited use ↓	Acceptable ↓	Unsuitable ↓
Metal press forming	Acceptable	Limited use ↓	Limited use ↓	Acceptable	Unsuitable ↓
Metal deep drawing	Acceptable			Limited use ↓	Unsuitable ↓
Machining speed (m/min)	140			9,75 ↓	21,3 ↓
★ Weldability	Poor			Good ↑	Poor
Weldability_Notes	Due to its susceptibility to stress corrosion cracking, welding should be extremely limited.			Preheating and post weld heat treatments are not required	Preheating and post weld heat treatments may be required
Primary production energy, CO2 and water					
Embodied energy, primary production (virgin grade) (MJ/kg)	189	-2 % ↓	+75 % ↑	+208 % ↑	-88 % ↓
Embodied energy, primary production (typical grade) (MJ/kg)	119	+56 % ↑	+47 % ↑	+126 % ↑	-88 % ↓
CO2 footprint, primary production (virgin grade) (kg/kg)	13,4	-1 % ↓	+63 % ↑	+151 % ↑	-82 % ↓
CO2 footprint, primary production (typical grade) (kg/kg)	8,53	+55 % ↑	+39 % ↑	+93 % ↑	-83 % ↓
★ Water usage (l/kg)	1130	-6 % ↓		-82 % ↓	-96 % ↓
Recycling and end of life					
Recycle	✓	✓	✓	✓	✓
Embodied energy, recycling (MJ/kg)	32,6	-1 % ↓	+53 % ↑	+135 % ↑	-80 % ↓
CO2 footprint, recycling (kg/kg)	2,56	-2 % ↓	+53 % ↑	+135 % ↑	-80 % ↓
★ Recycle fraction in current supply (%)	44,9	-100 % ↓	+20 % ↑	+38 % ↑	+16 % ↑
Downcycle	✓	✓	✓	✓	✓
Combust for energy recovery	✗	✗	✗	✗	✗
Landfill	✓	✓	✓	✓	✓
Biodegrade	✗	✗	✗	✗	✗
Geo-economic data for principal component					
Principal component	Aluminum	Aluminum	Magnesium	Titanium	Iron
Typical exploited ore grade (%)	32	0 %	-100 % ↓	-50 % ↓	+48 % ↑
Minimum economic ore grade (%)	31,2	0 %	-100 % ↓	-75 % ↓	+34 % ↑
★ Abundance in Earth's crust (ppm)	83200	0 %	-69 % ↓	-94 % ↓	-39 % ↓
Abundance in seawater (ppm)	0,00158	0 %	+7,59e7 % ↑	-37 % ↓	+73 % ↑
Annual world production, principal component (tonne/yr)	5,73e7	0 %	-98 % ↓	-87 % ↓	+3780 % ↑
★ Reserves, principal component (tonne)	2,69e10	0 %		-98 % ↓	+490 % ↑

Figure 21: Comparison table created in Ansys Granta EduPack for the material candidates considered for the bike crank. Note: Stars indicate material properties discussed in Section 5.2

Finally, in light of the objective of making production more responsible (sustainable Development Goal 12), there is not only scope for critically assessing and discussing the material choices but also the design itself. So instead of just considering recycling an even better liable solution would be to re-use and repair components as best as possible. Thus, one might consider a modular design, allowing for a part of the crank to be repaired, which would require less resources compared to producing an entirely new component. An example of such a design made from the titanium alloy is shown in Figure 22(a)/(b). This offers similar or improved structural performance while significantly reducing the amount of material required (see Table 6).

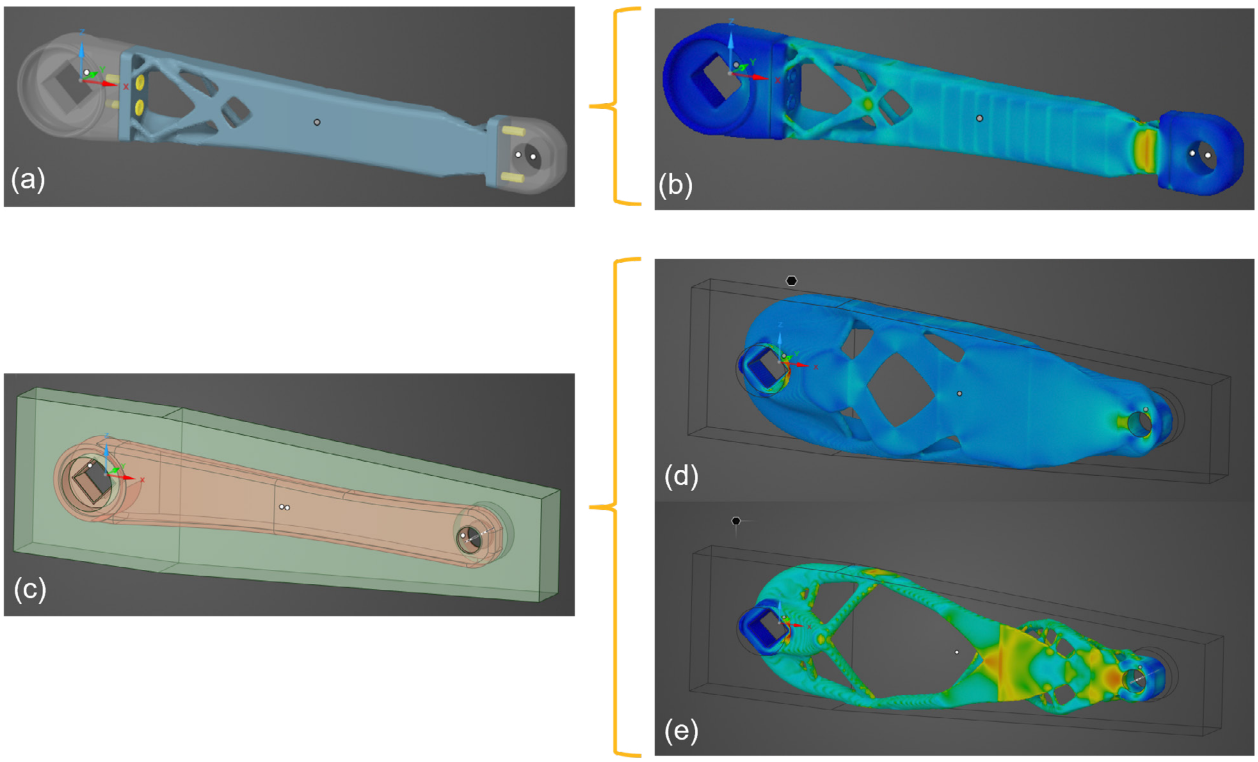

Figure 22: (a)/(b) 3-part design for ease of repairability with the central domain topology optimized (60% volume reduction) and assembled in a bolted connection considering Ti-8Al-1Mo-1V for the entire assembly and (ideal) bonded contacts. (c) Extended design space (green) with identical boundary conditions compared to the standard bike crank load cases yielding re-designed variants made of Al7075 with (d) identical weight and (e) performance (safety factor) as the reference design.

Similarly, numerical design optimization methods like topology optimization can be further exploited if one starts to re-think how a bike crank should look like. In this case study, designs were compared and optimized starting with the reference design, thus limiting the possible solution through the available design space. By increasing the design space, as indicated by the green domain in Figure 22(c) while keeping the boundary conditions consistent, significant performance and material savings can be achieved. Considering Al7075, and designing a new bike crank with the same mass as the reference design (see Figure 22(d)), a grater stiffness and strength can be achieved (compare '*Re-Design 1*' in Table 6). Even more material can be removed while matching the benchmark design performance in regards to the safety factor (compare Figure 22(e) and '*Re-Design 2*' in Table 6).

Table 6: Results of the key state variables (stiffness, strength, and weight) for different bike crank designs and material choices in comparison to the reference design made from AL 7075.

Design	Material	Factor of Safety	Max. Displacement [m]	Max. Von Mises Stress [MPa]	Mass [kg]	Volume Reduction [%]
Reference	AL7075,O	1.27	7.34e^{-4}	86.4	0.12	N/A
	Reference Design with Material Substitutes					
Modular Design	Ti-8Al-1-Mo-1V	2.86	7.05e^{-4}	294	0.11	60
Redesign 1	AL7075,O	1.55	1.67e^{-4}	70.6	0.12	76.8
Redesign 2	AL7075,O	1.32	4.00e^{-4}	83.2	0.06	88.6

Note: The colors denote a ***exceeding***, ***matching*** *or* ***insufficient or lower*** *stiffness, strength and part weight compared to the reference design.*

6. Reality check and conclusions

This case study presents a sustainable product design methodology, exploring the material selection, design optimization and life-cycle-assessment of a bike crank in pursuit of a responsible production. For this purpose, both the structural performance and ecological footprint (CO_2 and embodied energy) were already considered during the strategic material selection with Ansys Granta EduPack. Subsequently, and under the same premise, topology optimization was conducted using Ansys Discovery, with the goal of reducing the amount of material used. This has been done by comparing the material candidates chosen previously and identifying a material-dependent design while not compromising performance (stiffness and strength). The materials and design choices were subsequently evaluated regarding the different phases of life of a bike crank, using the *Enhanced Eco Audit* tool within Ansys Granta EduPack, to quantify ecological and economic performance indices. The final designs have been critically assessed in a conclusive trade-off analysis. Overall, the proposed sustainable product design methodology accounts for the consideration of alternative materials and designs concurrently, to facilitate an informed decision-making-process under ecological, structural, and economic standpoints.

As with any case study, it is important to compare and contrast your results with real life examples or current research. In fact, similar design optimized cranks are currently available on the market:

- Lightweight (design-optimized) aluminum bike crank manufactured using 5 axis CNC machines: 5DEV
- Fatigue-resistant design of a selective laser melting (SLM)-manufactured aluminum bicycle crank: Revealing the simulation-driven approach behind a 3D-printed bicycle crank (gknpm.com)
- Topology and response surface optimization of a bicycle crank arm with multiple load cases [7]

In addition, it must be noted that this case study represents a simplified structural analysis. In real life, more complex load cases would have to be considered:

- Modal Analysis (Bike Crank): Designing Bike Crank with Ansys Discovery | Ansys Courses
- Fatigue Analysis: Automotive Components Design: Structural Analysis | Ansys Innovation Courses & Harmonic Response Analysis in Ansys Mechanical | Ansys Innovation Courses
- Dynamic Analysis: BAJA SAE Chassis Dynamic Analysis Using Ansys Mechanical | Ansys Innovation Courses
- Topology Optimization: Besides the single-load case TO, Ansys Discovery enables an optimization of the design for multiple load cases concurrently. Moreover, a stress-based TO could also be taken into consideration for this case study

7. References

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