Consideration of reliability and sustainability in mechanical and civil engineering design to reduce oversizing without risking disasters

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Abstract. Technical systems have to be designed that the requirements regarding service life are met with high reliability to ensure safe product operation. In many cases, the design is still based on single events, such as extreme load levels and additional safety factors, in order to ensure reliability, which is accompanied by a high degree of oversizing. This means that significantly more resources are consumed than actually needed in order to ensure the reliability requirement. To prevent reliability from being ensured solely by oversizing, reliability criteria must be supplemented by the claim for sustainability starting with the product design. On the one hand, profound reliability considerations make safety factors obsolete. On the other hand, oversizing is limited by the claim for sustainability. The overall result is a sustainable design while ensuring reliability at the same time. Within this work, two case studies from two different industrial sectors are introduced to show the trade-off in which the design has to be developed and how an overall solution proposal can look like. In both case studies, the savings in terms of resources and greenhouse gases emitted are shown while considering reliability and sustainability during the product design phase.

1 Introduction & Research motivation

One of the main challenges in engineering design is to demonstrate the reliability of a product [1]. This is necessary to ensure that the product will achieve the required lifetime with a defined probability before market entry. Many failure mechanisms are still not fully understood, therefore empirical life data from tests are used for reliability demonstration. Since life data is exclusively based on samples, parameter estimation methods are used to determine the distribution function for all products to be delivered (population). The distribution can be used to describe at which point in time a certain fraction of components failed (Probability of Failure PoF). Due to the lack of information in the sample, the failure behavior is additionally subject to epistemic uncertainty, but this can be quantified with the

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confidence limits (CL) [1]. However, in addition to these test-related challenges, the product itself plays an important role in reliability demonstration. With the test, one is only able to make a more or less good statement about the inherent reliability of the product. The inherent reliability of the product is determined by the design process, i.e., the selected dimensions, diameters, tolerances, etc. If the design is very close to the specified requirement, then the epistemic uncertainty must be kept very small to be able to demonstrate the reliability requirement (see On-Target design in Fig. 1). Minimizing the uncertainty is accompanied by a high testing effort, because the confidence interval depends significantly on the number of failures collected in the test. To get rid of these problems, significantly oversized designs are often used (see oversized design in Fig. 1). The influence of the epistemic uncertainty is then no longer of high importance. Due to the oversized design, a reliability demonstration can also be performed with a very wide confidence interval, i.e., even with very few specimens.

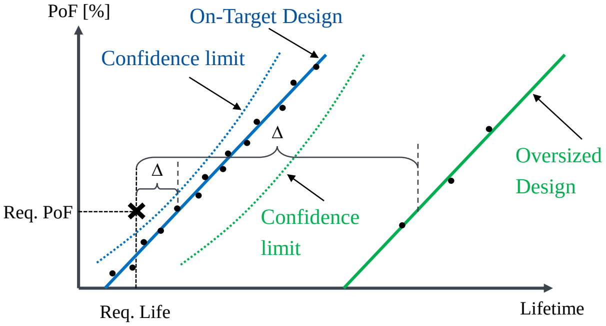

Fig. 1. Reliability demonstration for on-target and oversized designs

Oversizing causes a significant additional consumption of resources. This results in a significant additional environmental impact that is avoidable, especially in the case of products for the mass market. Despite the increasing challenges of the climate crisis, oversizing to avoid systematic failures is common industrial practice [2].

2 Reliability and sustainability for optimal product design

Research has already been carried out at the Institute of Machine Components (IMA) for several years on efficient test methods for reliability demonstration, as well as on the appropriate product design strategies. The additional consideration of sustainability criteria has proven to be particularly useful in addressing the problem of oversizing. Nevertheless, oversizing cannot be reduced arbitrarily, as in extreme cases reliability demonstration is no longer possible at all due to uncertainty: i.e., a product design requires a certain oversizing so that reliability demonstration can be successful. Nevertheless, oversizing must be reduced in order to limit the environmental impact of the product. Environmental impacts can be influenced most, especially in the early design stage. The pure consideration of reliability thus often leads to an oversized design. Otherwise, if only sustainability criteria were considered, the design would probably be undersized. In this trade-off, an optimal product design for the respective use case can only be identified by considering reliability and sustainability (see Fig. 2). If the most important parameters are regarded, a link is obvious. The time of usage forms the basis of every reliability analysis and life cycle assessment (LCA). In addition, the reliability analysis can be used to determine the necessary number of spare parts based on the probability of failures, which serves as input for the LCA. In this way, maintenance and servicing concepts could also be optimized in the context of sustainability.

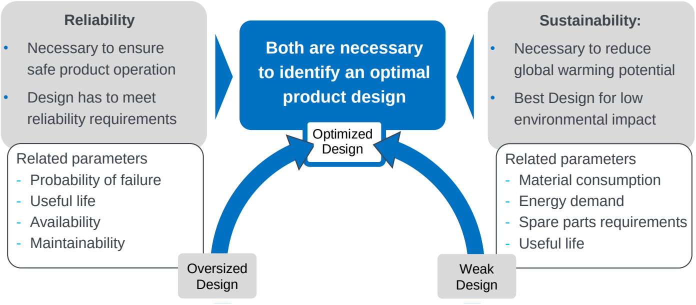

Fig. 2. Using reliability and sustainability to identify an optimized product design

3 Case Studies in mechanical & civil engineering design

By combining sustainability and reliability, optimal product designs have already been developed at IMA in two projects. In the field of mechanical engineering, the optimum tooth width of a gear wheel was identified in one case study. Another study was conducted in the field of civil engineering, in which it was possible to optimize load bearing structure of a newly developed adaptive high-rise building.

3.1 Designing the tooth width of a gear wheel

The basis of the case study is a cylindrical gear wheel pair which is also used in a similar form in the automotive industry. The tooth width is considered as the central design parameter in the trade-off between reliability and sustainability. An increasing thickness of the teeth leads to a rise in the durability of the gear wheel. However, the resource requirements increase at the same time and, with them, the environmental impact.

A reliability target (R = 99 %, CL = 50 %) is to be demonstrated for the gear wheel pair. This is typical according to DIN 3990-2, which is standard in the automotive industry. The required service life is $1.8 \cdot 10^7$ life cycles, with a loading torque of 150 Nm. For the reliability demonstration, the methods of Herzig [3] and Dazer [2, 4] are used to calculate the necessary test specimens and test time for different tooth widths. Herzig [5] provides further technical and statistical details on the application example. An LCA study is used to calculate the environmental impact for the test specimens and test hours required. The correlation between the tooth width and the global warming potential (GWP) is analyzed in this study. The LCA model is built in the GaBi software, version 10.5.1.124 with the content version 2021.2.

The LCA calculations are based on the manufacturing and processing of an alloyed steel billet (16MnCr5), using the electric arc furnace route. The billet is laser cut and ground to produce the gear wheels. For the end-of-life, a material recycling scenario is considered. Within the recycling scenario, sorting of the materials and remelting of the metal is considered. Credits for primary ferrous metal production are not given, because in the production process of the considered steel billet only secondary material is used.

For the test itself, a test rig is required which must be operated with electricity for the necessary test hours. The loading torque and the testing hours are used to determine the power consumption of the test rig [6]. The 2020 German electricity grid mix was used to calculate the GWP of the power consumption [7]. In addition to the expenses for reliability assurance, the GWP from sales also changes with oversizing. Three characteristic curves result from the calculations, as shown in Fig. 3. The resulting GWP for the reliability demonstration decreases exponentially with increasing tooth width. The reason for this is that significantly fewer test specimens and test time are sufficient to provide the reliability demonstration with increasing oversizing. At the same time, the GWP of the sales increases linearly as the dimensions increase with the tooth width proportionally. The correlation is given by:

$$GWP_{selling} = (1.16 \cdot m_{gear} - 0.00070) \cdot n_{sales},$$

using 1,000,000 units as the production volume within this case study. From the combination of the two curves, the optimum of the GWP can be derived at 8.1 mm tooth width. This design is able to provide a reliability demonstration and, at the same time, has the lowest total GWP. If the German standard DIN 3990-2 is used for the design with the recommended safety factor of 1.2, the result is a tooth width of 11.1 mm [6], which illustrates the problem of systematic oversizing to ensure reliability.

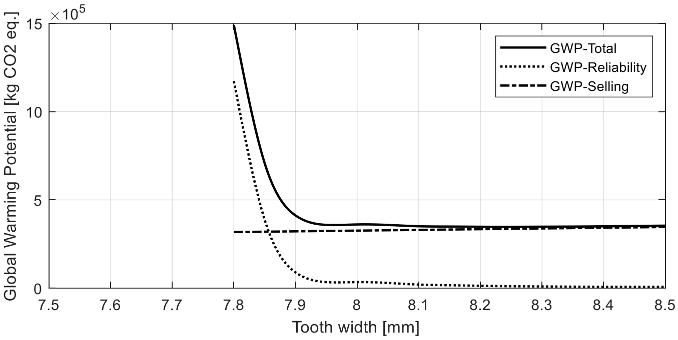

Fig. 3. GWP results for the different gear widths to identify an optimal design

3.2 Designing an adaptive load bearing structure

The civil engineering industry has been made responsible for a significant contribution to climate change [8]. A fundamental problem in civil engineering is that, in conventional load bearing design, the strength is designed for the worst-load case. However, structures are usually loaded much less, making them oversized for most of their service life. Within the Collaborative Research Center "Adaptive Skins and Structures for Tomorrow's Built Environment", an interdisciplinary design approach for adaptive load bearing structures was developed under the leadership of IMA [9].

Fig. 4. High-rise demonstrator and access tower

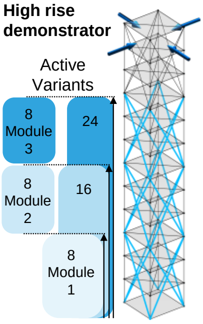

Fig. 5. Different variants of actuation

Actuators are integrated directly into the structure in order to damp dynamic loads such as wind and earthquakes. The adaptation to the respective load situation enables a reduction of the necessary cross-section, and thus a mass reduction, which ultimately leads to a saving of resources and greenhouse gases. Nevertheless, the reliability requirement must also be met in this new type of structure. The requirement according to Eurocode is $R(10\ \mathrm{a}) = 98\ \%$, in which the deflection at the top floor of the demonstrator must not exceed 40 mm (see Fig. 4 [10]). In addition to the limit state of the serviceability, buildings have to meet load capacity requirements (Ultimate Limit State). However, in the course of the project, it became apparent that designing to the USL was not expedient from the point of view of sustainability [9]. In the design process, an FE model was used to calculate the deflections for different cross-sections, which are simultaneously equipped with a different number of actuators. Controllability and energy requirements were also considered (see Fig. 5).

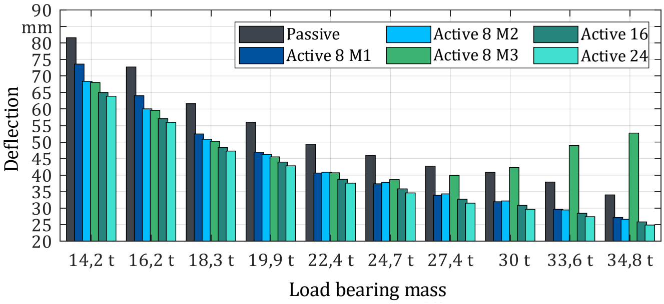

Fig. 6. Deflection of the different variants for different structural masses [9]

Unsurprisingly, the results initially show that the deflection decreases with increasing mass (see Fig. 6). However, they also show the effects of the damping properties of the variants compared to the passive support structure. In addition, these results now offer the possibility of identifying the particular structural mass that just meets the 40 mm requirement. It can be seen that activation close to the restraint point is most effective. With the exception of the variant Active 8 (M3), there is a recognizable damping for all variants, compared with the passive variant of the same structural mass. Using a Petri net, the system reliability was calculated with the result that all remaining variants achieve the Eurocode requirements. In addition, the spare parts requirement for 10 years of service life was determined and included in the LCA. The results of the LCA of the different variants are shown in Fig. 7.

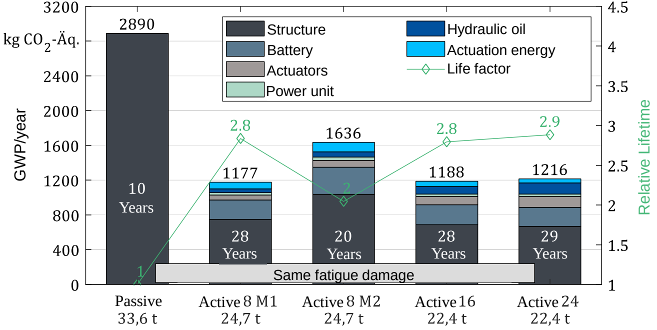

Fig. 7. GWP and lifetime of the different variants [9]

In addition to the GWP, the relative lifetime change can be read off on the right-hand scale, which was calculated using damage accumulation with a local representative load spectrum of the demonstrator site. What was already apparent from the results in Fig. 6 is illustrated once again here on the basis of the calculated GWP. By combining GWP and reliability, the optimal design can now be identified – in this case the "Active 8 M1" variant. In addition to the mass reduction, the massive savings in GWP come primarily from the longer service life. For example, the Active 8 M1 structure can be used for almost three times as long as the passive support structure due to the damping properties of the actuators. The results also reinforce the need for reliability and sustainability in the design process. If the actuator system had been integrated without considering reliability and sustainability as well as the associated mass reduction, the GWP of the overall structure would have been higher.

GWP expenditures for the battery, the actuation energy and the actuators themselves, which also offset parts of the savings again, would then have been added to the passive structure.

4 Conclusion & Outlook

As shown by the examples, oversizing is still a frequently used means for reliability assurance. This is accompanied by massive and avoidable environmental impacts. By combining reliability and sustainability, it was possible to show that optimal designs can be identified for individual boundary conditions on the basis of two examples from completely different industries. In part, the approaches are simplified or subjected to assumptions. In the next step, the approaches are to be generalized and thus made usable for industrial practice.

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