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Efficiency and attitude: On the relationship between lightweight structures and sustainability

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Abstract
In structural engineering, the principles of lightweight structures are often associated with sustainability. However, maximising structural efficiency while minimising the use of materials does not necessarily lead to the ecological efficiency of structures. This publication analyses the relationship between lightweight design strategies and sustainability, which are both approaches to the evaluation and optimisation of structures. The results indicate that while both lightweight structures and sustainability aim for efficiency, their relationship is characterised by complex dependencies. Only by expanding the principles of lightweight design through consistency and sufficiency strategies can they be redefined, with a holistic view already inherent in lightweight structures. The approach to sustainable design in engineering combines structural efficiency and a value-based attitude, towards holistic, sustainable, and therefore contemporary lightweight design principles.

Keywords: conceptual design, lightweight structures, sustainability, sustainable construction

1. Introduction

1.1. Background
The lightweight design philosophy leads to a wide variety of structural forms. By applying this fundamental principle, structural engineering has found a definition that has always been inherent in the way engineers express themselves: to maximise structural efficiency while minimizing material use (Wiedemann [1]). To achieve designs that are both lightweight and highly efficient, structural engineers use optimisation techniques to determine the optimum configuration for weight, strength, and other performance criteria.

However, recently there has been a shift towards a more holistic approach to design, considering not only the technical performance of a structure, but also its environmental and social impacts. This shift reflects a wider set of societal values that emphasise sustainability and the need to reduce the carbon footprint of the built environment. The historical development of lightweight design shows that it also reflects a set of societal values: during the world wars, material scarcity can be identified as driving influence (Leonhardt [2]); today, sustainability challenges the construction industry.

To integrate the goal of sustainability into the process of optimising structures, it must be expressed in measurable terms. For example, life cycle assessment is used to evaluate the environmental impact of design options. This leads to a trade-off between material efficiency and other objectives such as sustainability. For example, the use of lightweight materials with a short service life may be more efficient but not sustainable or socially responsible.

1.2. Aim and research questions

This paper discusses the relationship between lightweight structures and sustainability. Both terms are understood as attitudes towards the evaluation and optimisation of structures. The aim is to identify the interdependencies between these approaches and their objectives. In order to answer the question of whether lightweight structures are inherently sustainable, the underlying strategies of both approaches are defined and compared. The results of this analysis will contribute to the scientific discourse by providing a different perspective on current design and evaluation methods to understand how the challenges and opportunities of sustainable construction influence lightweight design principles.

The following research questions will be answered:

(1) Into which tendencies and strategies can lightweight structures and sustainability be subdivided?

(2) What is the relationship between the principles of lightweight construction and the principles of sustainable construction?

(3) To what extent can the principles of lightweight design contribute to the sustainable development of the building industry?

2. Approaches in lightweight structures and sustainability

This overview describes the trends and strategies into which the principles of lightweight structures and sustainability can be categorised. This serves to answer the first research question and provides a foundation for the subsequent analysis.

In traditional lightweight structural design, there are different classifications of the principle. In the mechanical engineering literature, a distinction is often made between five lightweight construction methods (see Klein [3]), while Wiedemann [1], coming from the aircraft industry, categorised lightweight structures into three trends: economical lightweight construction, eco lightweight construction and functional lightweight construction.

It was this categorisation of lightweight structures that Werner Sobek [7] finally transferred to the construction industry using adapted terms. This definition is followed in this publication. This means that material lightweight construction refers to the use of materials with low weight, structural lightweight construction optimises the design in line with the flow of forces and the aim of system lightweight construction is to integrate functions into as few structural elements as possible.

Sustainability strategies, in turn, are categorised into efficiency, consistency and sufficiency (Behrendt [4]). The efficiency strategy pursues the goal of using materials and energy more efficiently, which corresponds to an improvement in resource utilisation (better). Consistency, on the other hand, aims to enable the environmentally friendly use of resources by closing material cycles. Unlike the (eco-) efficiency strategy, it is not only about the quantity of materials, but also about their quality. Consistency is therefore also referred to as eco-effectiveness. The difference between efficiency and effectiveness is often described as "doing things right" in the former and "doing the right things" in the latter (Braungart [5]). The third of the sustainability strategies is sufficiency and, to remain in this context, poses the question of whether things need to be done at all. This strategy therefore focuses on reducing consumption and production and therefore places the responsibility on the individual, not the technical solutions (Stengel [6]). The associated change in behaviour leads to the question of the right balance in the use of resources such as materials and energy.

3. Comparison of lightweight and sustainability strategies

Previous examinations have shown that lightweight structures pursue various strategies as an overarching design principle to achieve their goals. However, sustainable construction also follows certain principles and strategies. In the following, the relationships between lightweight structures and sustainable structures are analysed. The analysis specialises in comparing the strategies of the two design principles.

3.1. Material lightweight construction and sustainability strategies

The aim of material lightweight construction is to use materials with the lowest possible specific weight that nevertheless have high strength properties. Optimum utilisation of the material strengths ultimately results in a ratio between the weight and the load-bearing capacity of a material (Sobek [7]).

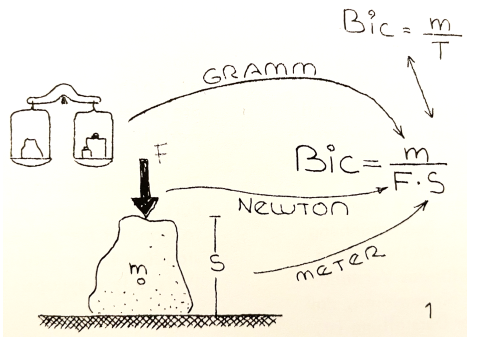

Figure 1: Illustration of the lightweight structure factor Bic [8].

There are several examples of these ratios in the history of lightweight structures. Frei Otto defined the lightweight structure factor Bic in g/Nm as the ratio of density to tensile and compressive forces (Schaur [8]) and thus established the first objective measure for lightweight structures. The standard works of mechanical engineering also define ratio values and lightweight indicators for lightweight structures. (Wiedemann [1]; Klein [3])

With the help of the ratios formed, the use of materials in lightweight structures can be quantified and thus also optimised. This is entirely in line with the efficiency strategy of sustainability. Efficiency aims to utilise resources such as materials and energy more efficiently. This efficiency can also be expressed as a quotient between the result achieved and the resources used. The direct link between the efficiency strategy and the strategy of material lightweight construction becomes evident at this point.

Eventually, Jörg Schlaich [9] made theoretical considerations "about the limits of what can be built" based on the limit height and tear length (compressive and tensile strength in relation to the specific weight of the building materials). However, he also assessed the possibilities of building materials regarding maximum building heights and spans and concluded that these "lie beyond the limits of what is reasonable and desirable" and that technical feasibility therefore exceeds reasonableness. Here it becomes clear that the bare figures only explore the technical possibilities, but that the evaluation of these figures lies in the hands of the engineer.

Sobek [10] also points out that material lightweight construction is of course not just a matter of discussing ratios. The structural design of the components in which the materials are used is also important. This means that questions of joining and detailing also play a decisive role, which in turn influence the assembly, disassembly, and recycling behaviour.

This leads to the second strategy of sustainability, the consistency strategy. In the construction industry, this strategy aims to achieve environmentally friendly material cycles and the recycling of building materials or components. This involves a fundamental change in production, which has a significant impact on the principles of material lightweight construction.

To be able to draw conclusions about the recyclability of building materials and, in their composition, of components, Sobek [10] refers to four different ways of joining materials, which are differentiated according to the construction method concept from aircraft and automobile construction (see chapter 2).

Differential construction is characterised by point connections of simple components, which are therefore detachable and can be separated by type after use. Components from the integral construction method can also be easily recycled due to their mono-materiality.

In contrast, integrating construction methods depend on the type of joining technology used to connect building materials. While welded joints can be seen as positive, the glues and adhesives that are frequently used are in most cases not compatible with the circular economy.

The greatest conflicts of interest between material lightweight construction and sustainability can be identified in the most frequently researched construction method today, composite construction. In composite construction, components made of at least two different materials are joined together, with the strength of the composite interacting with recyclability: If the composite effect is high, the force transmission is also high. However, this has a negative effect on recyclability, as it is more difficult to separate the materials by type. The opposite is the case with a low bonding effect, as concrete and steel, for example, can be separated comparatively easily and recycled. [10]

As a result, the efficiency of the load-bearing behaviour of composite materials is inversely proportional to their recyclability. It is true that ever lighter and higher-strength materials can be created using complex composites, thus increasing the ratio of mass used to output. On the other hand, this makes it difficult to fulfil the sustainability goal of consistency.

Materials research into composite materials is also increasingly moving in an environmentally friendly direction [11]. Nevertheless, conflicts remain here, as non-biodegradable epoxy resins are used.

To counter this dilemma, a re-evaluation of materials in terms of their eco-effectiveness is an option. This new ecological lightness is also called for by other authors (Blandini et al. [12]). The authors themselves have also already explored a new direction in lightweight structures (Zywietz et al. [13]). For example, a load-bearing structure made of ecological building materials and with efficient load-bearing behaviour can have a higher mass but be considered light in terms of its environmental impact.

Knippers and Helbig [14] provide an example of this in their article on the Stuttgart timber bridges. Thanks to an extremely efficient load-bearing structure, in which, for example, timber with a lower load-bearing capacity is used in suitable areas of the structure, lower CO_2 emissions are achieved despite a larger amount of material thanks to the material's storage capacity. This demonstrates that structures designed to be lightweight do not necessarily have to appear visually light but can also result in heavier structures if they meet the requirements of consistency and a low ecological footprint.

3.2. Structural lightweight construction and sustainability strategies

In lightweight structural engineering, loads should be transferred to defined support points as efficiently as possible and with minimum dead weight of the structure. To ensure an optimum flow of forces through a structure, load paths are primarily optimised by specifying boundary conditions (Sobek [7]). In lightweight structural design, the level of consideration therefore changes from the starting material to the component level.

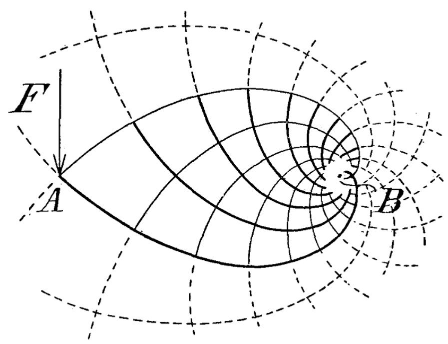

Figure 2: The Michell truss is an example of the optimisation of the bar arrangement under a single load [15].

Various form-finding methods have been developed to approach the optimum forms for the arrangement of structural elements in a design space. While the first experimental approaches were of a physical nature, current ones are characterised using numerical methods (Kemmler [16]). What all methods have in common is that they are intended to find the optimum shape for a specific load case.

By quantifying the structural problems, reliable figures can be used to compare different possible solutions and ensure efficient load-bearing behaviour. This is also in line with the efficiency strategy of sustainability, as the structural elements used are utilised sensibly and efficiently. Furthermore, this data can also be used in a life cycle assessment to evaluate the environmental impact of design options.

However, the relevance of lightweight structures for sustainable construction goes beyond the mere consideration of the mass used. Due to the design of the structures for absolute efficiency and towards a form-determining load case, other options are disregarded; the conversion of structures is made more difficult, which neglects an important component of sustainable construction. Structures optimised for one load case do not offer the possibility of adapting the structure to changing uses.

Considering the consistency criterion, the structural elements must either be recycled at the end of a structure's life or be able to be transferred to other uses. Sobek [10] warns that a design task loses transparency if the structural optimisation is too sharp, and the methods used cannot be understood. He therefore suggests that architectural and structural aspects must also be considered equally in the design process. This is where circular design could come in and include this as an additional factor in the optimisation.

For its potential to improve consistency, component reuse is highly valued. In addition to the necessary testing of components for their residual load-bearing capacity, designing with used components also requires a completely new design approach. Researchers are already looking at the optimal use of elements from a limited design space and the resulting reversed inputs and outputs in the design process (Fivet [17], Brütting [18]).

In structural lightweight construction, it is also crucial that the designed structural elements interact with each other at their joining points, which is why material-responsible design is particularly important. Reversible constructions offer the opportunity to design sustainable structures. This shows a wide range of development options and the need for research for the future of structural lightweight construction.

3.3. System lightweight construction and sustainability strategies

In system lightweight construction, components fulfil several functions at the same time, as they have load-bearing, but also space-enclosing or heat-insulating properties, for example. Weight can therefore be saved through the multifunctional use of load-bearing elements. As an example, Sobek [7] cites the involvement of glass panes in the stiffening of a load-bearing structure; in this case, they are both space-enclosing and load-bearing.

Figure 3: The glass panes are actively involved in load transfer in this Stuttgart glass shell. [10].

Klein [3] also defines a similar concept for design in mechanical engineering as "(...) a so-called lightweight construction in which all technological possibilities are exploited in order to realise the goal of functional integration (one-piece design) with the lowest possible use of materials and minimal joints".

The principle of system lightweight construction is always a concept in structural design that is rarely published or explicitly written about. The fact that it is rarely dealt with is certainly also because system lightweight construction is inherent in the construction industry: ceilings and walls have always combined several functions. However, it is only by visualising and becoming aware of this that the status quo can be changed (cf. Sobek [7]).

Due to the integration of functions, system lightweight construction is a fundamental and overarching approach: Compared to the other principles of material and structural lightweight construction, the application of this principle cannot be summarised in an optimisation function, as it cannot be described in figures. Instead, the output is measured by the extent to which resources such as material and energy are saved by changing the way of thinking and designing.

System lightweight construction thus goes beyond the typical efficiency concept of lightweight structures and requires thinking outside the box. As it does not ask how material and structure can be further optimised, but instead poses the question of the meaningfulness of the overall construction, there are obvious parallels to sufficiency, which as a sustainability strategy also poses the question of the right measure.

While the previously discussed material and structural lightweight construction as well as efficiency and consistency represent technical solution strategies, the sustainability strategy of sufficiency is a systemic one. If the principles of system lightweight construction are applied, less production is required overall, and resources are saved by changing the design approach. This corresponds to sufficiency.

Richard Buckminster Fuller also pursued the concept of "doing more with less", which is why he is also one of the most influential thinkers and pioneers of lightweight structures in the 20th century. In his 1938 book "Nine Chains to the Moon", he introduced the concept of ephemeralisation to describe the process of increasing efficiency in technological development, which leads to less and less mass as products take on several functions at the same time (Fuller [19]).

Efficiency = doing more with less.

∴ EFFICIENCY EPHEMERALIZES.

Figure 4: Fuller’s concept of ephemeralisation [19].

If we take the concept of ephemeralisation a step further, the result is that "(...) you can eventually do everything with nothing". The visionary Fuller therefore saw the concept as a solution to the problems of limited resources on earth. However, the utopia of ephemeralisation does not necessarily lead to more ecological material and energy consumption, as the reintegration of resources into their cycles is not an explicit part of the concept. Nevertheless, the concept of ephemeralisation demonstrates how the consistent application of the efficiency principle can become an integrative overall strategy, similar to the multifunctional idea of system lightweight construction.

4. Towards holistic sustainable lightweight design

The results of the research show that the strategies of lightweight structures and sustainability can be compared in principle, but that there are also conflicts of objectives. Overall, a multi-layered picture emerges due to the complex interdependencies between the two design concepts. No strategy, neither sustainability nor lightweight design, is effective on its own; instead, they influence each other.

In lightweight material construction, it can be summarised that the pure weight of materials is optimised in terms of their strength properties. When drawing up a life cycle assessment, this is virtually equivalent to the global warming potential; if fewer materials are used, the CO_2 emissions of a structure are also reduced. However, this is not the only way to achieve the much-described lightness. Optimised, lightweight materials are extremely efficient in terms of their load-bearing capacity, but not necessarily in terms of their recyclability. However, if efficiency is defined as a comparative value of mass to environmental impact, this leads to a reassessment of lightweight materials. In addition, the material itself must be considered closely for the criterion of consistency. Consistent material lightweight construction goes beyond weight minimisation and, in addition to the global warming potential, also considers the possibility of recycling in biological and technical cycles, which categorically rule out downcycling.

A new systemic approach to material lightweight construction can therefore mean that building lighter in ecological terms can also mean using more mass, as long as it consists of low-carbon materials. Another possibility is to use materials in a multifunctional way.

A new systemic approach is also opening new possibilities in structural lightweight construction. If production and consumption are to be reduced, structural lightweight construction offers the opportunity to do so thanks to its optimisation approach. By reconfiguring components that have already been used and optimising their use, building with existing structures is promoted and the extraction of new resources is avoided. In terms of sufficiency, however, it would not even be necessary to optimise the power flow, as the inefficient use of old components would also meet the criterion of sufficiency.

The initial hypothesis was that lightweight structures primarily follow the principles of efficiency but can also be interpreted as going beyond this due to their necessary attitude. It turned out that all three lightweight strategies are guided by efficiency, but that there are differences in their characteristics.

Both lightweight structures and sustainable construction require a clear attitude from designing engineers. This realisation fits in with the basic assumption that lightweight structures and sustainable construction are social values with which designs are evaluated. This is particularly evident in system lightweight construction and the sufficiency principle, as these offer an overarching approach, which also has a direct impact on the previously analysed material and structural lightweight construction.

Sufficiency is aimed at a change in behaviour, and lightweight structures in particular offer overarching opportunities for consideration here. In this context, "less is more" is not only a maxim for saving materials, but also a change in the demands placed on a load-bearing structure. Although technological development and the strategies of material and structural lightweight construction help to achieve sustainability goals, without a fundamental change in design thinking, this cannot stop the consumption of resources such as materials and energy, which already exceeds the environmentally acceptable level every year (Earth Overshoot Day).

The reduction of complexity towards more flexible uses has been applied in the past and is now experiencing a renaissance (e.g. Nagler [20]). Explicit visualisation in particular can bring about change here (cf. Sobek [10]) and reduce the ecological footprint of the building industry. Nevertheless, in addition to political framework conditions such as the transformation towards a circular economy, changing the design approach in particular is a task for engineers of the future, which also presents universities with an important challenge.

5. Conclusion

The principle of efficiency has always been a dominant factor in the design thinking of engineers. Innovative materials and modern optimisation techniques allow for weight reduction, while also incorporating ecological considerations into the design process. This results in the development of lightweight and highly efficient load-bearing structures. The building industry has embraced the concept of sustainability, which, like lightweight structures, takes a holistic approach to evaluating design options. However, conflicts of objectives between the two concepts are common, forming the basis for scientific investigation.

This paper categorises and describes lightweight structures as an overarching design principle, followed by an exploration of sustainability strategies. Each of these design principles follows specific guidelines, which were then compared and analysed. A range of interdependencies between the two concepts became apparent.

Fundamentally, the criterion of efficiency can be found in all three lightweight design strategies. However, the transfer of sustainability strategies offers great potential for further developing the classic approaches to lightweight design. Consistency considerations are particularly important in material and structural lightweight construction. By closing material cycles, a new systemic approach that goes beyond pure weight minimisation can lead to greater sustainability in the construction industry. However, system lightweight construction in particular shows that lightweight structures also offer overarching opportunities for consideration that correspond to the sustainability principle of sufficiency and must lead to changes in the design approach.

This clear attitude to the design and evaluation of structures in terms of their ecological and physical lightness will be required more and more in the future and should also be taught in university education. The holistic view needs to play an important role in the design process of load-bearing structures to combine efficiency and attitude. Lightweight structures and their diverse strategies provide a solid foundation for a holistic redefinition to address the challenges of sustainability in the building industry.

References

[1] J. Wiedemann, Leichtbau. Elemente und Konstruktion, Berlin Heidelberg: Springer-Verlag, 2007.

[2] F. Leonhardt, “Leichtbau - eine Forderung unserer Zeit,” *Bautechnik,* vol. 18, p. 413–423, 1940.

[3] B. Klein and T. Gänsicke, Leichtbau-Konstruktion: Dimensionierung, Strukturen, Werkstoffe und Gestaltung, Springer Fachmedien Wiesbaden, 2019.

[4] S. Behrendt, E. Göll and F. Korte, “Effizienz, Konsistenz, Suffizienz. Strategieanalytische Betrachtung für eine Green Economy,” 2018.

[5] M. Braungart, W. McDonough and A. Bollinger, “Cradle-to-cradle design: creating healthy emissions – a strategy for eco-effective product and system design,” *Journal of Cleaner Production,* September 2007.

[6] O. Stengel, Suffizienz: Die Konsumgesellschaft in der ökologischen Krise, Berlin: Oekom Verlag, 2011.

[7] W. Sobek, „Zum Entwerfen im Leichtbau,“ *Bauingenieur,* pp. 323-329, 1995.

[8] E. Schaur, “IL 21: Grundlagen: Form – Kraft – Masse 1. Mit einem Beitrag und einer Diskussion über das Ästhetische,” 1979.

[9] J. Schlaich, “Über die Grenzen des Baubaren. Eine Gedankenspielerei über die Leistungsfähigkeit unserer Baustoffe,” *DAI-Zeitschrift,* vol. 8/9, 1978.

[10] W. Sobek, “Entwerfen im Leichtbau,” *Themenheft Forschung - Leichtbau,* p. 71–84, 2007.

[11] H. Dahy, “`Materials as a Design Tool' Design Philosophy Applied in Three Innovative Research Pavilions Out of Sustainable Building Materials with Controlled End-Of-Life Scenarios,” *Buildings,* vol. 9, p. 64, March 2019.

[12] L. Blandini, A. Bögle, J. Knippers and K. De Rycke, “Leichtbau oder ökologisch leichter bauen. Was kann das heute bedeuten?,” in *Ingenieurbaukunst 2024*, 1 ed., Berlin, Ernst & Sohn, 2024, p. 160–165.

[13] M. Zywietz, K. Schlesier and A. Bögle, “Rethinking Lightweight: Exploration of Circular Design Strategies in Temporary Structures,” *Journal of the International Association for Shell and Spatial Structures,* vol. 63, p. 132–144, June 2022.

[14] J. Knippers and T. Helbig, “Das Prinzip Leichtbau und seine Bedeutung für das konstruktive Entwerfen,” *Stahlbau,* vol. 83, p. 777–783, November 2014.

[15] A. G. M. Michell, “The limits of economy of material in frame-structures,” *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science,* vol. 8, p. 589–597, November 1904.

[16] R. Kemmler, “Formfindung: Die Interaktion von Kraft und Geometrie,” *Stahlbau,* vol. 81, p. 476–480, June 2012.

[17] C. Fivet and J. Brütting, “Nothing is lost, nothing is created, everything is reused: structural design for a circular economy,” *The Structural Engineer,* vol. 98, p. 74–81, January 2020.

[18] J. Brütting, G. Senatore and C. Fivet, “Form Follows Availability – Designing Structures Through Reuse,” *Journal of the International Association for Shell and Spatial Structures,* vol. 60, p. 257–265, December 2019.

[19] R. B. Fuller, Nine Chains to the Moon: An Adventure Story of Thought, E. Blum, J. Fezer, G. Fischer and A. Schnell, Eds., Berlin, Boston: Birkhäuser, 2019, p. 384.

[20] F. Nagler, Einfach Bauen: ein Leitfaden, Basel: Birkhäuser, 2022.