1 Introduction

Industrial production technologies are strongly committed to optimizing the major market goals of product quality as well as manufacturing cost and time in order to strive for better competitiveness. Simultaneous optimization of two or even all three of these factors is often conflicting and in most cases merely resolved by innovative technologies. Therefore, innovations are the driving force for the improvement of product quality and the reduction of manufacturing cost and time.

This typically involves innovations in product design which are often derived from new developments in production technologies. These can help meet the above mentioned market goals. One such technology, which emerged recently, is the field of Laser Freeform Fabrication (LFF) meaning laser-based additive solid freeform fabrication processes. These processes typically consist of layered application of liquid or powder material on a building platform. Solidification of targeted geometries in each layer derived from a sliced 3D-CAD model is being achieved with heat induced by partial absorption of laser beam energy. For rapid production of functional or non-functional plastic parts (e.g. prototypes) this technology has been successfully used over the past 20 years. However, the demand for functional parts made from engineering materials rather than plastics has propelled the technology towards the latest developments such as so-called Selective Laser Sintering and Selective Laser Melting (SLM). Both processes, introduced in the late 1990's, allow fast freeform fabrication of functional parts from different metallic alloys that yield required quality properties. The greatest advantages of these manufacturing technologies are a fundamental CAD-CAM-integration, potential for fabrication of virtually randomly complex geometries and the capability of delivering individual part geometries with quick time-to-market response.

Until a few years ago typical applications for LFF processes were only deployed in the field of Rapid Prototyping and Rapid Tooling. Now, over the recent years, applications are shifting towards Rapid Manufacturing which focus engineering materials. Thus industries from medical technologies or tool and mould makers became aware of the potential of making product innovations available which are inherent in this production method. However, the powder materials used are typically very costly compared to solid engineering materials and today, the machine operation cost is still expensive, too. Therefore, the production cost for LFF parts can be considerably high.

Apparently, if cellular design is employed with LFF processes the manufacturing cost and time can be reduced while the product quality can be enhanced. This requires innovative part designs which incoroporate cellular approaches to make use of the geometric degrees of freedom available with LFF processes. ***Fig. 1.1*** shows the impact this innovative combination of methodology (cellular design) and technology (LFF) has on product quality as well as manufacturing cost and time due to the numerous advantages listed under the bullets. An example for a realization of this combination could be a tailored part design where internal solid volume is substituted with a lattice structure in order to obtain stiff but lightweight parts designed specifically for given load situations.

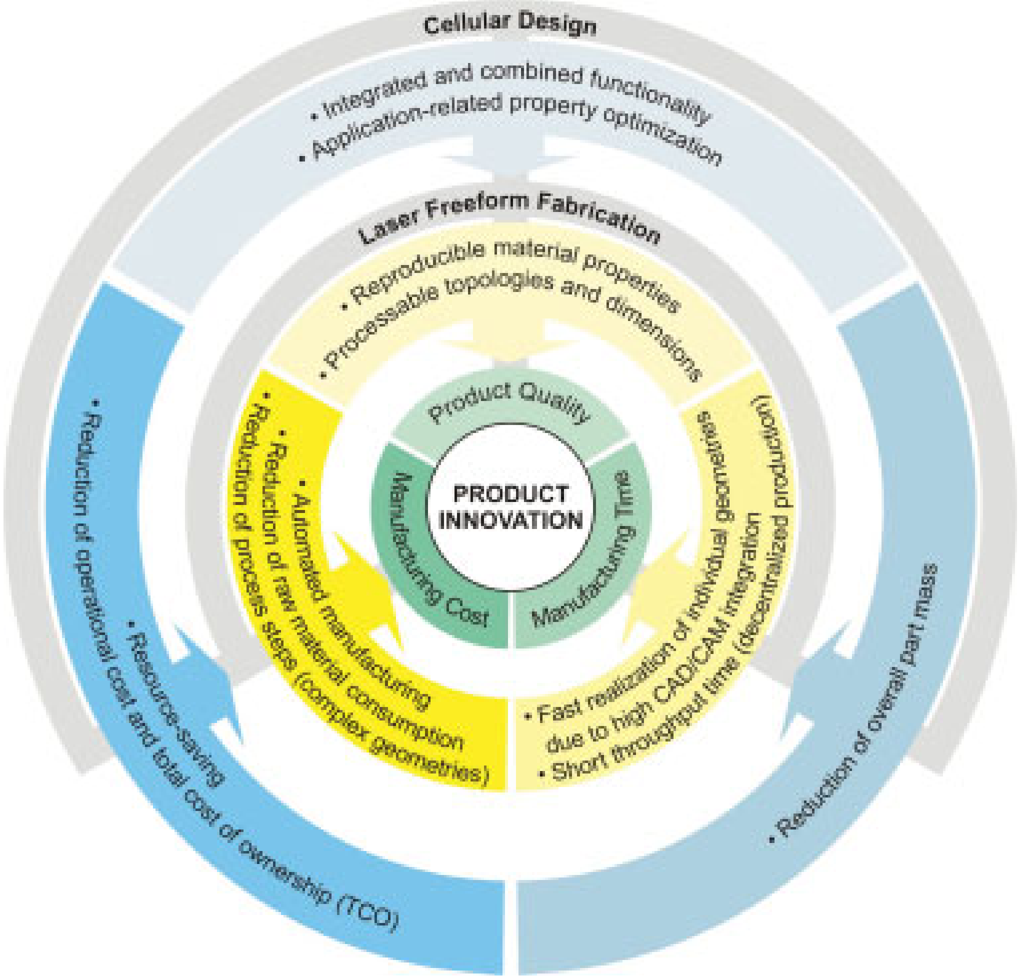

Figure 1.1: Impact of cellular design combined with Laser Freeform Fabrication on product innovations

Any optimization effort for LFF processes has to take into account that the quality properties for laser fabricated parts demanded by the customer must be achieved. This leads to the need of developing an engineering process for designing and manufacturing laser fabricated lattice structures at reproducible industrial quality standards. Therefore, the scope of the work presented in this thesis is to develop and analyze the design and the manufacturing of lattice structures made from Selective Laser Melting and to characterize their mechanical behaviour in regard of resulting product quality versus manufacturing cost and time. After a close scrutiny of the current state of technology in cellular material engineering and LFF processes, theoretical approaches to model SLM fabricated solids as well as failure mechanisms for SLM lattice structures are developed in order to design products with appropriate periodic, cellular structures. Subsequently, a comprehensive experimental analysis of SLM solids and lattice structures is carried out. Results of test specimens fabricated on a SLM machine developed by the company Realizer GmbH are evaluated in regard of their producibility and their material properties such as strength in compression, tension and shear load. According scaling laws are derived for the most promising cell types to answer the question of what part design should be aspired to if design engineers wish to incorporate SLM lattice structures into new applications. Finally, these laws are applied to suggested applications in medical implant design where cellular materials can be useful to improve ingrowth of bone tissue and to adjust the effective stiffness of implants to the surrounding tissue.

2 Cellular design and manufacturing processes

2.1 Cellular materials

2.1.1 Classification

Cellular materials can be found in nature as well as numerous engineering applications. They have a number of unique properties which allow new and innovative applications beyond the scope of solid engineering materials. They exhibit low density and therefore low mass along with high strength, high stiffness, high thermal conductivity (or in contrast high thermal insulation), high acoustic absorption as well as high gas permeability. Thus they make excellent lightweight structures with high stiffness-to-weight-ratios e.g. for sandwich cores loaded in bending. Their superior specific strength allows outstanding kinetic energy absorption characteristics while their high surface-to-mass ratio permits exceptional heat transfer capabilities. According to their properties introduced in ***section 2.1.4*** they are also well usable for acoustic absorption, for damping and absorption of mechanical energy, for vibration control, for filters, for thermal insulation, for heat exchange, for electric insulation and conduction, respectively and for catalyst usage among many other possible applications. Suitable design and configuration in terms of optimizing the cellular structure allows even the simultaneous fulfillment of multiple part functions. Often cellular materials do not necessarily excel over conventional materials in single properties and most often their costs are higher. Glass wool for instance can achieve much better sound absorption than any cellular material, however, it cannot be used for any kind of structural load. Therefore, using cellular materials in combined applications like e.g. lightweight, load-bearing heat exchangers is most promising.

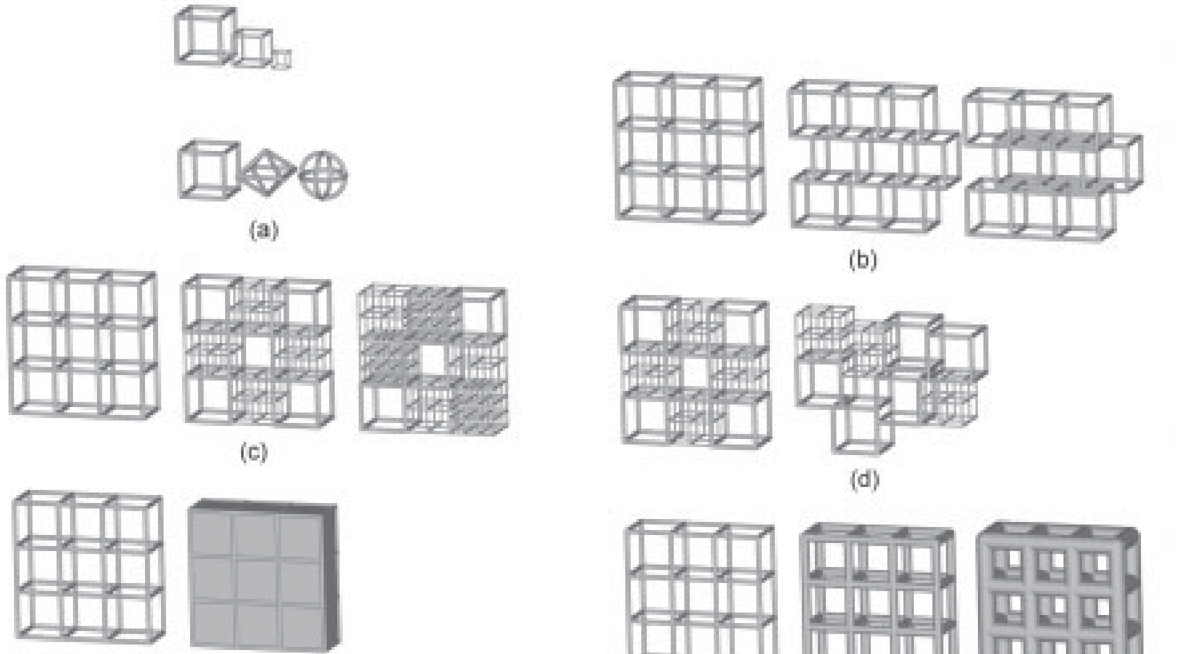

Figure 2.1: Classification of cellular structures

Cellular structures as illustrated in ***fig. 2.1*** can be classified by what shall be called the design parameters such as

- material,
- cell size and shape (a),
- topology (b),
- cell size variability (c),
- 2D- or 3D-periodic or stochastic appearance (d),
- type of porosity (open- or closed-cell structure) (e),
- relative density (f) and
- hierarchical structure.

Cell dimensions can typically range from several tens of microns to centimeters. They may also vary within periodic cellular materials featuring repetitive patterns that can either be the result of a characteristic, inherent in the manufacturing process, or the result of constructed design. If the repetitive pattern is translated in two dimensions, a prismatic material also known as honeycomb results. Three dimensional periodicity, however, yields a lattice structure (sometimes also named truss structure). Materials that cannot be described with a single unit cell and a repetitive pattern are named stochastic materials and they often show a distinct statistical variation of cell size and shape depending on manufacturing process parameters. Generally, better mechanical properties can be expected from regularly arranged cell structures than from randomly distributed formations which show low connectivity of the joints due to a small number of cell walls or struts linked in edges or vertices, respectively (Scheffler, 2005, p. 5, [270]).

The porosity of a cellular material can be described by either an open-cell or a closed-cell structure as depicted in ***fig. 2.2***. Open-cell porosity in a periodic cellular material occurs in lattice and honeycomb structures. Honeycomb, however, can be pseudo closed-cell if applied in its preferential environment in sandwich cores where both faces are typically bonded to sheet material. Open-cell stochastic cellular materials are refered to as sponges, whereas their closed-cell counterparts represent the wide spread group of foams. Only structures composed from hollow spheres can be periodic or, if post-processed e.g. by Hot Isostatic Pressing (aka HIPing), the cell size and shape of hollow spheres will become stochastic. Hollow spheres can

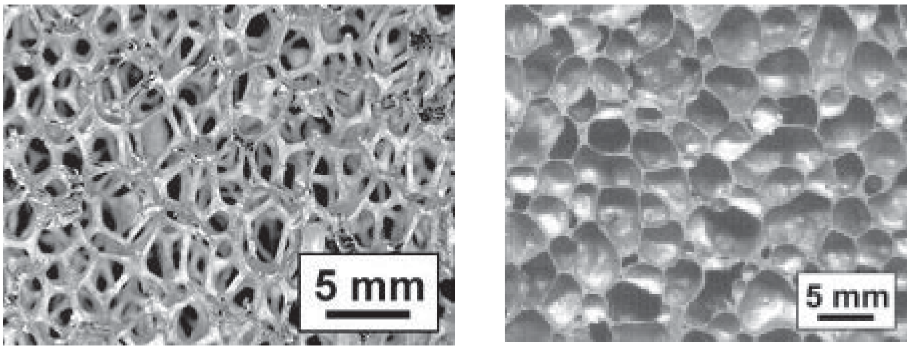

Figure 2.2: Examples for open- (left) and closed-cell porosity (right) [316]

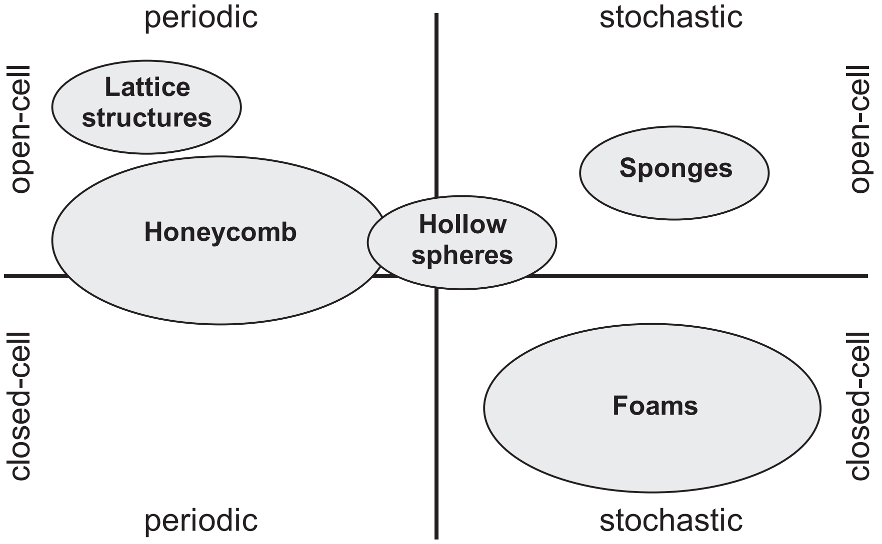

Figure 2.3: Classification and industrial relevance of cellular materials [256]

also show complex internal porosity, therefore, they should partially be added to the group of closed-cell materials. ***Fig. 2.3*** summarizes these categories for different metallic cellular materials and qualitatively specifies their current industrial relevance by giving a binary state of size for each category in which the bigger sized ellipse reflects a higher relevance.

The relative density of a cellular material is strongly influenced by the previously mentioned parameters of cell size, cell shape, cell size variability, type of porosity and thickness of cell walls and struts. Beyond these it can be influenced further by structural hierarchy, i.e. if structural features occur on different size scales. A typical example are e.g. cell walls and struts that comprise internal truss structures or voids. Structural hierarchy can contribute to improved strength properties compared to the same material without structural hierarchy that has the same relative density (Lakes, 1993, p. 511, [174]).

2.1.2 Product quality objectives

Quality is typically defined as the capability of the entirety of inherent properties of a product, a system or a process to fulfill the customer’s demands (DIN EN ISO 9000, 2005, p. 18, [91]). For products which incorporate cellular materials quality is mainly influenced by the cellular material properties and the functionality the cellular material provides. Both are subject to the design parameters as ***fig. 2.4*** illustrates. The most important design parameters and resulting cellular material properties required for comparing different cellular materials are

- obtainable dimensions such as cell size,
- relative density,
- obtainable degree of periodicity,
- flawlessness,
- resulting strength of a cellular structure (e.g. in mechanical applications) and
- its potential to be tailored for topology optimization (e.g. in mechanical or thermal applications).

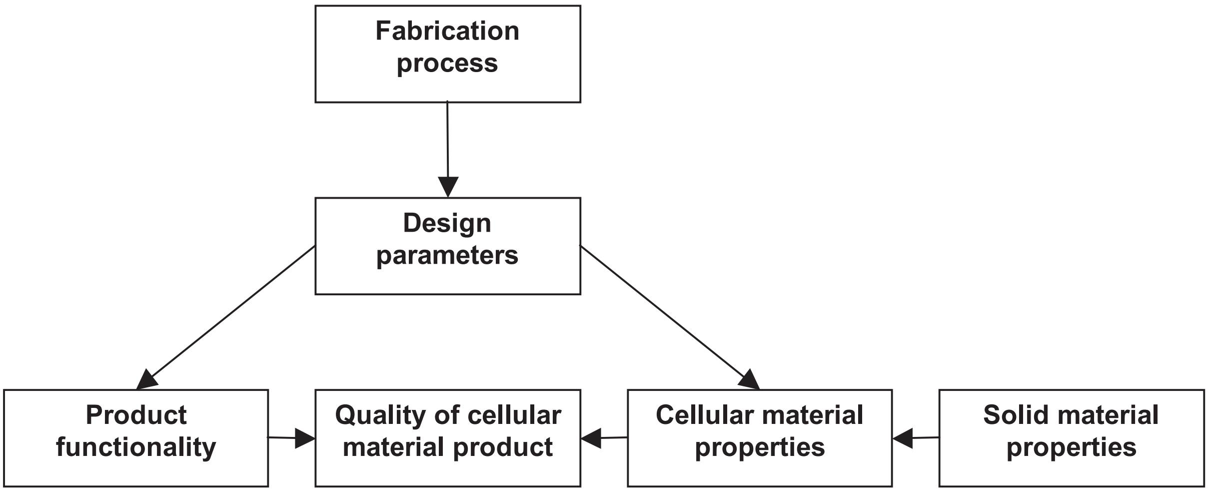

Figure 2.4: Influences on the quality of cellular material products

For most available cellular materials the design parameters are governed and hence limited by constraints of their fabrication processes as also shown in ***fig. 2.4***. Therefore, exploiting the possibilities for new product functionality implies that the according fabrication processes and the engineering design methods have to be mastered in order to obtain the desired product quality.

This thesis focuses solely on metallic materials though cellular structures made from plastics or ceramics should not be considered of lesser industrial relevance due to many investigations conducted with polymer foams and rapidly growing interest in ceramic foams although the latter are the least well characterized materials (Scheffler, 2005, p. 3, [270]). However, metallic, cellular materials are expected to allow the highest degree of freedom in the design parameters. Thus achievement of the product quality objectives like e.g. high strength at low weight or high heat transfer capability with structural integrity can be fulfilled. This chapter presents the occurrence of metallic, cellular materials, their typical fields of application, their properties in regard of achievable product quality and the various manufacturing processes available today. In ***section 2.2.3*** all these manufacturing processes are evaluated in respect to the design parameters.

2.1.3 Occurrence and applications

In nature one can find cellular materials nearly everywhere related to living tissue of plants, animals and humans. Such materials are e.g. wood, cancellous bone and sponge. Gibson (2005, p. 393, [122]) gives some typical examples how nature involves these materials in ‘sandwich core type’ items such as the human skull in ***fig. 2.5 (left)*** where overall robustness at minimum weight is important to protect the brain and a bird’s wing in ***fig. 2.5 (right)*** where high bending stiffness at low weight is required. Furthermore, of high interest is the glassy skeleton structure of the deep-sea sponge Euplectella sp. in ***fig. 2.6*** that was recently described by Aizenberg (2005, pp. 275-278, [6]). It overcomes the brittleness of its constituent solid, glass, due to seven hierarchical levels of structure at different length scales.

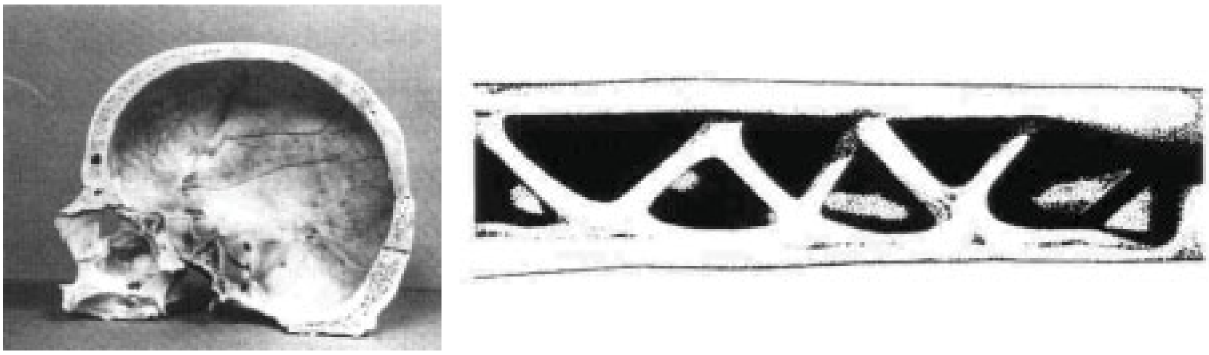

Figure 2.5: Natural sandwich cores: human skull (left) and a bird's wing (right) [122]

Three of these levels are situated on microscopic dimensions beyond the interest of this thesis. However, the four levels that can be found on a macroscopic scale deal with the formation of a very specific grid into a cylinder and build-up of helical surface ridges altogether making the sponge stiff against random load types and protecting it from ovalization which would weaken its strength against bending caused by underwater currents.

The properties of metallic cellular materials listed in ***section 2.1.4*** result in a variety of possible engineering applications. However, not all materials fulfill a designated purpose as well as others. Therefore, possible application groups are shown in ***fig. 2.7***. In a matrix that distinguishes open- and closed-cell as well as periodic and stochastic cellular materials, these groups are placed in the most probable position (Rehme, 2006). Apparently, the positioning of each group is not a definitive must, however, in those applications shown in the upper half of the figure where media such as gas, fluid or solid pass the cellular material or where tissue grows into it, only open-cell structures can serve the purpose. On the other hand only closed-cell materials allow suitable design for buoyancy devices and thermal insulation. However, in structural applications closed-cell materials should be used since they offer at least hypothetically better performing strength properties than open-cell materials as explained in detail in ***section 2.1.4.15***. Additionally, the greatest benefit for structural applications such as energy absorbers or implants of high stiffness can be found in periodic structures due to the same reason. Other applications such as filters and heat exchangers should as well be made from periodic materials as less pressure drop per unit length can be expected. Those application groups shown on the right hand side of ***fig. 2.7*** are typically made from stochastic materials as the use of periodic materials has no evident advantage. In contrast the

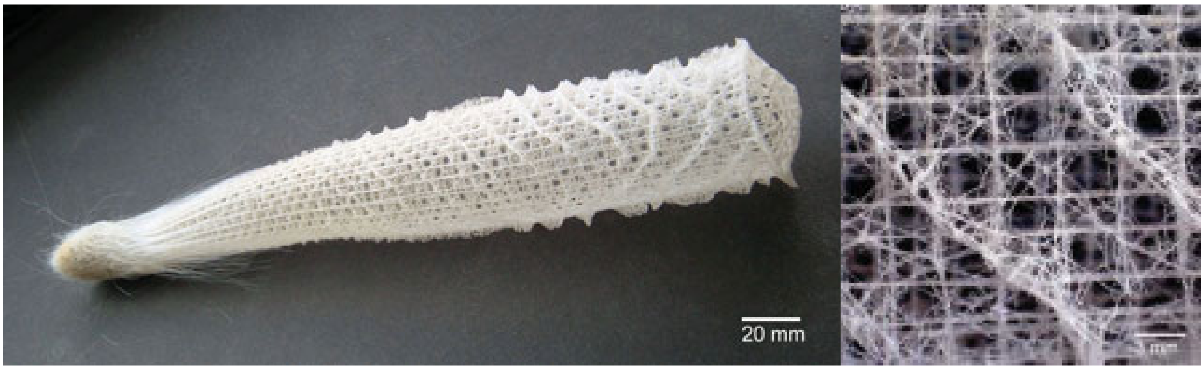

Figure 2.6: Skeleton of the deep-sea sponge Euplectella sp. [116]

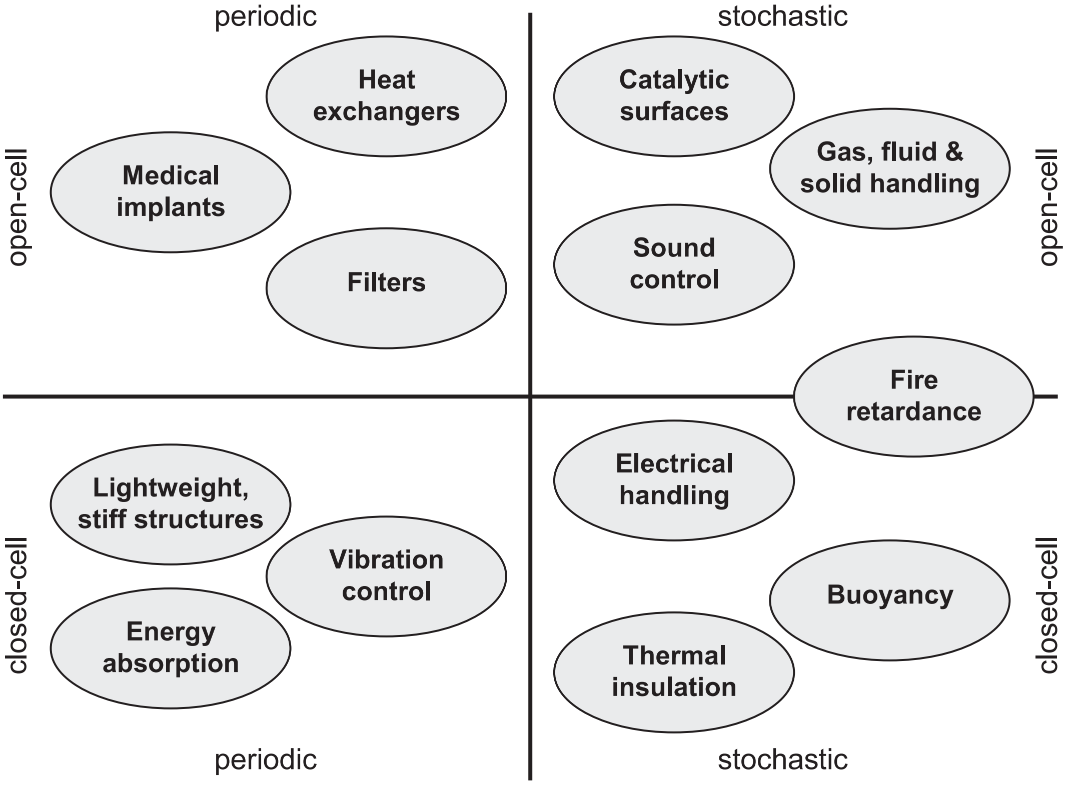

Figure 2.7: Application groups of cellular materials

manufacture of periodic cellular materials is often more costly per volume unit. It is therefore the task of the design engineer to make the best compromise between the options from ***fig. 2.7*** and the choice of materials, cell sizes, cell shapes, cell topologies, cell size distributions and relative densities for a given engineering application.

All these different application groups have resulted in numerous existing applications and in a number of currently developed implementations which were given by Ashby (2000, pp. 3-5, [17]), Banhart (2000, pp. 503-504, [26]), (2001, p. 609-621, [28]), ERG (2006, p. 4, [107]), Gibson (2005, pp. 391-395, [122]), Nieh (2000, p. 105, [217]), Stöbener (2003, p. 285, [281]), Wang (2005, pp. 21-23, [307]), Wicklein (2003, pp. 369-374, [315]) and various other authors. The span of industries making use of cellular materials has become quite wide. A summary of all these applications can be found in ***table 2.1*** sorted by their current importance in engineering design. This list may be comprehensive, however, not complete as new applications keep constantly emerging.