Engine Sound Weighting using a Psychoacoustic Criterion based on Auralized Numerical Simulations

Fabian Duvigneau, Steffen Liefold, Ulrich Gabbert
Institute of Mechanics, Otto-von-Guericke University, Magdeburg, Germany

Marius Höchstetter
BMW AG, München, Germany

Jesko L. Verhey
Department of Experimental Audiology, Otto-von-Guericke University, Magdeburg, Germany

Summary
Today the product quality of automobiles is increasingly influenced by the noise comfort and the acoustic perception of the customers. Consequently, a brand-specific design of sounds is applied by the car manufactures to offer a growing potential for qualitative differentiation. One major aspect of such a qualitative differentiation and a resulting auditory sensation is the emission of noise caused by the combustion engine. The primary objective of this paper is to evaluate the sound of an engine focusing on its auditory sensation of the sound quality. Instead of measuring the acoustic behavior of a real prototype an overall numerical model of the engine is applied to receive audible sounds of the engine. These audible sounds are used to carry out paired comparison listening tests, which finally lead to an interval scaled ranking of the stimuli. A psychoacoustic model is built, which shows the highest correlation with the subjective evaluation of engine sounds. This psychoacoustic model is a function, which consists of a weighted combination of well-chosen classical psychoacoustic parameters like loudness and sharpness. The resulting psychoacoustic model describes and predicts the auditory sensation of quality on the basis of signal processing of the sound signal only - without any further auralization or hearing test. The advantage of the presented concept is that the perceived quality can be optimized before a real prototype is built, because only simulation results are needed as input for the psychoacoustic model. In the paper at hand this approach is applied to evaluate different types of encapsulations of engines, which can reduce the emitted noise significantly. The example shows that the human sensation should be used during the design process to evaluate the sound quality, not just a physical parameter like the pressure level.

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1. Motivation

The design of industrial products can evoke customer satisfaction and associate high quality, if the individual's interests are fulfilled or even exceeded. As an essential requirement, all perceivable quality criteria need to match with the customer's expectation on general product design. To reach this target, car manufacturers focus increasingly on auditory sensation to evaluate the perception of sound quality. One major aspect for a qualitative differentiation is the acoustic performance and acceptance of the noise emitted by the combustion process. Due to the fact, that the technical quality of the engine sound appears highly present in each driving condition, the auditory perception of all related acoustic characteristics needs to be positive. Focusing on that objective, an engine encapsulation will evoke an improved acoustic behavior and lead to significantly reduced noise emissions. If suitable conditions are applied to include thermal effects, the encapsulation will increase fuel efficiency as well.

Based on these aspects, the aim of the study is to describe and predict the perceived sound quality of an engine noise in order to evaluate different types of encapsulation materials. The focus will be on a psychoacoustic prediction model to optimize the efficiency of an engine encapsulation while matching the

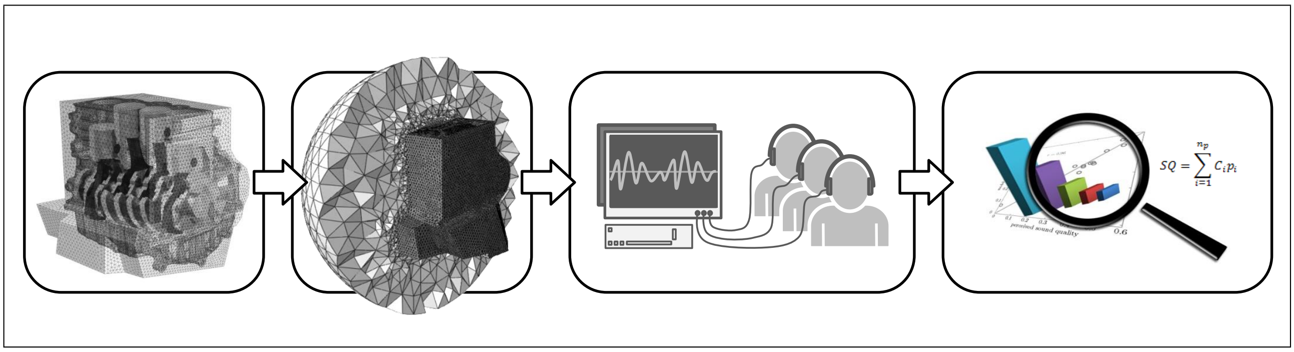

Figure 1. Basic concept to obtain the psychoacoustic prediction model to weight engine sounds.

customer's auditory sensation. With the purpose to simplify a qualitative validation of the different materials' effect on the perceived sound quality, the results will be visualized on a 3D envelope of the engine.
The basic idea of the current paper is drawn briefly in Fig. 1. As initial step of this approach, a complex numerical model of a running combustion engine with encapsulation and the surrounding air is used to investigate the acoustic behavior early in the product development process, before real prototypes are available [1]. Based on the auralization of the simulation results, hearing tests are carried out to classify the sound quality of the numerical generated engine sounds. Besides, basic psychoacoustic parameters like loudness, roughness, tonality and sharpness [2] are calculated with the help of the auralized simulation results. In addition, the gradients of these basic psychoacoustic parameters are calculated, too. Finally, the psychoacoustic prediction model is derived from the pool of all the calculated parameters using the method of linear regression analysis. A comparison from further subjective and objective investigations on independent engine sounds offered a high correlation, thus the built prediction model is validated. With the presented, advanced approach applied, the automotive engineer can benefit by influencing the acoustic behavior of an engine sound in a targeted manner by choosing an acoustic encapsulation that will lead to a higher perceived sound quality.

2. Methodology

The necessary steps of the holistic workflow to develop the psychoacoustic prediction model are shown in Fig. 2. The aim is a generally applicable psychoacoustic prediction model for a specific class of acoustic problems, like engine sounds of passenger cars. The simulation workflow up to the time signal generation consists of a multi-body simulation [3], a finite element analysis [4] of the structural vibrations and the sound radiation [5] followed by the time signal generation of the simulation results [6]. On the one hand these periodic time signals are an input of the signal processing to get psychoacoustic parameters like loudness (DIN 45631/A1, ANSI S3.4) or sharpness (DIN 45692) and on the other hand they are auralized to be part of the hearing tests. The results of the signal analysis and hearing tests were compared by a correlation analysis. Then the psychoacoustic prediction model is built as a linear function with the three psychoacoustic parameters, which show the best correlation with the hearing test results.
In automotive applications the engine sound is often dominated by multiples of the half or full so-called engine orders [7]. Thus, the paper at hand considers only multiples of the quarter and half engine order. It is necessary to analyze frequencies up to 16 kHz in detail, in order to preserve the physical characteristics of a sound signal for a most realistic sound that considers the whole human hearing range. Some important phenomena of combustion engines like knocking and ticking are caused already by small amplitudes in the higher frequency domain.

2.1. Numerical simulation

At first, the bearing reactions are obtained from an elastic multi-body simulation of the crank drive dynamics with consideration of the elasto-hydrodynamics [8]. This requires an experimentally determined cylinder gas pressure curve as characteristic input data [9]. The structural vibrations of the engine block are excited with the help of the bearing reactions, which affect in turn the bearing blocks of the cylinder crankcase. With the virtual engineering approach in [10], the lateral forces on the cylinder liners of the cylinder crankcase can be taken into account as additional excitation sources of the structural vibrations of the combustion engine. Subsequently, the resulting surface velocity of the engine structure is used to excite the surrounding fluid volume. This air volume is modeled as a sphere with a coarser discretization towards the periphery to decrease the numerical effort. Due to the computational costs, the vibration and acoustic analysis are exclusively executed in the frequency domain. For this reason, a fast Fourier transformation (FFT) [11] is used to transform the results from the time into the frequency do-

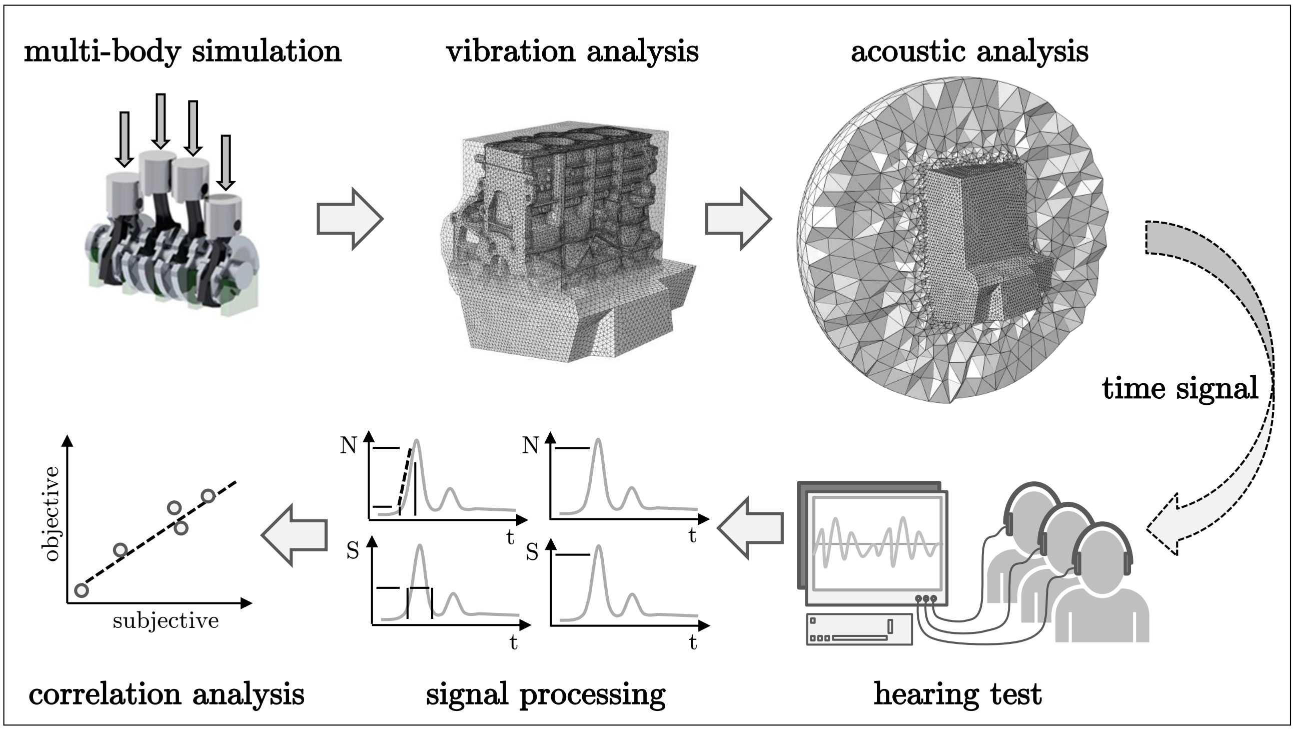

Figure 2. Holistic virtual engineering approach to develop the psychoacoustic prediction model.

main. In general quadratic tetrahedral elements are used in the numerical models of the engine, the encapsulation and the surrounding air as well.

In the present study absorbing boundary conditions [12] are applied for the simulation model to assure that the Sommerfeld radiation condition [5] is fulfilled and thus no sound waves are reflected at the boundary of the discretized fluid volume. The application of alternative acoustic boundary conditions like infinite elements [13] or perfectly matched layers (PML) [14] are not taken into account due to the computational effort. Moreover, the acoustic simulation can be performed in an uncoupled way as in [15], which means that the influence of the fluid on the vibrating structure is neglected. The engine structure is quite stiff compared to the air and is, consequently, not notably influenced by the surrounding air pressure under free field conditions.

The acoustic simulation calculated in the frequency domain results in a complex sound pressure in the whole air volume. The superposition of a cosine function per calculated frequency with the corresponding amplitude and angular phase shift leads to the time signal of the sound pressure at each point of the air volume [6]. In order to ensure a correct signal processing several aspects have to be taken into account [16].

2.2. Psychoacoustic modeling

The hearing test took place in an acoustically optimized room with homogeneous light conditions. For a minimum of disturbing influences, the acoustic sense was stimulated by open headphones, type STAX SR-202, to contribute to a most possible realistic playback for the participants. To evaluate the perceived sound quality, reliable and ordinal scaled data are received by applying the paradigm of paired comparison tests [17]. The sounds were combined to each other by the algorithm of Ross [18] with the number of pairs between the first and the following playback of a sound being maximized and all elements appearing equally often on the first and the second position. Additionally, the test design considered the restrictive criterion of context independence whilst making a choice [19].

Prior to an experiment, a written, standardized text explaining the method of paired comparison and the test procedure was handed out to the participants. At the beginning of the experiment, the experimenter presented the sounds to the participants. After this initial phase, the participants were asked if they had any further questions concerning the upcoming evaluation task. These questions were answered by the experimenter before the acoustic experiment started.

In total, 13 women aged between 19 and 34 years and 22 men from 21 to 53 years participated in the experiments. The total average age of the participant group was 31.7 years. All of them showed a normal hearing ability in their tone audiograms. Based on the χ^2-Test, participants with inconsistent responsiveness were excluded from further analysis by a confidence level of $\alpha = 0.05$. Based on this, one male and one female person were not considered. A broad spectrum of subjects was covered consisting of 14 laymen and 11 experts working in the field of acoustic development.

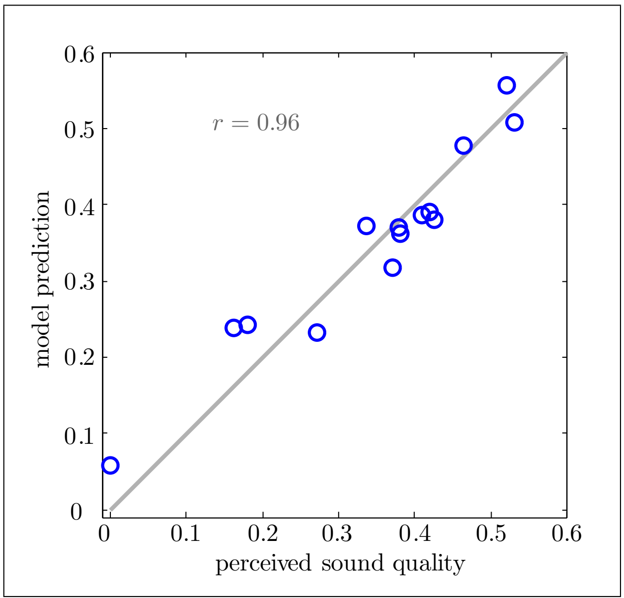

Figure 3. Correlation analysis of the developed model with a dataset of fourteen independent sounds, $r = 0.96$.

As the preference decision is made on the psychological continuum, no information about the actual difference of the sounds is provided. This aspect has to be derived from the cumulative frequency, which listeners prefer one stimulus to another [20]. Finally, the approach of Bradley, Terry and Luce was chosen to transform the cumulative results via dominance matrix to an interval scale [20, 21, 22, 23].
The descriptive psychoacoustic model was developed by a regression analysis between the results of the hearing test and several parameters like the maximum gradient N'_{max} of the percentile loudness N_5 and the maximum sharpness S_{max} out of the signal processing [24, 25]. Another important derived measure out of the signal processing is the duration of sharpness T_S. The duration is calculated as long as the signal exceeds a constant threshold of sharpness level. Different to former analysis [26, 27] on singular impulsive sounds, the average value of sharpness level was identified as constant threshold that works properly for each sound.

3. Results

After finishing the described steps for generating the psychacoustic prediction model (see Fig. 2), a second hearing test with fourteen different sound signals was carried out in order to validate the developed psychoacoustic model. The stimuli of this hearing test are new ones, which were not used to develop or improve the psychoacoustic prediction model. The data of the correlation analysis between the results of the second hearing test and the developed prediction model are shown in Fig. 3. The result of this correlation analysis proofs the applicability of the generated model to predict the human's perceived sound quality by achieving the high correlation coefficient of 0.96 (see Fig. 3).
Consecutively, the developed psychoacoustic prediction model is used to calculate the spatial distribution in the whole surrounding fluid volume around the encapsulated engine. Fig. 4 shows the calculation results visualized by a central cutting plane through the spherical air volume, which is orthogonal to the crank shaft axis. All results are normed, because of confidentiality obligations. In Fig. 4 the sound radiation of an engine encapsulations is compared with respect to their spatial distribution of the A-weighted sound pressure level and the perceived sound quality. The A-weighted sound pressure level which is a standard method of acoustic evaluation is visualized on the left hand side of Fig. 4. The right hand side shows the human's perceived sound quality, which is calculated by the developed prediction model.
However, it is notable that the perceived sound quality is only slightly influenced by the A-weighted sound pressure level. In regions of larger sound pressure amplitudes the perceived sound quality is not necessarily much worse than in other regions. To the contrary, regions far away from the highest sound pressure amplitudes show the worst sound quality in Fig. 4. This discrepancy between A-weighted sound pressure level and perceived sound quality shows the necessity of the presented consideration of psychoacoustic dependencies. In the spatial distribution of the A-weighted sound pressure level of the encapsulation the region near the oil pan and especially under the oil pan is detected as the critical region with respect to the directional characteristic. In contrast, the spatial distributions as well as the amplitudes of the calculated sound quality show a very different behavior. Consequently, the detected critical regions are also different. These reasons emphasize the importance of the application of a more complex psychoacoustic model to consider the human's acoustic perception in a better way.

Figure 5. Different foam materials for engine encapsulations.

In Fig. 5 a few examples for potential foam materials in encapsulation applications of combustion en-

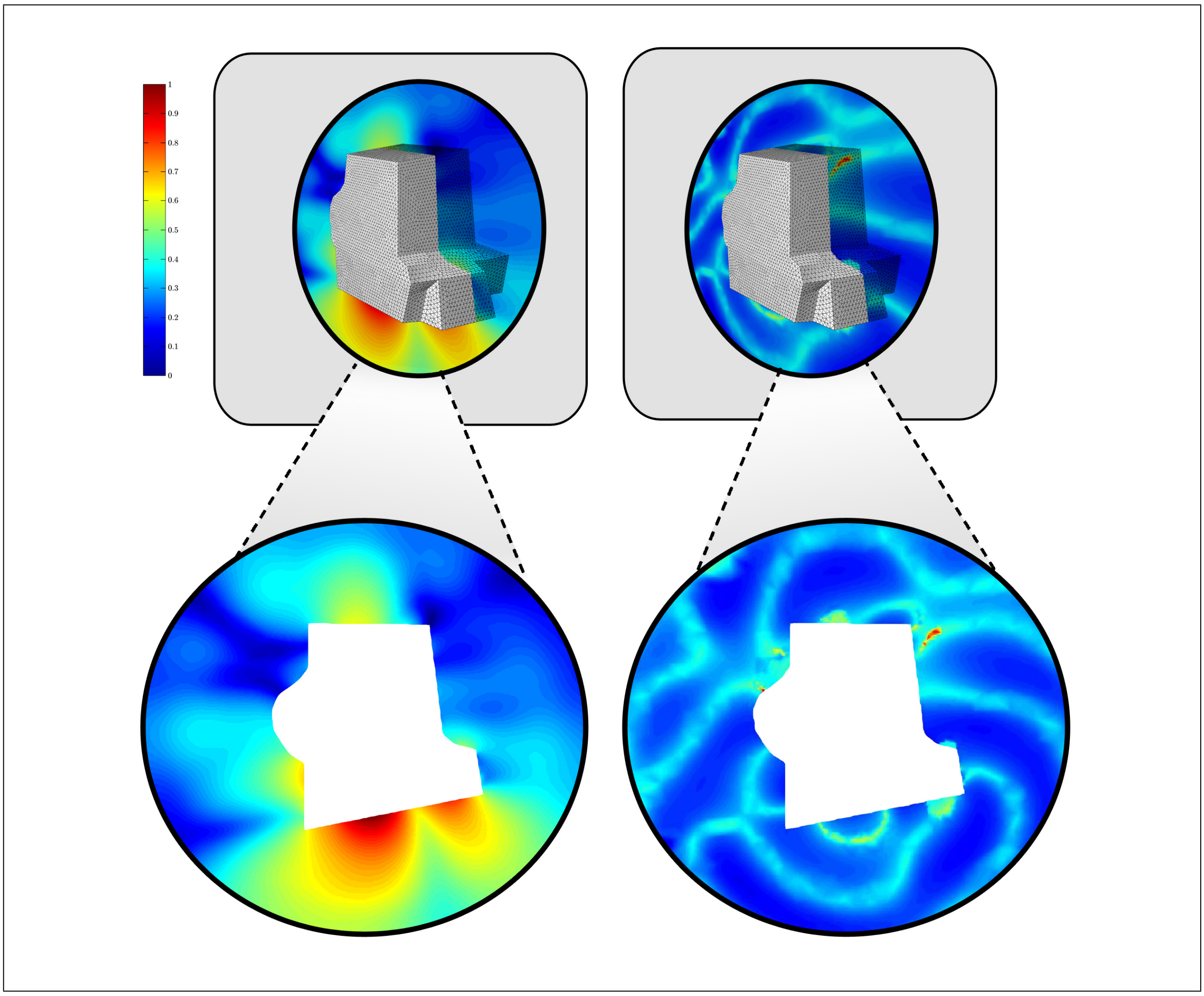

Figure 4. The A-weighted sound pressure level (left) and the perceived sound quality (right) of an engine encapsulation.

gines are shown. The presented approach enables the evaluation of several encapsulation materials with respect to the resulting perceived sound quality. This is important, because the consideration of the radiated sound power is not sufficient for an acoustic evaluation of an engine. In Fig. 6 the result of such an exemplary comparison of the sound quality caused by different encapsulation materials is visualized. It is clearly observable that there are large differences between the different used materials in the calculated sound quality. The investigated encapsulation materials consist of two nonmetallic layers of foam and fiber materials. These material systems basically consist of a very soft and highly absorbing foam layer that surrounds the vibrating structure with a much stiffer fiber material on its outside. Both, the foam and the fiber materials have to be as light as possible and also temperature resistant. The investigated encapsulation materials in this paper differ mainly in the thickness, loss factor, stiffness and density. The decision, which material is the best one for an engine encapsulation with respect to the improvement of the human' perceived sound quality, can be drawn from a comparison like shown in Fig. 6. This comparison of the predicted sound quality leads to the conclusion, that the result of the engine encapsulation shown on the right hand side of Fig. 6 is the better one. In contrast to Fig. 4, in Fig. 6 the spatial distribution of the calculated sound quality of two engine encapsulations made from different materials is visualized through a vertical sectional plane in the 3D air volume parallel to the crank shaft axis.

4. CONCLUSIONS

The paper at hand presents a holistic simulation approach of the acoustic behavior of engines including elastic multi-body simulation, vibration analysis, acoustic analysis, auralization and psychoacoustic modeling. Additionally, the comparison of a second hearing test and the prediction by the developed psychoacoustic prediction model with respect to new configurations verifies the applicability of this virtual en-

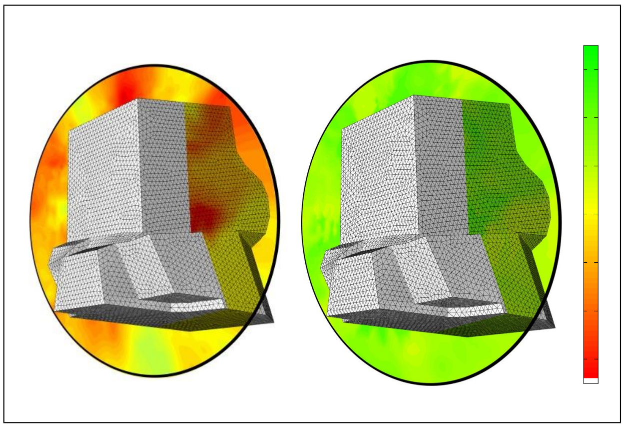

Figure 6. Comparison of the sound quality of two different engine encapsulations.

gineering approach. It is shown that it is very important to consider more complex psychoacoustic models to evaluate the acoustic of an engine - not only the basic psychoacoustic parameters like loudness or sharpness. Furthermore, it is proven that the presented approach is applicable for an evaluation of several encapsulation materials with respect to their influence on the perceived sound quality. The next step is to optimize the material and the topology of an engine encapsulation based on the presented approach.

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