

GETTING INSIGHT INTO NOISE, VIBRATION, AND HARSHNESS SIMULATION DATA

Krešimir Matković
Rainer Splechtna

VRVis Forschungs-GmbH
Donau-City Straße 11
1220 Vienna, AUSTRIA

Denis Gračanin

Department of Computer Science
Virginia Tech
2202 Kraft Drive
Blacksburg, VA 24060, USA

Goran Todorović
Stanislav Goja
Boris Bedić

AVL-AST d.o.o.
Strojarska cesta 22
10000 Zagreb, CROATIA

Helwig Hauser

Department of Informatics
University of Bergen
Postboks 7803
5020 Bergen, NORWAY

ABSTRACT

Due to ever stricter noise regulations and increasing passenger comfort requirements, noise, vibration, and harshness (NVH) simulation remains very important in the automotive industry. Noise simulation data analysis is challenging due to the data size and complexity. The Campbell diagram is a standard tool for noise analysis that summarizes noise for all frequencies and all operational points. We propose an interactive approach to a detailed analysis of the noise simulation data by means of interactive visualization. This approach, as an addition to the conventional analysis, provides additional insight into the data and facilitates the understanding of the simulated phenomenon. We deploy a coordinated multiple views configuration consisting of a parallel coordinates view, a 3D view, and three multi-view projections. The approach is illustrated using NVH simulation data for a four cylinder internal combustion engine.

1 INTRODUCTION

Simulation is used in all phases of automotive design. Advanced computing technology makes it possible to simulate using very detailed models, usually resulting in a large amount of data to be analyzed. Novel approaches to data analysis are needed to meet these challenges. Modern automatic analysis methods can usually find an optimum or a sufficiently good solution. Interactive visual data exploration and analysis has established itself as a valuable approach, when, besides finding an optimum, the engineer also wants to better understand the phenomena under investigation and get further insight. In this paper, we exemplify such a case for noise simulation.

Ever stricter noise regulations, as well as requirements on increased passengers comfort are the main driving force in noise, vibration, and harshness (NVH) simulation and analysis. One of two main sources of noise and vibrations are vibrating mechanical parts of a vehicle, excited both externally (e.g., by the road) and internally (e.g., by the engine). While at lower frequencies these vibrations can produce an unpleasant shaking of cabin parts, those at higher frequencies produce so-called structure-borne noise. Expert experience and knowledge is indispensable in the analysis of NVH simulation data. Currently,

engineers are creating a set of mostly static charts, and combine them in a report which is a tedious, error-prone, and time-consuming procedure. The Campbell charts, one of the mostly used charts in such reports, show aggregated noise levels for many engine operation points and many frequencies.

In this paper, we focus on a detailed exploration of data for a single operating point. We deploy a new, interactive visual analysis approach that supports the engineer in getting insight and in exploring detailed information on individual frequency band levels for each cell of the simulation model. Our approach does not replace the conventional workflow, but augments it when a more detailed analysis is needed. We, a group of simulation and visualization experts, have designed the proposed approach in a series of participatory design sessions (Hartson and Pyla 2019). We have carefully evaluated the needs of the engineers, who deal with NVH simulation data analysis, and, as a result, we propose to use a coordinated multiple views system to analyze the data. Very positive feedback from the engineers confirms the usefulness of the new approach.

2 RELATED WORK

Computational simulation produces high-dimensional, large data that is in general very challenging to visualize and analyze (Doleisch et al. 2003; Matković et al. 2014; Matković et al. 2018). Accordingly, we need tools that can support an interactive analysis of such data, such as a framework for the flexible and interactive specification of high-dimensional and/or complex features in simulation data (Doleisch, Gasser, and Hauser 2003). Feldkamp et al. (Feldkamp et al. 2015) propose a much broader, visually aided analysis of simulation data that includes farming approaches for obtaining data with many combinations of input and output data. Before interactive visual analysis, data can be processed by data mining and machine learning methods.

Interactive visual analysis requires customized views that help analysts to gain insight into all facets of multi-run, multi-field spatio-temporal simulation data. However, not all visualization techniques are well-suited for simulation. Vernon-Bido et al. (Vernon-Bido et al. 2015) describe a basic taxonomy of visualization in modeling and simulation and discuss issues faced by each type. Similarly, Müller et al. (Müller and Schumann 2003) provide a taxonomy and discuss general aspects of time-dependent data. They also discuss techniques for analyzing time-dependent multivariate simulation data, as well as dynamic presentation techniques, and event-based visualization. Fofonov et al. (Fofonov and Linsen 2018) describe their MultiVisA tool for the interactive visual analysis of multi-run data from physical simulations based on a number of aggregated plots and coordinated interactions.

Individual application domains introduce additional requirements for the effective visualization of simulation data. For example, Leite et al. (Leite et al. 2016) identified challenges related to the construction industry. Unger et al. (Unger et al. 2012) described a visual analysis concept for the validation of geo-scientific simulation models.

The visualization of NVH simulation data must take into account the physical representation of the simulated system and the used simulation/modeling techniques. Computer aided engineering (CAE) techniques are frequently used to simulate noise and vibration (Hampl 2010; Prajith and Sagade 2020). CAE techniques include finite element (FE), boundary element (BE), multi-body dynamics, computational fluid dynamics (CFD), statistical energy analysis (SEA) and transfer path analysis (TPA).

There is a number of NVH automotive noise and analysis tools/workflows. Altair HyperWorks NVH Director is an integrated solution that includes object-oriented assembly environment, specialized NVH functionalities, structural analysis solver, powerful post-processing utilities, optimization, and advanced simulation technologies (Altair 2021).

EOMYS MANATEE (Magnetic Acoustic Noise Analysis Tool for Electrical Engineering) provides the vibro-acoustic design optimization of electrical machines under electromagnetic excitation (or e-NVH in automotive applications) (Eomys 2021).

3 NVH SIMULATION

One of the main automotive design process components during a new product development (e.g., a car or an engine) is **NVH** (**N**oise, **V**ibration and **H**arshness) analysis. NVH is an umbrella term in the automotive industry that covers noise suppression, noise design, vibration suppression and suppression of squeaks, rattles, and ‘tizzes’ (Harrison 2004). In this context, noise refers to audible sound while vibration refers to tactile vibration.

Noise describes audible sound, with particular attention paid to the frequency range 30–4000 *Hz*. Two main contributing sources of noise are:

- **Structure-borne noise:** radiated by structural surfaces that are vibrating; it is induced by both internal sources (e.g., engine vibrations) and external sources (e.g., road surface roughness).
- **Airborne noise:** resulting from fluid pressure fluctuations transferred to a vehicle’s structure (e.g., flow turbulence around side wing mirrors or over an open roof window).

Vibration describes tactile vibration in the frequency range of 30–200 *Hz* (Wang 2010). Vibrations at higher frequencies mainly contribute to above-explained noise; vibrations at the lower end of spectrum can produce discomfort and even health and safety issues.

Harshness describes human perception related to the quality and transient nature of the former ones. Unlike noise and vibration that can be objectively measured as physical quantities, harshness is a more subjective measure.

A variety of physical measurement methods is used to identify noise sources in engines and cars. While modern methods, like intensity and holography techniques, require specialized testing setup, even the basic measurement methods can provide useful results (Inavolu et al. 2017).

Structure-borne noise analysis targets the higher end of the vibration spectrum. The analysis starts with a time-domain multi-body model simulation of the initial design at a number of engine speeds, switching subsequently to frequency domain to calculate model’s outer surface velocity levels that are responsible for noise radiation.

First we need to calculate the mean normal-to-surface velocity value ${}_j\bar{a}$ of the j th surface patch (typically the face of a 3D finite element) for each harmonic using equation (1) where n_{patch} is number of patch nodes.

$${}_j\bar{a} = \sqrt{\frac{\sum_{\text{node } i \text{ belonging to patch } j} a_i^2}{n_{patch}}} \quad (1)$$

We can then calculate either the integral *mean* velocity level ${}_AL$ on a surface of area A_{tot} using equation (2) or the integral *normalized* velocity level wrt. a reference surface of area A_0 using equation (3).

$${}_AL = 10 \cdot \log_{10} \left(\frac{1}{a_0^2 A_{tot}} \sum_{j=1}^N {}_j\bar{a}^2 \cdot A_j \right) \quad (2)$$

In equation (2) A_{tot} is the total surface area, N is the number of surface patches with areas A_j ($j = 1, \dots, N$), ${}_j\bar{a}$ is the mean (average) velocity amplitude on the j th patch, and a_0 is the reference velocity.

$${}_AL = 10 \cdot \log_{10} \left(\frac{1}{a_0^2 A_0} \sum_{j=1}^N {}_j\bar{a}^2 \cdot A_j \right) \quad (3)$$

In equation (3) A_0 is the reference (normalized) area. The integral mean and integral normalized velocity levels (expressed in [dB]) given by equation (2) and equation (3) are evaluated for a single frequency. They can be defined/evaluated also for frequency bands like octave bands, third octave bands, or user defined

bands. The integral normalized velocity level is thus defined by equation (4).

$${}_A L = 10 \cdot \log_{10} \left(\sum_{freq. \ band} \frac{1}{a_0^2 A_0} \sum_{j=1}^N j \bar{a}^2 \cdot A_j \right) \quad (4)$$

The expression given by equation (5) represents the contribution to the integral velocity level of an individual frequency band (harmonic).

$$\frac{1}{a_0^2 A_0} \sum_{j=1}^N j \bar{a}^2 \cdot A_j \quad (5)$$

Term $\frac{1}{a_0^2 A_0}$ does not depend on the frequency, so the final expression for the integral normalized velocity level is given by equation (6).

$${}_A L = 10 \cdot \log_{10} \left(\frac{1}{a_0^2 A_0} \sum_{freq. \ band} \sum_{j=1}^N j \bar{a}^2 \cdot A_j \right) \quad (6)$$

The integral mean velocity level for a frequency band is defined similarly.

4 VISUAL ANALYSIS OF NOISE SIMULATION DATA

The data used in this paper is based on a multi-body dynamics (MBD) simulation of a front-wheel drive (FWD) demo model using AVL EXCITE™ (AVL 2021), a tool for advanced durability and NVH analysis. We compute velocity levels for each finite element face (cell) at the outer surface of the 3D FE model. In our case, it is a four-cylinder internal combustion engine with 12 173 cells in the model. We use the aggregated values for 22 third octave bands for each cell.

The analysis of the simulation data results in Campbell diagram (Figure 1a). It summarizes overall integral velocity levels for all frequencies and for all engine speeds. It is of great help for spotting critical points and identifying potential problems. Still, it is a highly aggregated depiction, and many computed values remain hidden. One horizontal line in the plot shown in Figure 1a corresponds to one engine speed. For a single speed we have values for 22 third octave bands for each of the 12 173 cells. Sometimes, engineers need means to drill down into the data to get more detailed insight. In a case when all velocity levels of all cells are needed, the use of a 3D depiction of the model with color-coded levels is a logical next step. Figure 1b shows such a visualization for our engine and for one third octave frequency band, i.e., the 2000 Hz band in this case.

When analyzing velocity levels, experts are primarily interested in:

- Comparison of velocity levels across frequencies — what are the velocity levels across all frequencies for certain cells?
- Feature localization — which cells have a certain velocity level?
- Local exploration — what are the velocity levels of cells at a certain location?

Answering these question helps engineers to understand the system under investigation and provides insight and understanding regarding the underlying physical phenomena. Identifying maximum velocity levels is certainly necessary, but understanding why they happen adds additional value.

By now, interactive visualization has established itself as a premium medium that provides insight into complex data. In order to support the engineers in answering the identified analysis tasks, we propose to use coordinated multiple views (Roberts 2007), a well known concept from interactive visual analysis, in explore and analyze the velocity levels at different levels of detail.

Figure 1a shows aggregated values of all cells for all frequencies, and the 3D view in Figure 1b shows the values for one third octave band only. We only see a subset of the cells and the user has to rotate, zoom,

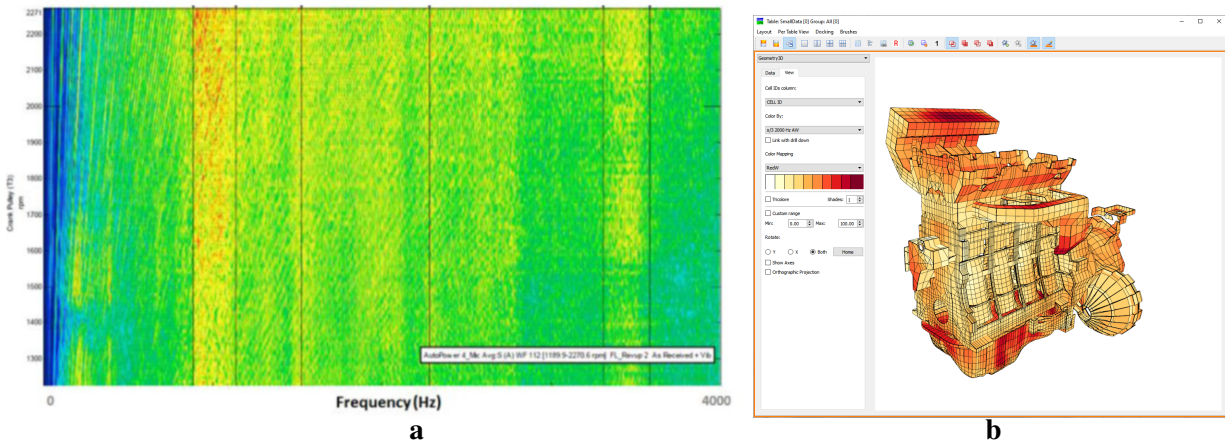


Figure 1: **a)** The Campbell diagram is a standard way of depicting noise data. Aggregated noise levels for all frequencies (x -axis) and all engine operational points (y -axis) are shown. **b)** A 3D view with color coded velocity levels is often used to examine data for a single frequency and a single operational point.

or cut through the model in order to see all cells. As we want to show the values for all frequency bands and for all cells at once, another type of visualization is needed. The parallel coordinates plot (Inselberg and Dimsdale 1990; Inselberg 2009) has been designed to depict multidimensional data. It represents an appropriate choice for the first task, i.e., for the comparison of velocity levels across frequencies.

4.1 Parallel Coordinates

The main idea of the parallel coordinates plot is to use a vertical axis for each attribute of the data records. For each record, the points on the axes that correspond to the values of the attributes, are visually connected in that each data record is represented with a polyline across all axes. Figure 2a shows the parallel coordinates plot of our data. Each axis stands for one third octave band, and the values for each cell are connected by a polyline. Usually, each axis is scaled individually so that the attribute's minimum–maximum range spans the entire axis. As we are interested in absolute velocity levels, we scale the axes with the global minimum and maximum as shown in Figure 2b.

Parallel coordinates represent an excellent choice for our task of comparing velocity levels across the frequency bands. We can see which third octave bands cause the highest velocity levels. In our case it is the 63 Hz third octave band. The engineers need to decide if almost 130 db is too high for this frequency. As the frequency is relatively low, the velocity level will not be perceived as uncomfortable for humans.

Static parallel coordinates provide some valuable insight. In order to fully exploit their potential, support for user interaction is needed. Correlations between neighboring axes can be easily seen without interaction, but if we want to see what is happening with certain records over all dimensions, interaction is needed. We support two types of interaction: (1) mouse over highlighting and (2) composite brushing. Each of them is motivated by a different task. The mouse over highlighting emphasizes the records under the mouse cursor. Figure 3a shows an example. The user places the mouse cursor over low values for the 1600 Hz third octave band. All records with low values are highlighted. Now we can see that the highlighted records have mostly low values for the third octave bands with higher frequencies, and that they are spread over a much wider range for the lower frequencies. Mouse over highlighting provides immediate response and it is an excellent way for a quick and flexible exploration to get a first impression.

When it comes to a deeper drill down, we need composite brushing. Here, the user brushes (selects) a range on an axis, and all brushed records are highlighted. Now the selection can be moved or re-scaled on the axis, or a new brush can be created. The brushes can be combined by Boolean operations. In the case shown in Figure 3b, two brushes are combined using *AND* operation. The records having high values

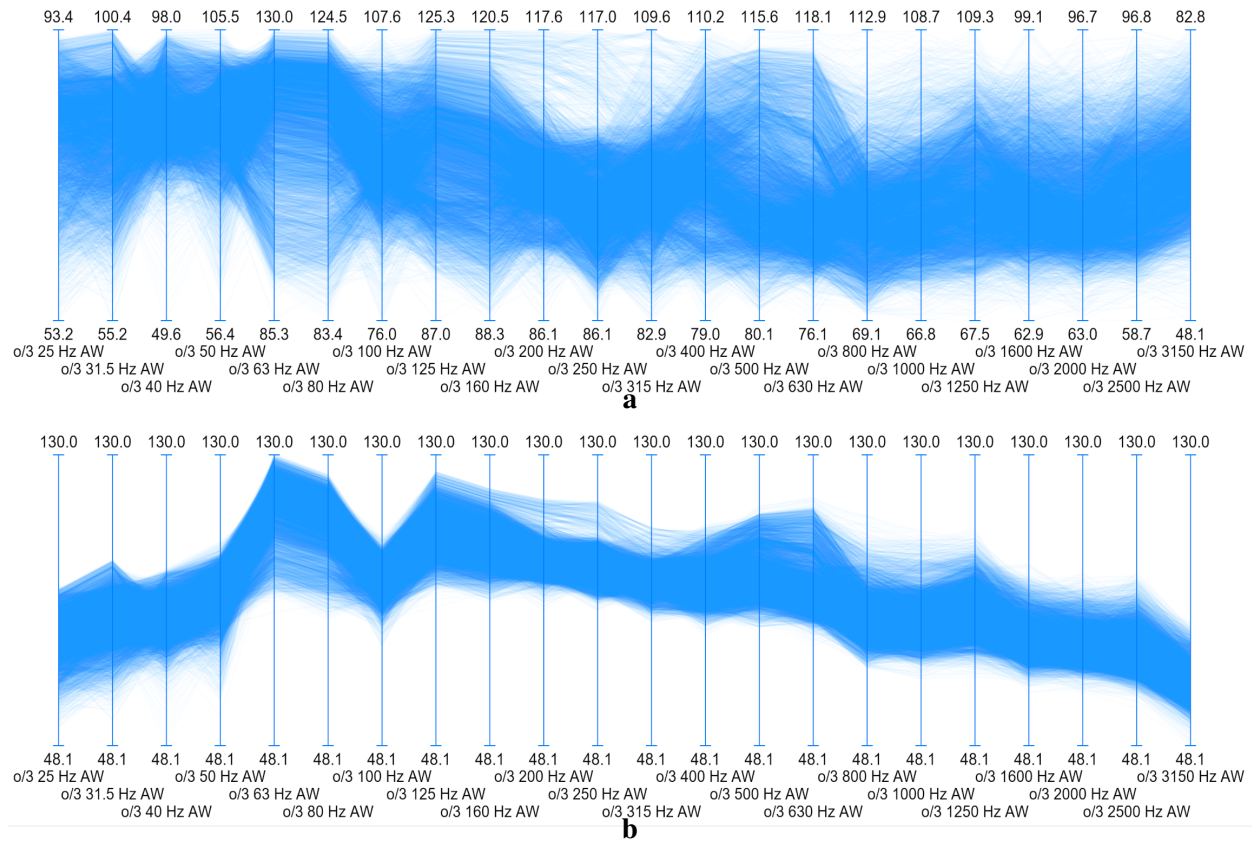


Figure 2: **a)** A parallel coordinates plot shows the velocity levels for all cells of the simulation model. Each axis represents one frequency band, and each cell is represented by a polyline that connects the cell’s velocity levels across all frequency bands. All vertical axes are scaled according to the band’s minimum and maximum values. **b)** The same data is shown with different axis scaling. All axes are scaled according to the global minimum and maximum values.

for the 630 Hz and for the 250 Hz third octave bands are selected. Interestingly, these records form two clusters for some bands (31.5, 63, or 315 Hz, for example). We can further brush with an additional brush to see if these are two clusters that are consequently split over the frequencies.

4.2 3D Views

We deal with spatial data, so we need 3D views in order to support the remaining two tasks, i.e., feature localization and local exploration. The conventional 3D view (Figure 1b) conveys the 3D model very efficiently, but it suffers from two drawbacks. First, it shows only a subset of the data, back-facing surfaces are not visible. The user has to turn the model in order to see all brushed cells. Secondly, it is not easy to select cells on the surface due to ambiguity resulting from the projection to 2D.

In technical drawings, for example, a similar problem is solved by a multiview projection—a set of orthographic 2D projections that represent the form of the 3D object. In such a solution, there are mostly 3 views, i.e., front view, top view and end view. We use the same idea in combination with a points-based 3D view. As shown in Figure 4a, in the top left corner the 3D model is depicted by points placed in the center of each cell. The point size corresponds to the cell’s area, so that engineers can see if cell areas are large or small. The use of points instead of cell rectangles makes it possible to see through the model. Since the engineers are familiar with the 3D model, the mental model of the engine remains intact although

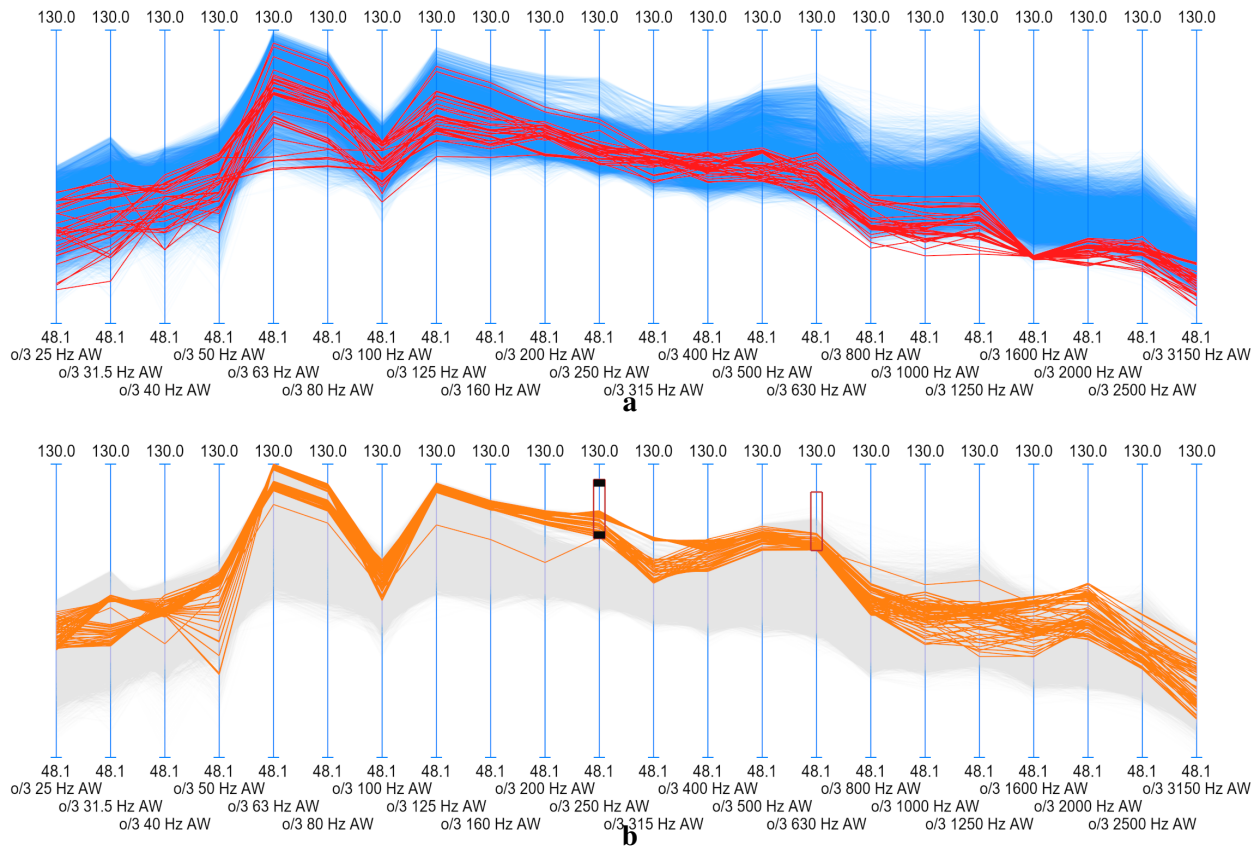


Figure 3: **a)** Mouse-over highlighting shows the values for data items under the mouse cursor when user hovers over the plot. The user sees the data distribution and the correlation between frequency bands. **b)** Brushing or interactive range selection makes it possible to select certain ranges on the axes. Here, two ranges are selected (black rectangles) and combined by the Boolean *AND* operation. An arbitrary number of brushes can be combined.

only points are used to show the 3D geometry. The three projections make it easy to select certain parts of the model much more efficiently compared to the direct selection in a 3D view. Figure 4b shows an example where user brushed the manifold in the lower left projection using a simple rectangular brush.

4.3 Coordinated Multiple Views

All proposed views are linked, which means that brushing in any view (data subset selection) highlights the corresponding items in all views. If the user brushes high velocity levels for the 630 Hz band, for example, as shown in the parallel coordinates plot in Figure 5, the projection views and the 3D points-based view highlight the cells that have these high values. In this case, there are two parts of the engine that are affected. The three conventional 3D views on the right in Figure 5 show how the user needs to rotate the view in order to see all parts. This slows the exploration.

It is plausible to reason that different engine parts will have different noise characteristics. We thus refine the selection in our example and combine the brush in the parallel coordinates plot with a brush in one of the projections. Figure 6a shows the views when the upper part of the engine is selected, in addition to the high values of the 630 Hz band. We see now higher velocity levels for the lower frequencies compared to the original brush, as seen in Figure 5. If we now move the brush, so that the lower part of the engine is selected, the situation changes (Figure 6b). As there are more cells in the lower engine part, we

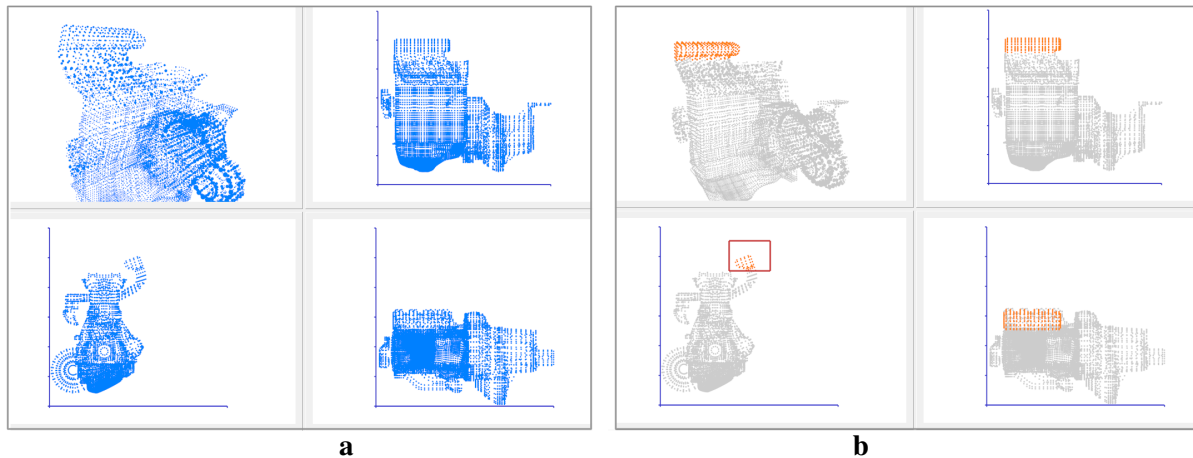


Figure 4: **a)** In addition to the conventional 3D view (Figure 1b), we use a points-based view that shows a point for each cell center. The advantage is that the user can see all points at once, no faces are hidden. The point size corresponds to the cell area. We also show three orthographic projections to ease interaction. **b)** The user selects a part of the engine in a 2D projection. A simple rectangular brush (red rectangle in the lower left projection) is sufficient. Such a selection would be more complex in 3D.

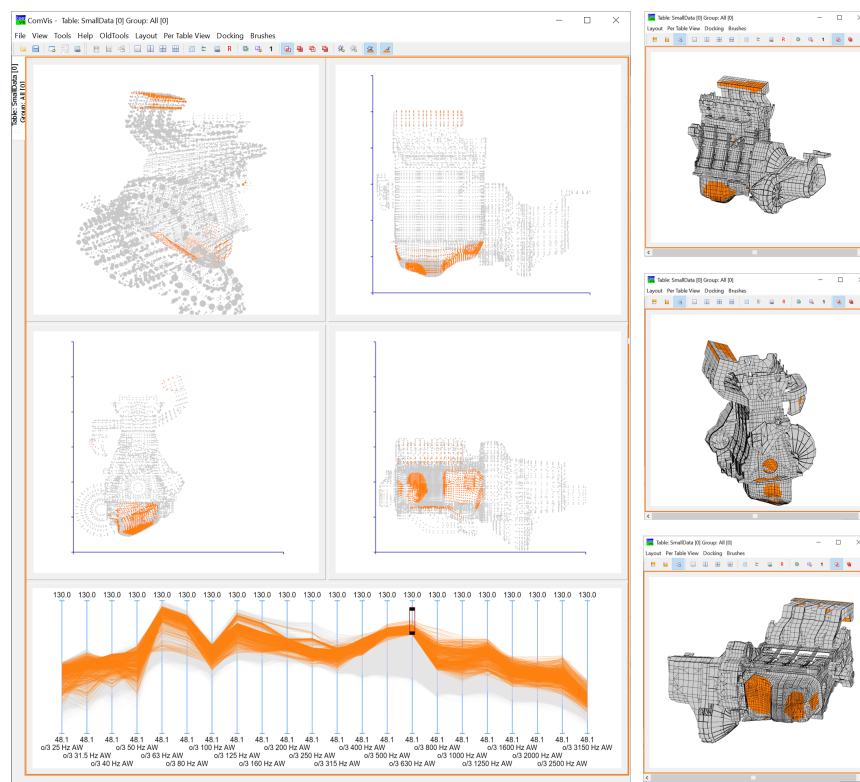


Figure 5: Data subsets can be selected (brushed) in any view (the parallel coordinates plot is brushed here) and all linked views emphasize the corresponding data items. The three 3D views on the right show how the user needs to rotate the 3D model in order to see all brushed cells. In the points-based 3D views with 2D projections all cells are visible.

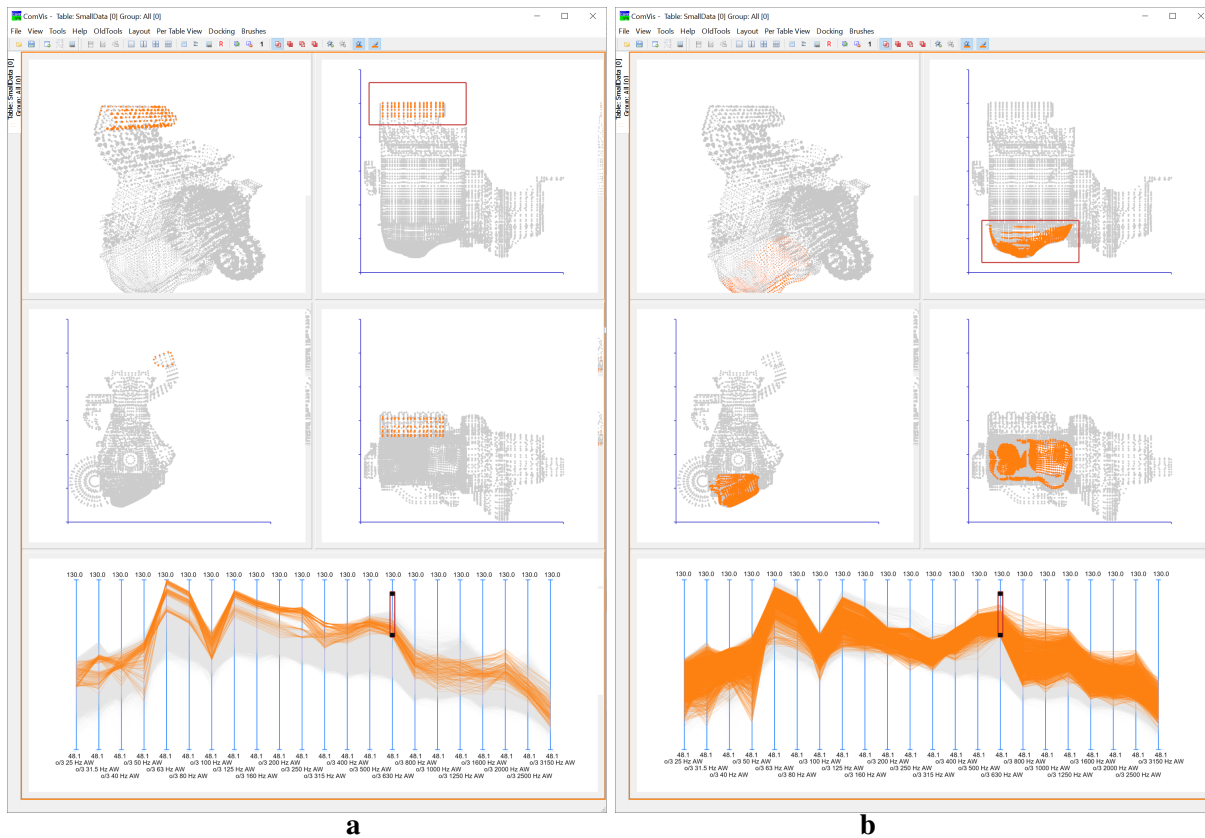


Figure 6: Composite brushing makes it possible to drill-down by refining selections. **a)** The user refines the brush on the parallel coordinates plot with a selection in the 2D projection view. **b)** The user moves the brush to compare velocity levels across different engine regions.

want to refine this selection for more investigation. We can easily add a brush in any view that selects just a part of the selection. We use the lower right view to refine the brush (Figure 7a). Moving the brush to the right selects another subset (Figure 7b). In this way, the user explores the data in an iterative way, refining the selections as needed. Finally, for the last selection there are many high values of the high frequency bands. The user can now further refine this selections by adding brushes in the parallel coordinates plot. We added two more brushes in this example to identify the most excited cells as shown in Figure 8. Only two views are shown here due to space constraints.

This short example illustrates the main idea of our new approach to an interactive visual exploration of the simulation data. This approach makes it possible to quickly identify potential areas that have to be further examined, and, at the same time, it helps the engineers in understanding the whole system. It is a quick and easy entry point to the analysis. Once potential problems are identified, the engineers have to carefully think about possible improvements and suggest ways of achieving them. Numerous tools help them on the way towards the final result.

5 CONCLUSION

Analyzing NVH simulation data is a challenging task, relying substantially on the expertise of engineers. In order to support them in a deep analysis of simulation data, we propose to use interactive visualization with coordinated multiple views. This approach nicely complements the common analysis workflow, providing an interactive quick way to identify possibly problematic areas. Simulation experts who evaluated our

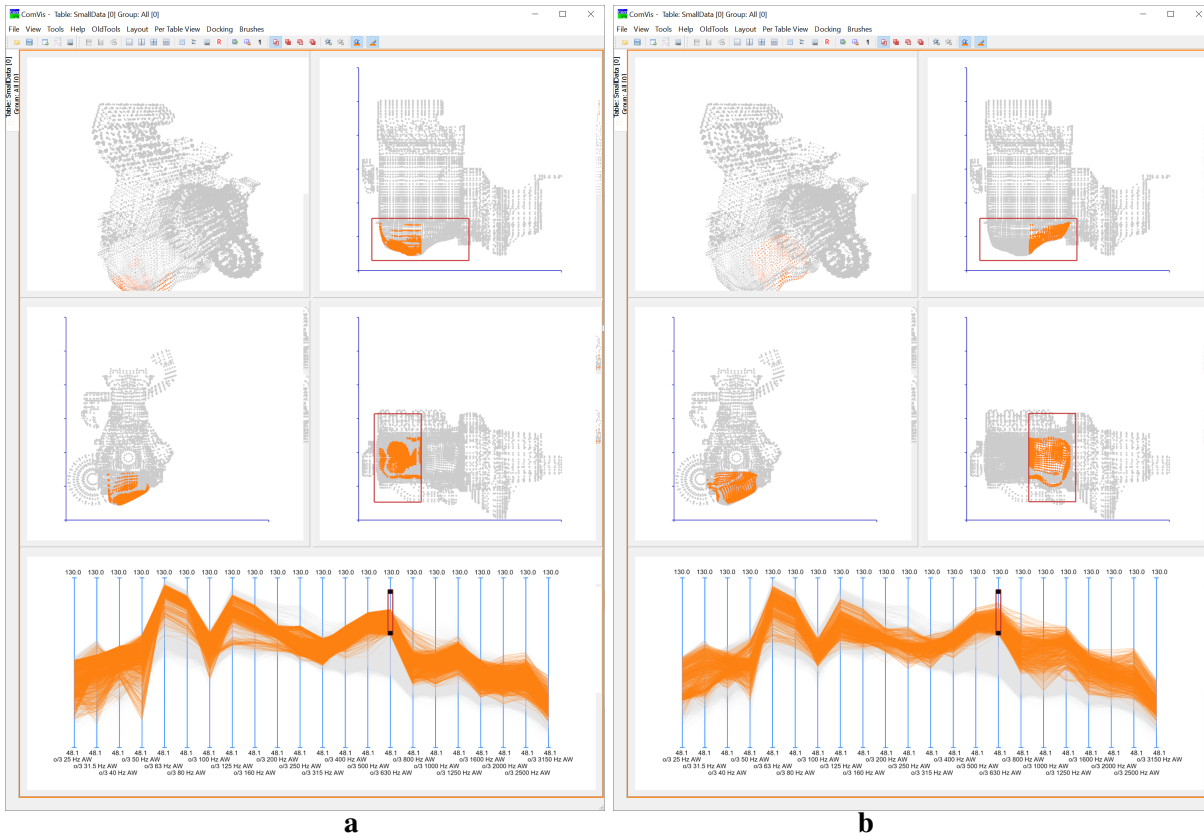


Figure 7: **a)** The user further refines the selection from Figure 6b by selecting only the left part of the engine in the lower right projection view. **b)** The user moves the last brush to select the right part of the engine. All views are updated instantly.

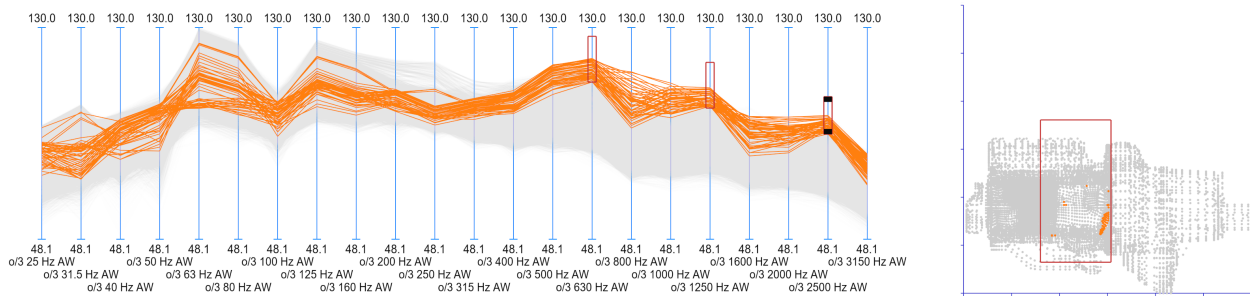


Figure 8: The selection can be further refined in any view. Here, the user brushes the parallel coordinates plot again to see the most excited cells. This can serve as a basis for a subsequent investigation.

new approach appreciate the intuitiveness and high interactivity of the system which makes it possible to quickly explore various scenarios.

The proposed approach supports the comparison of velocity levels across all frequency bands by parallel coordinates. It makes it possible to localize identified features by the use of the points-based 3D view, together with its corresponding projections. Finally, it supports neighborhood exploration by means of composite brushing.

Due to the ever increasing time pressure, simulation experts strive to automate the analysis as much as possible. Nevertheless, despite all the disadvantages that an interactive approach has (e.g., the results are not easy to reproduce, a lot of time has to be invested by well-trained experts), the proposed interactive approach received very positive feedback. This indicates that interactive approaches should be considered for other tasks in simulation workflow, as well.

ACKNOWLEDGMENTS

VRVis is funded by BMK, BMDW, Styria, SFG, Tyrol and Vienna Business Agency in the scope of COMET, Competence Centers for Excellent Technologies (879730), which is managed by FFG. Parts of this work have been supported by Virginia Tech Institute for Creativity, Arts, and Technology. Parts of this work have been done in the context of CEDAS, i.e., the Center for Data Science at the University of Bergen, Norway.

REFERENCES

- Altair 2021. “HyperWorks for Automotive Noise and Vibration Analysis”. <https://www.avl.com/excite/>, accessed 31st July.
- AVL 2021. “AVL EXCITE™”. <https://altairhyperworks.com/solution/NVH>, accessed 31st July.
- Doleisch, H., M. Gasser, and H. Hauser. 2003. “Interactive Feature Specification for Focus+Context Visualization of Complex Simulation Data”. In *Proceedings of the 2003 Eurographics / IEEE VGTC Symposium on Visualization*, edited by G.-P. Bonneau, S. Hahmann, and C. D. Hansen, 239–248. Geneva: Eurographics Association.
- Eomys 2021. “MANATEE Software”. <https://eomys.com>, accessed 31st July.
- Feldkamp, N., S. Bergmann, and S. Strassburger. 2015. “Visual Analytics of Manufacturing Simulation Data”. In *Proceedings of the 2015 Winter Simulation Conference*, edited by L. Yilmaz, W. K. V. Chan, I. Moon, T. M. K. Roeder, C. Macal, and M. D. Rossetti, 779–790. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.
- Fofonov, A., and L. Linsen. 2018. “MultiVisA: Visual Analysis of Multi-run Physical Simulation Data using Interactive Aggregated Plots”. In *Proceedings of the 13th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications*, edited by A. Telea, A. Kerren, and J. Braz, Volume 2: HUCAPP, 62–73: SciTePress.
- HAMPL, N. 2010. “Advanced Simulation Techniques in Vehicle Noise and Vibration Refinement”. In *Vehicle Noise and Vibration Refinement*, edited by X. Wang, Chapter 8, 174–188. Woodhead Publishing.
- Harrison, M. 2004. *Vehicle Refinement: Controlling Noise and Vibration in Road Vehicles*. Burlington, MA 01803: Elsevier Butterworth-Heinemann.
- Hartson, R., and P. Pyla. 2019. *The UX Book: Agile UX Design for a Quality User Experience*. Second ed. Cambridge, MA: Morgan Kaufmann.
- Inavolu, N., J. R. Medisetti, S. N. Kumar, J. Lingeshkumar, A. Loya, and M. MV. 2017. “A Structural Analysis Approach for Engine Noise Source Identification and Refinement”. In *Technical Papers presented at Noise and Vibration Conference and Exhibition*, Number 2017-01-1799. Warrendale, PA, USA: SAE International.
- Inselberg, A. 2009. *Parallel Coordinates: Visual Multidimensional Geometry and Its Applications*. Berlin, Heidelberg: Springer-Verlag.
- Inselberg, A., and B. Dimsdale. 1990. “Parallel Coordinates: A Tool for Visualizing Multi-Dimensional Geometry”. In *Proceedings of the First IEEE Conference on Visualization*, edited by A. Kaufman, 361–378. Washington, DC: IEEE Computer Society Press.
- Leite, F., Y. Cho, A. H. Behzadan, S. Lee, S. Choe, Y. Fang, R. Akhavian, and S. Hwang. 2016. “Visualization, Information Modeling, and Simulation: Grand Challenges in the Construction Industry”. *Journal of Computing in Civil Engineering* 30(6):04016035.
- Matković, K., D. Gračanin, and H. Hauser. 2018, 9–12 December. “Visual Analytics for Simulation Ensembles”. In *Proceedings of the 2018 Winter Simulation Conference*, edited by M. Rabe, A. A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, 321–335. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.
- Matković, K., D. Gračanin, R. Splechtina, M. Jelović, B. Stehno, H. Hauser, and W. Purgathofer. 2014, December. “Visual Analytics for Complex Engineering Systems: Hybrid Visual Steering of Simulation Ensembles”. *IEEE Transactions on Visualization and Computer Graphics* 20(12):1803–1812.
- Müller, W., and H. Schumann. 2003, 7–10 December. “Visualization Methods for Time-Dependent Data — An Overview”. In *Proceedings of the 2003 Winter Simulation Conference*, edited by S. Chick, P. J. Sánchez, D. Ferrin, and D. J. Morrice, Volume 1, 737–745. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.
- Prajith, J., and V. Sagade. 2020. “NVH Full Vehicle Development — Virtual Simulation Process for Low Frequency Structure-Borne Regions”. *SAE International Journal of Advances and Current Practices in Mobility* 2(4):2297–2311.

- Roberts, J. C. 2007. "State of the Art: Coordinated Multiple Views in Exploratory Visualization". In *Proceedings of the Fifth International Conference on Coordinated and Multiple Views in Exploratory Visualization*, edited by G. Andrienko, J. C. Roberts, and C. Weaver, 61–71. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.
- Unger, A., S. Schulte, V. Klemann, and D. Dransch. 2012, December. "A Visual Analysis Concept for the Validation of Geoscientific Simulation Models". *IEEE Transactions on Visualization and Computer Graphics* 18(12):2216–2225.
- Vernon-Bido, D., A. Collins, and J. Sokolowski. 2015. "Effective Visualization in Modeling & Simulation". In *Proceedings of the 48th Annual Simulation Symposium*, edited by A. Tolk, J. J. Padilla, and S. Jafer, 33–40. San Diego: Society for Computer Simulation International.
- Wang, X. 2010. "Rationale and History of Vehicle Noise and Vibration Refinement". In *Vehicle Noise and Vibration Refinement*, edited by X. Wang, Chapter 1, 3–17. Woodhead Publishing.

AUTHOR BIOGRAPHIES

KREŠIMIR MATKOVIĆ is a senior researcher, area coordinator of the complex systems area, and head of the interactive visualization group at VRVis Research Center in Vienna. Since 2000, he has been leading basic and applied research projects at VRVis with numerous national and international partners. He is interested in extending visual analysis technology to challenging heterogeneous data, in particular to a combination of multi-variate data and more complex data types. He also focuses his research on developing a structured model for visual analysis that supports a synergetic combination of user interaction and computational analysis. He teaches at TU Vienna where he received his doctoral degree and habilitation (in 1998 and 2016) and at the University of Zagreb, where he received his graduate degree in 1994. His email address is Matkovic@VRVis.at.

DENIS GRAČANIN received the BS and MS degrees in Electrical Engineering from the University of Zagreb, Croatia, in 1985 and 1988, respectively, and the MS and PhD degrees in Computer Science from the University of Louisiana at Lafayette in 1992 and 1994, respectively. He is an Associate Professor in the Department of Computer Science at Virginia Tech. His research interests include virtual reality and distributed simulation. He is a senior member of ACM and IEEE and a member of AAAI, APS, ASEE, and SIAM. His email address is gracanin@vt.edu.

RAINER SPLECHTNA graduated in computer science at Vienna University of Technology in 2003. He is currently working as researcher at VRVis Research Center in Vienna. His research interests include virtual and augmented reality, scientific visualization, information visualization, and visual analytics with special focus on interaction techniques and visualization and analysis of multivariate time-dependent data. His email address is splechtna@vrvis.at.

GORAN TODOROVIĆ received BS and MS degrees in Mechanical Engineering from the University of Zagreb, Croatia in 1987 and 1993, respectively. He started career at Electrotechnical Institute "Rade Končar" dealing with material strength calculations. He spent several years in Switzerland working on projects of a new generation of gas turbines (ABB Kraftwerke AG) and European Robotic Arm for International Space Station (HTS AG). Since 1999 he works in AVL-AST d.o.o. Zagreb. Currently he is senior software developer working in area of Powertrain Dynamics. His email address is goran.todorovic@avl.com.

STANISLAV GOJA received MS degree in Mechanical Engineering from the University of Zagreb, Croatia in 1993 where he worked for 6 years as teaching assistant at Faculty of Mechanical Engineering and Naval Architecture. He is a senior NVH analysis engineer at AVL-AST d.o.o with focus on Multi-Body dynamics and vibration analysis. He has more than 20 years of experience in various worldwide customer projects for automotive, marine, auto-moto sport and process industry. His email address is stanislav.goja@avl.com.

BORIS BEDIĆ received MS degree in Aeronautical Engineering from the University of Zagreb, Croatia in 2007. He is a senior NVH analysis engineer at AVL-AST d.o.o with focus on Multi-Body dynamics and vibration analysis. Boris is working at AVL since 2008 on variety projects for automotive, marine and process industry. His email address is boris.bedic@avl.com.

HELWIG HAUSER is professor in visualization at the University of Bergen (UiB), Department of Informatics (since 2007), as well as leader of CEDAS, i.e., UiB's Center for Data Science (since 2019). Before moving to Norway, Helwig Hauser was the scientific director of the VRVis Research Center in Vienna, Austria. He is educated in computer science (specialization on visualization) with MSc and PhD degrees from the Vienna University of Technology (1995 & 1998), where he later also completed his Habilitation (2003). Helwig Hauser received several awards, including the biannual Heinz-Zemanek Award in computer science from OCG in 2006 and the Dirk Bartz Prize for visual computing in medicine in 2013. His email address is Helwig.Hauser@UiB.no.