CAE/VR INTEGRATION – A PATH TO FOLLOW? A VALIDATION BASED ON INDUSTRIAL USE

Holger Graf and André Stork
Department of Virtual and Augmented Reality, Department of Interactive Engineering Technologies
Fraunhofer IGD
D-64823, Darmstadt, Germany
E-mail: {holger.graf|andre.stork}@igd.fraunhofer.de

KEYWORDS
Virtual Reality (VR), CAE/VR Integration, Interactive Preliminary Design Analysis, Industrial Evaluation

ABSTRACT

Numerical simulations have become crucial during the product development process (PDP) for predicting and validating different properties of new products as well as the simulation of various kinds of natural phenomena. Especially the engineering domain (CAE – Computer Aided Engineering), is seeking for new ICT solutions to cover broad ranges of physical simulations. Virtual Reality (VR) has matured in the past allowing a rapid consolidation of information and decision-making through visualization and experience. These new man machine interfaces offer advanced interaction possibilities with the digital domain and allow engineers to variate over several hypothesis. This enlightened ideas to deploy VR for "what-if-scenarios" also in the CAE domain. However, while CAD/VR integration has been sufficiently researched, the integration of CAE into VR is still facing a long road ahead. Despite recent criticism that the application of VR technology has been considered unnecessary in CAE, this paper aims to refute this by presenting methodologies for linear static FEM analysis allowing "what-if-scenarios" within interactive environments. It validates the elaborated methodologies and advantages of VR front ends by an evaluation performed within industrial engineering departments.

INTROCUCTION

Computer Aided Engineering methods have influenced the PDP significantly. Popular application areas include structural mechanics (e.g. stress analysis, dynamic analysis, modal analysis, kinematics) and computational fluid dynamics (such as the analysis and validation of fluidal behaviour). Following an analysis step, engineers have been provided with an insight into material characteristics or physical properties. Those are described by numerical values of some kind of physical quantities (e.g. pressure, stress concentration, deformations, velocities) that are available at discrete points within space. Nevertheless, computer engineering methods are complex and resource intensive, consuming significant computational power and time, thus leading to long and cost intensive analysis processes. On the other hand, the demand for shortening the time intervals within the product life cycle is crucial to remain competitive.

Here, the trend to front-loading of product life-cycle steps in order to simulate a design, validate its behaviour and derive decisions about its manufacturing has become more and more important during the last decade. Especially, tools to allow fast decision-making through an intuitive grasp of the situation have improved to reduce development cycles. One of the key driving technologies for a better communication, representation, interaction, and visualisation of design and engineering/manufacturing data has been Virtual Reality (VR). Though mainly developments in the CAD/VR domain with an emphasis on an integration into the product development process have been driving research efforts, applications demonstrated the advantage of being able to review interactively designs, conduct ergonomic studies and check feasibility of assemblies. The potential of VR for postprocessing of engineering/manufacturing data raised hopes to deploy this advanced man machine interface for *interactive conceptual simulations (ICS)* within the CAE domain (Graf and Stork 2011), (Graf and Stork 2013). While it is a valid hypothesis, still many challenges and problems remain due to the nature of the "change'n play" paradigm imposed by conceptual simulations, the real-time operations within a VR environment as well as the fragmentation of tools and workflows used especially within CAE. Choi et al. (Choi et al. 2015) presented a comprehensive literature survey of VR research within the product development since the 90's and showed, that VR technology has been mostly applied to design reviews and assembly tests of products, whereas research endeavours for an integration of VR within the computer-aided engineering (CAE) domain remained very little. Based on the number count of publications the authors' stated *"…This likely means that we can only achieve relatively little profit by applying VR to CAE. The application of VR technology has been considered unnecessary in CAE: relatively simple visualization provided enough support to make decisions.[…]"*, (Choi et al. 2015).

Aim of this paper is therefore twofold: First, it aims at presenting recent research results for CAE/VR integration, and secondly, objecting the above

Proceedings 31st European Conference on Modelling and Simulation ©ECMS Zita Zoltay Paprika, Péter Horák, Kata Váradi, Péter Tamás Zwierczyk, Ágnes Vidovics-Dancs, János Péter Rádics (Editors)
ISBN: 978-0-9932440-4-9/ ISBN: 978-0-9932440-5-6 (CD)

hypothesis, by presenting an evaluation that has been conducted with automotive, aerospace, and urban planning engineering departments demonstrating the benefit and profit of using VR within engineering domains. As a conclusion it aims at answering the question "CAE/VR integration – A Path to Follow?".

To start, we should briefly recall the complications, that researchers face in order to deal with a CAE/VR process chain.

"WHAT-IF-SCENARIOS" IN CAE-VR

In typical CAE postprocessing sessions, engineers are able to get an in depth snapshot of a specific physical behaviour, and depending on the maturity of the visualisation tool, a tidy showcase. In many cases, however, analysts are much more interested in creating effects due to some physical phenomena, changing parameters, changing materials, changing constraints, changing domain, and actively wanting to drive the engineering discovery process within *"What-if-analysis"*[1] set-ups. Nevertheless, interactive conceptual changes within engineering analysis require real-time turn-around loops for model manipulation, simulation and visualisation. Depending on the complexity of the underlying models, real-time FEA simulations are not possible in complex industrial applications. This usually antagonises ideas for VR-based front-ends. Computer Graphic approaches (e.g. Georgii 2008, Weber 2016) for real-time FEA in order to simulate deformations and visualise animations rely on simplified mathematical models, that do not comply with the eningeering demand for precise validation of a physical phenomena.

Any proposed new method for an appropriate interactive exploration, suitable for engineers, requires integrated workflows. Isolated solutions lead to the bottleneck of data transfer, data preparation and interpretation, spanning different phases of the engineering analysis workflow. Here, the workflow is inherently depended on the CAD/CAE transfer process (Tierney et al. 2015), which is error prone and time consuming. De-featuring and cleaning/healing of models are typically done within dedicated tools, whereas the meshing of the domain in others. Thus, many media breaks inbetween tools lead to long design/re-design iterations for the domain.

IDEFIx

This section should provide a brief overview of the framework IDEFIx (Interactive Data Exploration for Immersive CAx), that has been developed based on a consensus on engineering requirements which have been collected throughout this research work. It summarises the results of a range of own research work, and for implementation details the reader should be referred to those papers. Thus it leaves space for an evaluation that has not been presented. Several techniques and methodologies of IDEFIx aim at faster turn-around loops within engineering tasks for *linear static analysis* and some basic simulation possibilities for CFD (Computational Fluid Dynamics). They are embedded within one sinlge point of access workplace opening engineers a seamless access to several tools required for preliminary design analysis. Main efforts have been dedicated to a design which respects the pragmatic engineering demand of a scalable integration into existing environments. Here, VR should not be used as an additional tool rather than an operational one, from which several CAE tasks can be steered if required. Tasks that cannot be performed within VR, should have been made available at the workplace also, requiring access to legacy systems for engineers. The introduced hybrid workplace, thus, is based on the capability to support traditional point-and-click applications as well as innovative VR-based postprocessing steps. It is powered by a service oriented approach, see e.g. (Graf 2011), that enables access to pre-processor functionalities, simulation module and VR postprocessor. An adequate event mechanism is capable of distributing requests from one service to other services interested in that query. As a major result several preprocessing and postprocessing steps could be integrated into one environment supporting typical CAD/CAE processes and engineering analysis steps in an immersive set-up.

Remeshing within postprocessing tools coupled to advanced, sensory based interaction possibilities and a closed re-simulation loop has not been realised up to now and provides engineers the capability to shorten their design/analysis cycles.

In view of the ICS methodology the developed techniques can be performed at different levels of interactivity combining advancements in the CAD/CAE transfer as well as VR techniques easing the variations of the underlying domain. IDEFIx offers intuitive postprocessing with preprocessing capabilities as well as coupled simulation runs, allows for conceptual changes of the basis domain by moving features or groups of mesh entities based on ensured consistencies by new element quality metrics, adaptive local refinements (see Figure 1), and offers realtime simulations by steering computation through loadcase manipulation and re-modelling of the underlying domain. Aside a coherent software engineering approach, several strategies embedded within the framework are based on formalised mathematical models that build the basis for an automation of numerical simulation processes not being available until now. New error estimates enable adaptive refinements that can be applied within user-centric and goal-oriented conceptual simulations (Larson et al. 2014) for linear static analysis, see Figure 2. This in turn enables faster

[1] "*What-if-analysis"* within this work is meant as to investigating "what-if-scenarios" within engineering analysis tasks, i.e. playing on the real world effect for various design decisions, such as feature and de-featuring of the CAD model, changing analysis mock-up, boundary conditions, acquiring a higher level of detail or interpreting results in different presentations.

engineering cycles based on numerical simulations and thus shortens the turn around cycles within the engineering analysis domain. For the evaluation we considered few basic functionalities that could be performed with IDEFIx:

Figure 1 Adaptive meshing and local mesh refinements

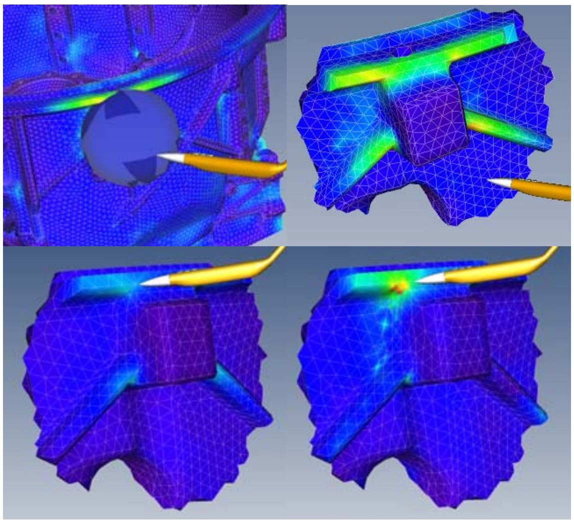


Figure 2 Conceptual simulation – local enhancement; Domain decomposition of complex domain, get deeper insight into local problems (Refinement/Re-analysis).

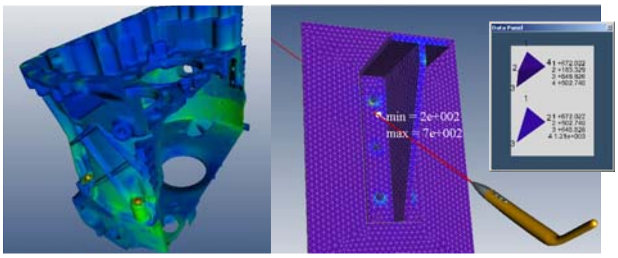


Figure 3 Interactive postprocessing of CAE data (left, mid: cross sectioning with clipping, right: element probing using laser beam metaphor)

As workplace concept we used a hybrid desktop that allowed us to integrate CAE and VR into one workplace.

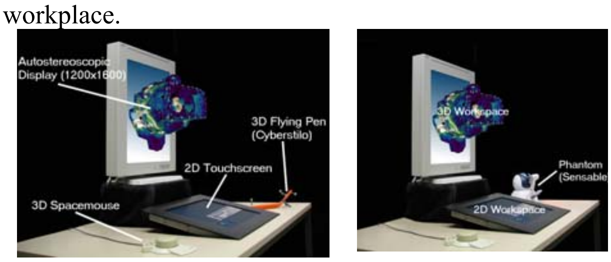


Figure 4 Hybrid Desktop combined with optical tracking system and different 6DOF input devices.

To address the shortcomings of an ergonomic use of advanced VR devices such as shutter glasses, interaction, or output devices, a system specifically designed for the desktop application of VR within an engineering environment has been proposed in earlier own work, e.g. (Graf and Stork, 2013). It is based on an autostereoscopic display paired with a second LCD touch screen in an L-shape configuration (see Figure 4). The set-up relieves the user from wearing shutter glasses or HMDs opposed to "classical" VR installations. As input device a wand like device is used that allows for 6 DOF interactions (Cyberstilo©) as well as is capable of creating 2D input for the touch screen. This allows for an easy navigation and interaction in a "*hybrid*" configuration. Interactions are possible with traditional legacy point-and-click applications inherent to the engineering domain but also 3D-based navigation and system control within the VR environment.

EVALUATION

Methodology

We conducted specific validation sessions addressing selected workflows of engineers being defined for the VR enhanced workplace. Here, we were setting up the hybrid desktop in which the engineer was capable of using legacy systems and VR tools for model preparation, model simplification, simulation and analysis. Several validation sessions were conducted in three iterations over a total period of four months within a first tier OEM (ZF[2]), Airbus and CSTB[3], covering the requirements from automotive, aerospace and urban planning departments[4]. As in-house COTS ("Commercial-Off-the-Shelf")- tools MSC.Patran/ Nastran, PERMAS, IDEAS-NX, ANSYS Fluent were used. Three questionnaires suited as basis to gather feedback from the test subjects. The intention was to collect qualitative as well as quantitative data during each validation session. The time required to conduct certain tasks within the new integrated workflow is considered as the quantitative parameter within the subsequent evaluation. In a first iteration focus was given to the completeness and availability of the required functionalities in order to conduct certain tasks. A subsequent validation session addressed the integration of tasks within one workflow and finally the system was benchmarked in a real life setting in which two installations were moved to end user sites and were evaluated under daily working conditions over a total period of two months. At the final stage, specific benchmarks were conducted in order to compare time savings of the new approach with the traditional workflow. Due to the limitations of this paper, only

[2] ZF – ZF Friedrichshafen, www.zf.de

[3] CSTB – Centre Scientific et Technologie du Batiment, France, www.cstb.fr

[4] It should be noted that the urban planning scenarios have been restricted to "simulate-'n-explore", rather local enhancements.

some findings can be presented. We focus on the most interesting ones.

Participants

The group of test subjects comprised experts from two engineering domains, 6 from engineering analysis and 3 from urban planning. In general, all involved experts from the CAE/CFD domain had little experience with VR technology. None of them had VR or user interface design experience, the majority is using traditional keyboard and mouse interactions, and several test subjects were using standard (or dual) LCD output screens.

Test Cases and Tasks

Three test cases from each domain had to be examined and analysed: A small and medium size model to verify the entire process chain within solid mechanics applications, and a large model to experience the current limits of the approach and to check the postprocessing capabilities within the hybrid desktop. The engineers had to accomplish the task list for each model:

- Import mesh with results from external solver
- Change visualisation options
- Display and evaluate principal stresses
- Display displacements and animate
- Conduct a submodel analysis
- Conceptual simulation (local enhancement)
- Define local mesh refinement (re-mesh)
- Solve local mesh (re-simulate)
- Postprocess sub-/local model (use freely definable cross section and element probes, based on a laser beam metaphor ‘glued’ to the virtual interaction device)
- Compare refinements and result sets

Analysis

In order to analyse the questionnaires, the experiments conducted by the test subjects were modelled as discrete random variables. The realizations of a random variable are called random variates. Thus, let Ω be a probability space and E a measurable space. The random variables $X_i : \Omega \rightarrow E,\ i = 1...l$, model a stochastic process on Ω, with $X_i^{-1}(A) \doteq \{\omega \mid X(\omega) \in A\}, A \subset E$. For l observations $X_i\ (\omega) = x_{i,n_i},\ i = 1,...,l$ of samples with size $n = n_1 + ... + n_l$ the realisations (variates) are x_{i,n_l}.

For the analysis of returned feeback by the test subjects the software suite SPSS of IBM was used in order to derive the descriptive statistics of several modelled variables. The results have been analysed according to the descriptives: mean (M), variance (V) and standard deviation (SD). Where required, further information to the presentation is added, such as quartiles q_{25}, q_{50}, q_{75} of an observation. Quantitative evaluations are based on a one-way ANOVA (Analyis of Variance) which provides a statistical test whether three or more means are the same thus testing compared observations to be equal (“null hypothesis”).

For the *quantitative* evaluation it uses a F-test based on the ratio of two scaled sums of squares reflecting different sources of variability (“degrees of freedom” /“df”). The construction of the test provides a possibility to evaluate the variational differences between obeservations in a way that its quantum tends to be greater if the null hypothesis is not true.

QUANTITATIVE ASSESSMENT

This section presents some quantitative benchmarks in order to compare the new developments with in-house COTS-tools. For this, the experts did use the following models

Table 1 Models used during the evaluation

	KB	Nb Elements	DOF
smaller models	12.300	23.000	120.000
larger models	154.000	332.000	1.800.000

The following table summarise the benchmarks for smaller sized and medium sized models in view of the postprocessing and coupled interactive refinement/re-simulation/postprocessing loop. A detailed presentation of the quantitative assessment on submodelling and local enhancement techniques for very large models, the reader should be referred to (Larson et al. 14).

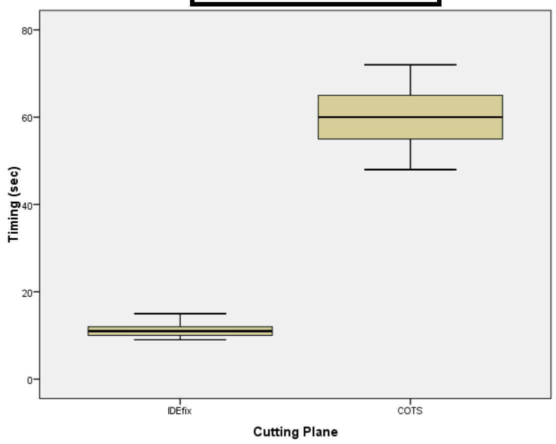
Postprocessing

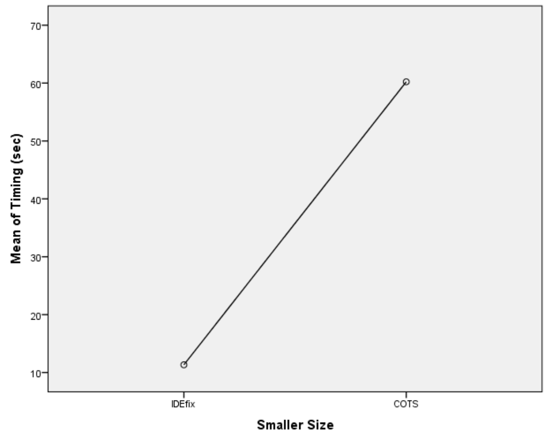
In a first step the experts had to identify area of high stress using typical postprocessing functionality. Here the time was captured from the start of the postprocessing session until he did come to a final assessment of the mock-up. Upload time was not taken into account. During a second step, the most important modalities data probing and cutting planes (i.e. cross sectioning incl. data probes incl. assessment) were evaluated separately (Table 2, Table 3).

Table 2 Quantitative Analysis ‘Postprocessing’ comparing IDEfix and COTS – Cutting Planes

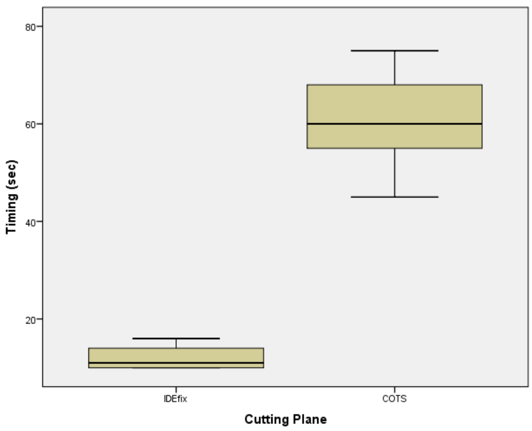
Smaller Models	Descriptives (sec)	Std. Error	Smaller Models	df	F	Sig.
IDEfix	M(9) = 11,333	,645	Between	1	333,793	,000
	V(9) = 3,750		Groups	16		
	SD(9) = 1,936		Within			

			Groups			
COTS	M(9) = 60,222 V(9) = 60,69 SD(9) = 7,79	2,596				





Medium Sized	Descriptives (sec)	Std. Error	Medium Sized	df	F	Sig.
IDEfix	M(9) = 12,11 V(9) = 5,361 SD(9) = 2,315	,771	Between Groups Within Groups	1 16	213,591	,000
COTS	M(9) = 60,556 V(9) = 93,528 SD(9) = 9,67	3,222				



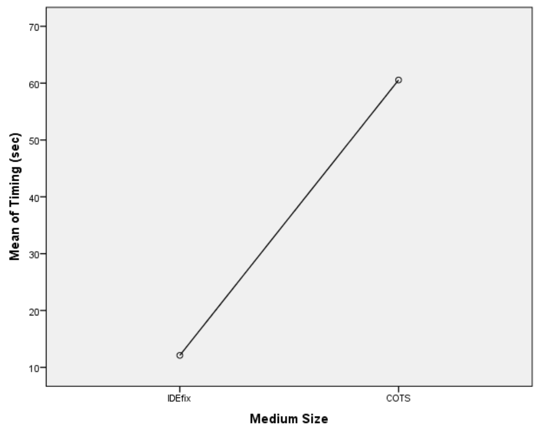
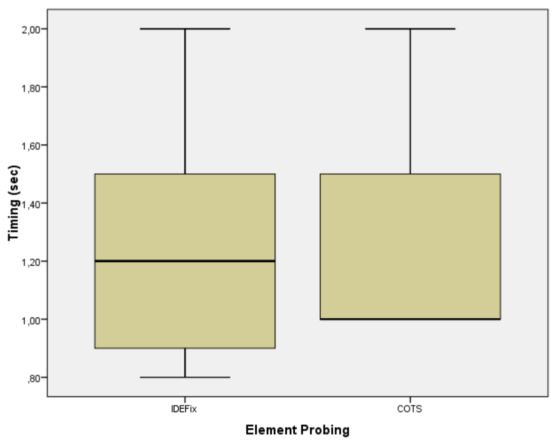
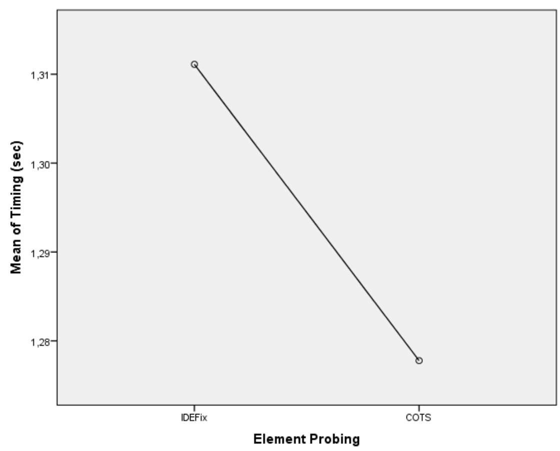


Table 3 Quantitative Analysis 'Postprocessing' comparing IDEfix and COTS – Element Probing

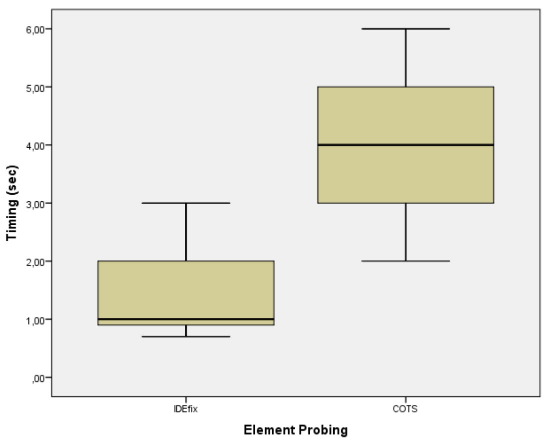
Smaller Models	Descriptives (sec)	Std. Error	Smaller Models	df	F	Sig.
IDEfix	M(9) = 1,3111 V(9) = 0,216 SD(9) = 0,464	,154	Between Groups Within Groups	1 16	,024	,878
COTS	M(9) = 0,9388 V(9) = 0,194 SD(9) = 0,441	,147				

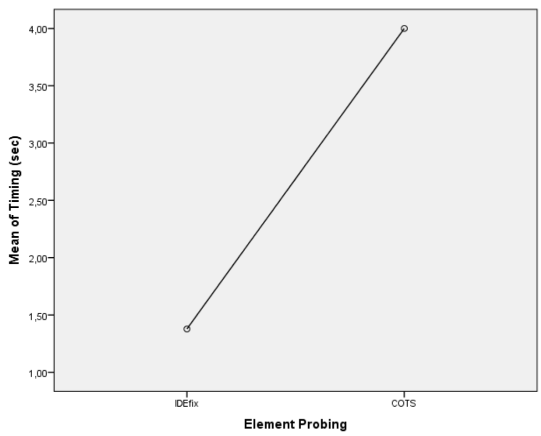




Medium Sized	Descriptives (sec)	Std. Error
IDEfix	M(9) = 1,377 V(9) = 0,607 SD(9) = 0,779	,259
COTS	M(9) = 4,00 V(9) = 2,00 SD(9) = 1,414	0,4714

Medium Sized	df	F	Sig.
Between Groups	1	23,738	,000
Within Groups	16		





According to the F-statistics, IDEfix offers a significant better performance in several used test cases (except the element probes on smaller models). This is in line with the qualitative assessment (below) and being observed by several engineers. Nevertheless, the postprocessing tasks in general are better supported by IDEfix as indicated by the descriptives and related figures.

QUALITATIVE ASSESSMENT OF IDEFIx

This section reflects on the results obtained for a qualitative assessment of IDEfix according to the task list and related questionnaire. As first task the user had to evaluate on the clarity, availability, efficiency and fulfilment of the requested functionality within the VR component. For both domains the implemented modes for visualisation and interaction have been similar. The variables $X_i : \Omega \to E, E = \{1, 2, ..., 5\}, \Omega =$ ("not available", "poor", "satisfactory", "good", "very good") reflect on "clarity (c)", "efficiency (e)", "consistency (cs)" as well as "fulfilment of demands (f)" of the developed solutions. Here, the consistency reflects on the need of the functionality to be competitive to in-house COTS-tools. The mark "good" mirrors the same level of possibility provided by typical working tools, "very good" being superior to the traditional way. The efficiency reflects on the need of the functionality to allow the engineer to quickly get to an assessment of the problem areas or the overall mock-up. The higher the mark the faster he could accomplish his task.

Conceptual Simulation – Local Enhancement

The following table (Table 4) indicates the results for the implemented conceptual simulation based on substructuring and local enhancements of the resolution within structural mechanics. As it was not implemented for CFD and urban planning only feedback of the two involved structural mechanics departments has been gathered. It was expected that this functionality improves the workflow of current processes for substructuring and local refinements. During the first testing session the test subjects had to provide feedback on the available integrated simulation/visualisation/ post-processing functionality and state their perception on the current realisation. A high ranking of the efficiency is expected.

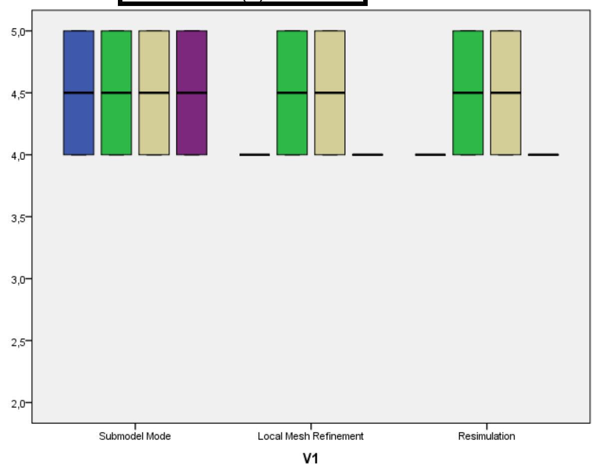
Table 4 Qualitative assessment of IDEfix – Conceptual simulation/substructuring/local enhancement

"Clarity" (c)	Descriptives	Std. Error
Submodel Mode	M(6) = 4,50 V(6) = 0,500 SD(6) = 0,707	,500
Local Mesh Refinement	M(6) = 4,0 V(6) = SD(6) = 0	,0
Re-simulation	M(6) = 4,0 V(6) = SD(6) = 0	,0

"Efficiency" (e)	Descriptives	Std. Error
Submodel Mode	M(6) = 4,60 V(6) = 0,300 SD(6) = 0,548	,245
Local Mesh Refinement	M(6) = 4,50 V(6) = 0,500 SD(6) = 0,707	,500
Re-simulation	M(6) = 4,60 V(6) = 0,300 SD(6) = 0,548	,245

"Consistency" (cs)	Descriptives	Std. Error
Submodel Mode	M(6) = 4,50 V(6) = 0,500 SD(6) = 0,707	,500
Local Mesh Refinement	M(6) = 4,50 V(6) = 0,500 SD(6) = 0,707	,500
Re-simulation	M(6) = 4,50 V(6) = 0,500 SD(6) = 0,707	,500

"Fulfilment" (f)	Descriptives	Std. Error
Submodel Mode	M(4) = 4,75 V(6) = 0,333 SD(6) = 0,577	,333
Local Mesh Refinement	M(4) = 4,0 V(6) = SD(6) = 0	,0
Re-simulation	M(4) = 4,0 V(6) = SD(6) = 0	,0



(As several observations achieved values above 3 ("satisfactory"), it was decided to start the y-scale at 2 in order to maximize scaling factors for the purpose of visualization)

X_i(not available, poor, satisfactory, good, very good) → $X_i \in \{1,2,3,4,5\}$, $i \in \{c,e,cs,f\}$

- Several functionalities realising the conceptual simulation based on substructuring and refinement process were perceived as "very good". The fulfillment of the demands was marked as "good" for local resolution enhancements.
- The engineers provided very positive feedback and expected to cut down individual substructuring and local remeshing tasks by 3-5 working hours.
- In view of the defined scenarios the realisation was sufficient, however, specialists need a larger number of elements being involved in an analyis.
- In general, the experts were missing the support of more elements for a dedicated analysis. As very positive statement, the experts were satisfied with the speed of simulation and re-simulation within an interactive environment.
- Some quotes of the free-text fields:
  - *"This function is extremely practical for large models" (ZF).*
  - *"The postprocessing tool with the mesh refinement and the nearly real time solver is the most valuable part" (ZF).*
  - *"In the VR environment Mesh refinements can easily be performed. The speed is outstanding compared to standard technologies. All tests of remeshing have been performed just within a few seconds only. A similar remeshing with MSC.Patran needs minutes." (Airbus)*
  - *"The advantages in standard packages are that they give the user more capabilities in influencing the meshes. For this reason the new approach is better for casual users (which needs quick and easy to use tools) whereas the standard tools are better for specialists" (Airbus)*

Assessment of the Hybrid Workspace

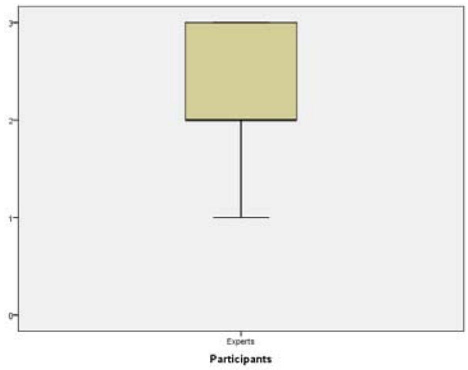
This section presents the results obtained for the validation of the overall Hybrid Workspace. The experts have been asked whether a hybrid approach embedding 2D and 3D functionality into one workspace concept and hybrid objects are suitable for daily work, whether they got exhausted, how long they might be able to work on it and if they would deploy VR as immersive CAE modelling tool. The variables have been modelled according to different variates. Thus the $X_i : \Omega_i \rightarrow E_i, E_i \subset \{1,2,...,5\}$. The following table (Table 5) shows the final results

Table 5 Hybrid Workspace – Suitability, exhaustiveness, duration of work, hybrid objects

Variable	Descriptives	Std. Error
Suitability of Workspace	M(9) = 2,33 V(9) = 0,500 SD(9) = 0,707	,236

X_{Suit}(obsolete, not very useful, quite useful, useful) → $X_{Suit} \in \{0,1,2,3\}$,

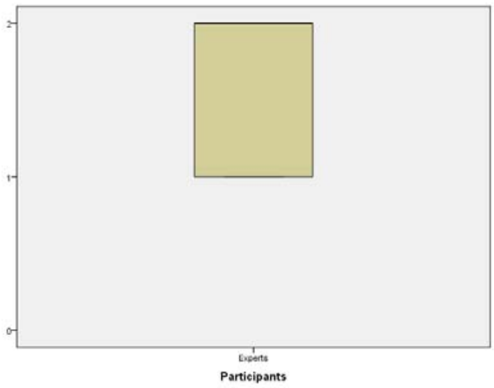
- Up to 75% of the feedback indicated the usefulness of the concept. The mean of 2,33 indicates that more than half of the experts found the concept "quite useful" for daily work.



Variable	Descriptives	Std. Error
Exhaustiveness	M(9) = 1,67 V(9) = 0,250 SD(9) = 0,500	,167

X_{Exh}(no, not sure, yes) → $X_{Exh} \in \{0,1,2\}$,

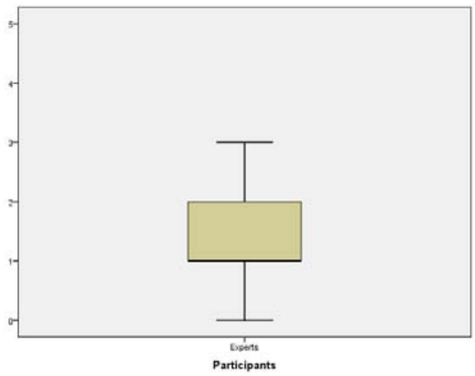
- Several experts felt exhaustive working with the hybrid workspace. This has several reasons:
- The new interaction device has been too heavy for hourly work,
- the experts got tired working with the autostereoscopic display, indicating the change of depth perception from 2D space into 3D space is causing eye strain, and
- workspace ergonomics lacked due to aiming at very precise positioning tasks (back/neck stiffness were reported).



Variable	Descriptives	Std. Error
Duration	M(9) = 1,89 V(9) = 0,861 SD(9) = 0,928	,309

X_{Dur}("<1","1-2","2-3","3-4","4-5","5-6") → $X_{Dur} \in \{0,1,\ldots,5\}$

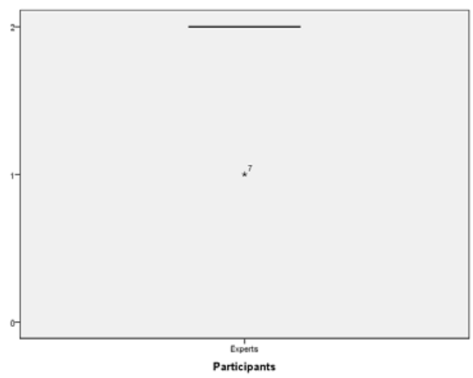
- The experts indicated to be able to work in average 1-2 hrs with the interactive desktop.
- In general up to 75% of the feedback ($q_{X_{Dur}75} = 2$) indicated to work longer, but no more than 2-3 hrs.



Variable	Descriptives	Std. Error
Hybrid Objects	M(9) = 1,89 V(9) = 0,111 SD(9) = 0,333	,111

X_{hUI}(not suitable at all, confusing, suitable) → $X_{hUI} \in \{0,1,2\}$

- Asked for the work with hybrid user interface elements, the engineers found it important to also steer the VR environment from the desktop. Thus only one outlier indicated that the user interface is confusing.



Interaction Paradigm

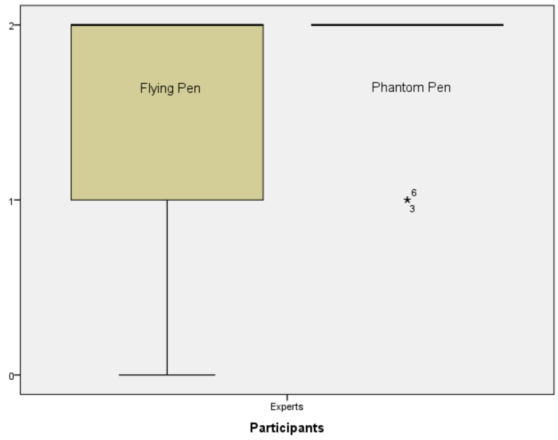
Within the different on-site set-ups several variants of interaction devices and paradigms were tested (Table 6): One, using the Cyberstilo© (FP) and the other using a phantom pen haptic device (PP). Furthermore, engineers were asked for the dislike or like of an "object in hand" metaphor at a virtual table (VT – a table like backprojection system used with active stereo glasses), indicating that they were able to keep a tracked artefact (assigned to the digital mock-up) in their free hands. This metaphor was tested subsequently at the hybrid desktop (HD).

Table 6 Interaction paradigm – Suitability, ergonomy, "object in hand"

Variable	Descriptives	Std. Error
Interaction Paradigm (FP)	M(9) = 1,44 V(9) = 0,528 SD(9) = 0,726	,242
Interaction Paradigm (PP)	M(9) = 1,78 V(9) = 0,194 SD(9) = 0,441	,147

X_{IntP} (not useful at all, not sure, easy to use) → $X_{IntP} \in \{0,1,2\}$

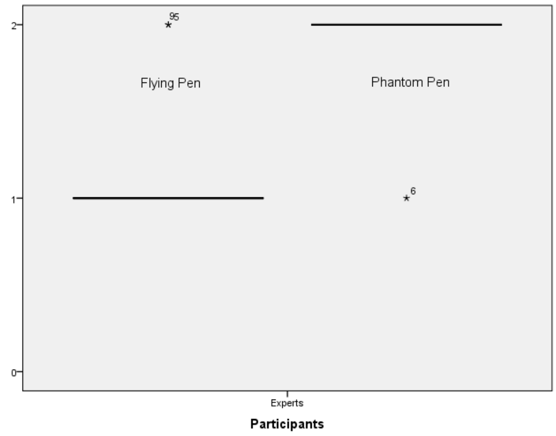
- The evaluation of the preferred interaction paradigm based on the new interaction device and a phantom pen indicated a clear preference to the phantom pen.
- This is mainly due to the control provided by the haptic device. The degrees of freedom are limited to a small interaction volume in contrary to the flying pen.



Variable	Descriptives	Std. Error
Ergonomy (FP)	M(9) = 1,22 V(9) = 0,194 SD(9) = 0,441	,147
Ergonomy (PP)	M(9) = 1,89 V(9) = 0,111 SD(9) = 0,333	,111

X_{Erg} (does not fit, needs to be improved, does fit) → $X_{Erg} \in \{0,1,2\}$

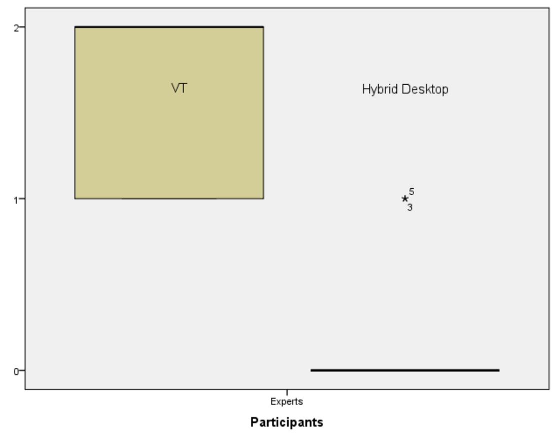
- The evaluation on ergonomical aspects reveiled that the flying pen requires improvements, whereas the phantom pen fits well and does not burden any heavy load.
- As main drawbacks, the experts named the weight, and the dimensions of the pen.



Variable	Descriptives	Std. Error
Object in Hand (VT)	M(9) = 1,44 V(9) = 0,528 SD(9) = 0,726	,242
Object in Hand (HD)	M(9) = 1,44 V(9) = 0,528 SD(9) = 0,726	,242

X_{IntP} (no, not sure, yes) → $X_{IntP} \in \{0,1,2\}$

- Asked for the like (yes) or dislike (no) of keeping an object in hand a clear voting for this metaphor was fed back by the experts.
- However, at the desktop they disliked this idea mainly due to the limited interaction space as well as imprecision introduced by additional degrees of freedom.



Remarks within the free-text fields indicated a high degree of satisfaction with the realisation of the Hybrid Desktop and integrated VR environment. Some excerpts of the validation protocols:

Hybrid 2D/3D Set-Up

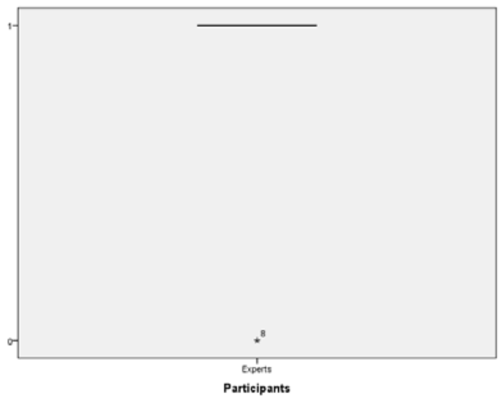
- *"The hybrid setup is from our testing experience mandatory, as it seems not to be suitable to perform all tasks in VR only. Performing the work in such a hybrid setup is suitable. Display quality is more or less ok as a starting point, but the area of finding positions for a* good 3D view, needs to be expanded. Also all screens should be not too small" (Airbus).*

- *"The display seems to be in general suitable, but not for an 8 hour day. As an additional display for specific tasks, it is ok. Technological enhancements may lead soon to an acceptable 8 hour usage" (Airbus).*
- *"Estimation of time savings: At least 50% for all tasks needing 3D perception: Precise interaction with the model (picking, BC definition, data probing, area selection for submodelling). Visualisation / analyze of simulation results." (CSTB).*
- *"Benefits working with such a system during the process chain:*
  - *Increased automation to clear faults in CAD-models*
  - *Speed up of the meshing process*
  - *More precise results with the intuitive mesh refinement tool" (ZF)*
  - *"Enhanced understanding of non experts for calculation results" (ZF).*
  - *"Advantages: Very accurate display of a 3D structure. Low cost" (Airbus).*
  - *"This hybrid 2D/3D approach is very interesting, especially is the 2D GUI is used via a touchscreen" (CSTB).*

Finally, asked for the take-up and use of VR within their environments, several experts would make use of VR within their environment (Table 7)

Table 7 Hybrid Workspace – Use of VR for CAE tasks

Variable	Descriptives	Std. Error
Immersive Use	M(9) = 0,89 V(9) = 0,111 SD(9) = 0,333	,111



X_{ImU}("no", "yes") → $X_{ImU} \in \{0,1\}$

- The feedback did indicate that the engineers would be in favour of using VR within their workflow. However:
  - as additional tool not as a complement to current COTS, and
  - embedded within a hybrid workspace concept.

CONCLUSION

The open framework exposes an integrated CAD-to-CAE-to-VR process chain and an inclusion of typical preprocessing steps such as automatic geometry clean-up into a VR-based analysis tool. We have shown in earlier work that with our approach, the overall preparation, simulation and analysis time could be significantly shorten using VR. The presented evaluations here, show, that using advanced and integrated 3D interactive pre-/postprocessing facilities based on VR, leads to a faster assessment of the results (down to minutes and seconds compared to inhouse COTS). The elaborated new techniques for conceptual simulations proved to allow an engineer being concentrated on local problems without a need to re-calculate the overall global problem. Further on, it provides a basis for the engineer to find an answer to his question: "where do I have to spend my analysis time?". The involved engineers evaluated the VR-based hybrid desktop as an easy to use and intuitive access technology. Finally, they estimate to be able to shorten down their engineering workflow by several days. As a consequence, we have to object the hypothesis of Choi et al., having shown, how engineers could benefit from new simulation methodologies integrated into advanced front ends such as VR. Yet, still major challenges remain for making VR a widely accepted front end in the CAE domain as the way to more advanced simulations require new mathematical models, methodologies to control the creation of elements and assembly of matrices and thus, is stony and tough, but worth a try!

REFERENCES

Georgii, J., "Real-Time Simulation and Visualisation of Deformable Objects", *PhD Thesis, Institut für Informatik*, Technische Universität München (TUM), 2008

Graf, H., Stork, A, "Enabling Real-Time Immersive Conceptual CAE Simulations based on Finite Element Masks", In: *Proc. of the the ASME World Conference of Innovative VR, (WINVR'11),* Milan, Italy, 2011

Graf, H., Stork, A., "Virtual Reality based Interactive Conceptual Simulations Combining Post-Processing and Linear Static Simulations", *In: Proceedings of the International Conference on Human-Computer Interaction (HCII) – Virtual Augmented and Mixed Reality (VAMR)*: Part I (2013), Las Vegas, NV, USA, LNCS, pp. 13-22, 2013

Graf, H., "A 'Change n'Play' Software Architecture integrating CAD, CAE and Immersive Real-Time Environments for Conceptual Simulations", In: *Proc. of the IEEE International Conference on CAD/Graphics'11*, Jinan, China, 2011

Larson, M., Graf, H., Stork, A., "Interactive 3D Subdomaining using Adaptive FEM based on Solutions to the Dual Problem", In: *Proceedings of the ACM Virtual Reality International Conference,* Laval, France, ACM New York, NY, USA, 2014

Choi, S.S., Jung, K., and Do Noh, Sang, "Virtual reality applications in manufacturing industries: Past research, present findings, and future directions", *Concurrent Engineering: Research and Applications*, Vol23 (1), 2015

Tierney, C., Nolan, D., Robinson, T., Armstrong, C.G., "Using mesh-geometry relationships to transfer analysis models between CAE tools". *In: Journal of Engineering with Computers, Springer London*, July 2015

Weber, D., "Interactive Physically Based Simulation Efficient Higher-Order Elements, Multigrid Approaches and Massively Parallel Data Structures", *PhD Thesis, Technical University of Darmstadt*, 2016