



Directory of Modules

M.Sc. Computational Engineering

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Introduction

The Module handbook provides detailed information regarding the course content and curriculum of the Master's Program 'Computational Engineering'.

1. Modularization (Modularisierungskonzept)

- The course curriculum has a modular structure. It consists of compulsory modules, elective modules and optional modules.
- Credit points (CP) according to the European Credit Transfer System (ECTS) are awarded for the successful completion of each module. One CP according to the ECTS corresponds to an average student workload of 30 hours. The number of credit points awarded for a certain module depends on the workload (see module description of the lecture for further details).

2. Curriculum (Studienplan)

- The Master's program has a duration of 4 semesters. The compulsory courses in the first semester build a core set of skills in Numerical Mathematics, Computational Mechanics, Computer Science and other relevant courses. The specialization phase in the second and third semesters is flexible and allows students to focus on the different lines of Computational Engineering by choosing courses of their own choice from the course catalogue. In the fourth semester, students prepare their master's thesis in a research field that is relevant for computational engineering. In total, 120 CP according to the ECTS are required for the successful completion of the Master's program. The complete course catalogue is provided below.

3. Types of examinations (Prüfungsform) and examination regulations (Prüfungsordnung)

- With the exception of the Master's thesis, examinations are module examinations, either graded or ungraded (see module descriptions for further details). They may be conducted in the form of a written examination, an oral examination, by working on tasks during the course, a project, a seminar paper, a report or a colloquium presentation. Please refer to the examination regulations (Prüfungsordnung) for further details.

4. Grading of the master's examinations

- The overall grade (avg) of the master's examination arises as a weighted arithmetic mean (weighted with the CPs) of all graded module examinations with the exception of the optional modules. When calculating the overall grade, the grades for the compulsory modules with a factor of 1, the grades for the compulsory optional modules with a factor of 1.5, and the grade for the master's thesis with a factor of 2.0 are weighted in addition. Decimal values are to one decimal place.

5. Counseling (Beratung)

- The CompEng Coordination Office is maintained by the Faculty of Civil and Environmental Engineering. Its members offer counseling on study related matters to students of the Master's program. In addition, the lecturers of the Master's program provide consultation hours, during which students may clarify questions concerning the respective course.

Modifications:

Module No.	Module Name	Modification
CE-WP36	Automation in Design and Construction	Additional Information Regarding the Exam Format
CE-WP09	Numerical Simulation in Geotechnics and Tunneling	Change in teaching staff
CE-W06	Advanced Constitutive Models for Geomaterials	Changes to Module Coordinator and teaching staff

Master's Program Computational Engineering Curriculum						
Curriculum						
		Code	Module Name	hours per week	CP	Semester
1 st & 2 nd semester	P Compulsory Courses 39 CP	CE-Po1	Mathematical Aspects of Differential Equations and Numerical Mathematics	4	6	1
		CE-Po2	Mechanical Modeling of Materials	4	6	1
		CE-Po3	Computer-based Analysis of Steel Structures	4	6	1
		CE-Po4	Scientific Programming	4	6	1
		CE-Po5	Finite Element Methods in Linear Structural Mechanics	4	6	1
		CE-Po6	Fluid Dynamics	2	3	2
		CE-Po7	Continuum Mechanics	4	6	2
	Subtotal CP: Compulsory Courses				39	
1 st , 2 nd & 3 rd semester	WP Compulsory Optional Courses 35 CP	CE-WPo1	Variational Calculus and Tensor Analysis	3	5	1
		CE-WP31	Scientific C++ Programming (Basics)	2	3	1
		CE-WPo3	Adaptronics	3	5	2
		CE-WPo4	Nonlinear Finite Element Methods for Structures	4	6	2
		CE-WPo5	Computational Fluid Dynamics	4	6	2
		CE-WPo8	Numerical Methods and Stochastics	4	6	2
		CE-WPo9	Numerical Simulation in Geotechnics and Tunneling	4	6	2
		CE-WP10	Programming the Finite Element Method	2	3	2
		CE-WP11	Applied Finite Element Methods	4	6	2
		CE-WP12	Computational Plasticity	4	6	2
		CE-WP25	High-Performance Computing on Multicore Processors	4	6	2
		CE-WP28	Machine Learning: Supervised Methods	4	6	2
		CE-WP30	Transient Finite Element and Finite Difference Methods	4	6	2
		CE-WP32	Scientific C++ Programming (Advanced)	2	3	2
		CE-WP33	Deep Learning for Engineers	4	6	2
		CE-WP34	Advanced Discretization Methods	2	3	2
		CE-WPo6	Inelastic Finite Element Method for Structures	3	6	3
		CE-WP13	Advanced Control Methods for Adaptive Mechanical Systems	4	6	3
		CE-WP14	Computational Wind Engineering	2	3	3
		CE-WP15	Coupled Multiphysical Modeling and Simulations	4	6	3
		CE-WP16	Computational Modeling of Membranes and Shells	4	6	3
		CE-WP17	Numerical Methods for Conservation Laws	4	6	3
		CE-WP19	Computational Fracture Mechanics	4	6	3
		CE-WP20	Materials for Aerospace Applications	4	6	3
		CE-WP21	Quantum Computing	4	6	3
		CE-WP26	High-Performance Computing on Clusters	4	6	3
		CE-WP29	Uncertainty Quantification in FE Analyses with Surrogate Modeling	4	6	3
		CE-WP35	Computational Structural Optimization	4	6	3
		CE-WP36	Automation in Design and Construction	4	6	3
	CE-WP24	Case Study A	2	3	2+3	
Minimum Subtotal CP: Compulsory optional courses				35		
1 st , 2 nd & 3 rd semester	W Optional Courses 16 LP	CE-Wo1	Training of Competences (part 1)	4	4	1
		CE-Wo2	Training of Competences (part 2)	4	4	2
		CE-Wo4	Recent Advances in Numerical Modeling and Simulation	2	2	2
		CE-Wo5	Numerical Optimization	4	6	3
		CE-Wo6	Advanced Constitutive Models for Geomaterials	2	6	2
		CE-Wo3	Case Study B	2	3	2+3
		CE-WI1	Seminar Computing in Engineering	2	3	3+4
		CE-WI3	German A1	4	5	1+3
		CE-WI4	German A2	4	5	2+4
		other relevant courses of the faculty or from engineering faculties of other universites			1+2+3	
Minimum Subtotal CP: Optional Courses				16		
4 th Semester	M Master-Thesis	CE-M	Master Thesis	-	30	4
Subtotal CP: Master Thesis				30		
Subtotal CP: Compulsory Courses				39		
Subtotal CP: Compulsory optional courses				35		
Subtotal CP: Optional courses				16		
Subtotal CP: Master Thesis				30		
Sum CP in total:				120		

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Computational Modeling of Membranes and Shells (BI-WP57/CE-WP16).....	28
Computational Plasticity (CE-WP12/CoPla).....	30
Computational Structural Optimization (CE-WP35/BI-W74/SE-O-19).....	32
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Mechanical Modeling of Materials (CE-P02/SE-CO-19/MMoM).....	65
Nonlinear Finite Element Methods for Structures (BI-WP05/CE-WP04/SE-CO-23).....	67
Numerical Methods and Stochastics (CE-WP08/SE-CO-8/NMS).....	69
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Quantum Computing (CE-WP21/QC).....	79
Recent Advances in Numerical Modelling and Simulation (BI-W35/CE-W04).....	81
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Index by areas of study

1) M.Sc. CE Compulsory Courses, ECTS: 39

Weight of the mark for the final score

FAK = 1

DIV = 167,5

Mathematical Aspects of Differential Equations and Numerical Mathematics (CE-P01/SE-C-1/MADENM, 6 ECTS, each winter semester).....	63
Mechanical Modeling of Materials (CE-P02/SE-CO-19/MMoM, 6 ECTS, each winter semester).....	65
Computer-based Analyses of Steel Structures (CE-P03/CbASS, 6 ECTS, each winter semester).....	36
Scientific Programming (CE-P04/SE-O-10/SP, 6 ECTS, each winter semester).....	85
Finite Element Methods in Linear Structural Mechanics (CE-P05/BI-P08/SE-C-2/FEM-I, 6 ECTS, each winter semester).....	43
Fluid Dynamics (CE-P06/FD, 3 ECTS, each summer semester).....	45
Continuum Mechanics (CE-P07/CM, 6 ECTS, each summer semester).....	38

2) M.Sc. CE Compulsory Optional Courses, ECTS: 35

Weight of the mark for the final score

FAK = 1,5

DIV = 167,5

Variational Calculus and Tensor Analysis (CE-WP01/SE-O-6/VCTA, 5 ECTS, each winter semester).....	96
Adaptronics (CE-WP03/ADAP, 5 ECTS, each summer semester).....	8
Nonlinear Finite Element Methods for Structures (BI-WP05/CE-WP04/SE-CO-23, 6 ECTS, each summer semester).....	67
Computational Fluid Dynamics (CE-WP05/CFD, 6 ECTS, each summer semester).....	23
Inelastic Finite Element Methods for Structures (BI-WP59/CE-WP06/SE-CO-20, 6 ECTS, each winter semester).....	55
Numerical Methods and Stochastics (CE-WP08/SE-CO-8/NMS, 6 ECTS, each summer semester).....	69
Numerical Simulation in Geotechnics and Tunneling (BI-WP24/CE-WP09/SE-CO-3, 6 ECTS, each summer semester).....	75
Programming the Finite Element Method (BI-W39/CE-WP10, 3 ECTS, each summer semester).....	77
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Computational Plasticity (CE-WP12/CoPla, 6 ECTS, each summer semester).....	30
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Computational Modeling of Membranes and Shells (BI-WP57/CE-WP16, 6 ECTS, each winter semester).....	28
Numerical Methods for Conservation Laws (CE-WP17/NMfCL, 6 ECTS, each winter semester).....	71
Computational Fracture Mechanics (CE-WP19/CFM, 6 ECTS, each winter semester).....	26
Materials for Aerospace Applications (CE-WP20/MAA, 6 ECTS, each winter semester).....	61
Quantum Computing (CE-WP21/QC, 6 ECTS, each winter semester).....	79
Case Study A (CE-WP24/CaStuA, 3 ECTS, each semester).....	19
High-Performance Computing on Multicore Processors (BI-WP56/CE-WP25/SE-O-8, 6 ECTS, each summer semester).....	53
High-Performance Computing on Clusters (CE-WP26/HPCC, 6 ECTS, each winter semester).....	51
Machine Learning: Supervised Methods (CE-WP28/ML:SM, 6 ECTS, each summer semester).....	57
Uncertainty Quantification in FE Analyses with Surrogate Modeling (BI-WP58/CE-WP29/SE-O-17, 6 ECTS, each winter semester).....	94
Transient Finite Element and Finite Difference Methods (BI-WP60/CE-WP30/TFEM, 6 ECTS, each summer semester).....	92
Scientific C++ Programming (Basics) (CE-WP31/SCPb, 3 ECTS, each winter semester).....	84
Scientific C++ Programming (Advanced) (CE-WP32/SCPA, 3 ECTS, each summer semester).....	83
Deep Learning for Engineers (CE-WP33/DLE, 6 ECTS, each summer semester).....	42
Advanced Discretization Methods (CE-WP34/ADM, 3 ECTS, each summer semester).....	14
Computational Structural Optimization (CE-WP35/BI-W74/SE-O-19, 6 ECTS, each winter semester).....	32
Automation in Design and Construction (BI-WP48/CE-WP36, 6 ECTS, each winter semester).....	17

3) M.Sc CE Optional Courses, ECTS: 16

Weight of the mark for the final score

$FAK = 0$

$DIV = 167,5$

Training of Competences (Part 1) (CE-W01/SE-O-14/ToC I, 4 ECTS, each winter semester).....	89
Training of Competences (Part 2) (CE-W02/SE-O-15/ToC II, 4 ECTS, each summer semester).....	91
Case Study B (CE-W03/CaStu B, 3 ECTS, each semester).....	21
Recent Advances in Numerical Modelling and Simulation (BI-W35/CE-W04, 2 ECTS, each semester).....	81
Numerical Optimization (CE-W05, 6 ECTS, each winter semester).....	73

Advanced Constitutive Models for Geomaterials (BI-WP44 /SE-CO-10/CE-W06, 6 ECTS, each summer semester).....	10
Seminar Computing in Engineering (CE-W11, 3 ECTS, each semester).....	87
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German A2 (CE-W14/SE-O-24, 5 ECTS, each summer semester).....	49

4) M.Sc. CE Master's Thesis, ECTS: 30

Weight of the mark for the final score

FAK = 2

DIV = 167,5

Master Thesis (CE-M, 30 ECTS, each semester).....	59
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Adaptronics Adaptronics					
Module number CE-WP03/ ADAP	Credits 5 CP	Workload 150 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Adaptronics (126505)			Contact hours a) 3 WLH (45 h)	Self-study a) 105 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr. Tamara Nestorovic a) Prof. Dr. Tamara Nestorovic					
Admission requirements Recommended previous knowledge: Basic knowledge in Structural Mechanics, Control Theory and Active Mechanical Structures is of advantage. (Englischer Test)					
Learning outcome, core skills Acquiring knowledge in fundamental control methods, structural mechanics and modeling and their application to the active control of mechanical structures. After successfully completing the module, the students • have basic knowledge in behavior and modeling of piezoelectric materials for adaptronic structures and systems, • have knowledge in model development of mechanical structures for the control system design (linear time invariant systems in state space and transfer function form), • are able to perform the model based system analysis in time and frequency domain, • are able to design basic control structures with compensator and feedback gain systems, • are able to independently simulate control systems (PID and pole placement controller), • have knowledge in discrete-time control systems, • are able to use Matlab/Simulink software and Toolboxes for the control system analysis, design and simulation.					
Contents a) An overall insight of the modeling and control of active structures is given within the course. The terms and definitions as well as potential fields of application are introduced. For the purpose of the controller design for active structural control, the basics of the control theory are introduced: development of linear time invariant models, representation of linear differential equations systems in the state-space form, controllability, observability and stability conditions of control systems. The parallel description of the modeling methods in structural mechanics enables the students to understand the application of control approaches. For actuation/sensing purposes multifunctional active materials (piezo ceramics) are introduced as well as the basics of the numerical model development for structures with active materials. Control methods include time-continuous and discrete-time controllers in the state space for multiple-input multiple-output systems, as well as					

methods of the classical control theory for single-input single output systems. Differences and analogies between continuous and discrete time control systems are specified and highlighted on the basis of a pole placement method. Closed-loop controller design for active structures is explained. Different application examples and problem solutions show the feasibility and importance of the control methods for structural development. Within this course the students learn computer aided controller design and simulation using Matlab/Simulink software. Students will implement the acquired knowledge in the framework of a seminar paper related to the controller design supported by Matlab Software.

Educational form / Language

a) Lecture with tutorial / Tutorial / English

Examination methods

- Term paper 'Adaptronics - Seminar paper' (30 h., Part of modul grade 0 %, Deadlines will be announced at the beginning of the semester)
- Written exam 'Adaptronics' (90 min., Part of modul grade 100 %)

Requirements for the award of credit points

- Passed final module examination
- Passed Seminar paper

Module applicability

- M.Sc. Computational Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $5 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

DIV: The values can be taken from the table of contents.

Further Information

Advanced Constitutive Models for Geomaterials					
Advanced Constitutive Models for Geomaterials					
Module number BI-WP44 /SE-CO-10/CE-W06	Credits 6 CP	Workload 180 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Advanced Constitutive Models for Geomaterials (128055)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr.-Ing. Merita Tafili a) Prof. Dr.-Ing. Merita Tafili					
Admission requirements					
Learning outcome, core skills After successfully completing the module, the students are able to • model the material behavior of soil using suitable, advanced constitutive models, • select suitable numerical methods and constitutive models for practical questions and assess limitations according to the selected approaches, • calibrate the parameters of the advanced constitutive models and evaluate the model performance based on single integration point simulations					
Contents a) The course deals with the introduction of advanced soil mechanical behavior and appropriate constitutive models allowing to capture advanced effects. Model formulations and parameter calibration for different soil model families are taught. In addition, an introduction to single integration point finite element simulations with Incremental Driver (ID) is provided and simulations of different laboratory tests are conducted with ID using different elasto-plastic and hypoplastic constitutive models. Advanced soil mechanics: • Critical state soil mechanics • Crushable soil mechanics • Unsaturated soil mechanics • Soil memory effects and their modelling • Clay structure and small-strain stiffness anisotropy • Influence of temperature on soil behavior and its modelling Sophisticated constitutive models for soils: • Modified Cam-Clay model • Sanisand • Hypoplasticity with Intergranular Strain • Clay Hypoplasticity • Hypoplasticity for crushable soils • Visco-hypoplasticity					

• Barcelona Basic Model
Educational form / Language a) Lecture (4 WLH) / English
Examination methods • Written exam 'Advanced Constitutive Models for Geomaterials' (180 min., Part of modul grade 100 %) • Optional homework to achieve bonus points for the written exam
Requirements for the award of credit points • Passed final written exam
Module applicability • M.Sc. Civil Engineering • M.Sc. Subsurface Engineering • M.Sc. Computational Engineering
Weight of the mark for the final score Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$ FAK: The weighting factors can be taken from the table of contents. DIV: The values can be taken from the table of contents.
Further Information

Advanced Control Methods for Adaptive Mechanical Systems					
Advanced Control Methods for Adaptive Mechanical Systems					
Module number CE-WP13/ ACMAMS	Credits 6 CP	Workload 180 h	Semester[s] 3. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Advanced Control Methods for Adaptive Mechanical Systems (127505)			Contact hours a) 4 WLH (60 h)	Self-study a) 0 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr. Tamara Nestorovic a) Prof. Dr. Tamara Nestorovic					
Admission requirements Recommended previous knowledge: Adaptronics (CE-WP03), fundamentals of control theory and structural control.					
Learning outcome, core skills Extended knowledge in adaptive mechanical systems, advanced control methods and their application for the active control of structures. After successfully completing the module, the students • have advanced knowledge in control systems design, • are able to design full order observer of the states in a state space model, • have basic knowledge in observation using Kalman filter, • have basic knowledge in the system identification of state-space models, • have knowledge in experimental modal analysis, • are able to independently design a velocity feedback vibration suppression for basic mechanical structures.					
Contents a) Advanced methods for the control of adaptive mechanical systems are introduced in the course. This involves the recapitulation of the fundamentals of active structural control and an extension to advanced control. Observer design is introduced as a tool for the estimation of system states. In addition to numerical modelling using the finite element approach, system identification is explained as an experimental approach. Theoretical backgrounds of the experimental structural modal analysis are introduced along with the terms and definitions used in signal processing. Experimental modal analysis is explained using the Fast Fourier Transform. Advanced closed loop control methods involving optimal discrete-time control, introduction of additional dynamic approaches for the compensation of periodic excitations and basic adaptive control algorithms are explained and pragmatically applied for solving problems of vibration suppression in civil and mechanical engineering.					
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English					
Examination methods					

- Written exam 'Advanced Control Methods for Adaptive Mechanical Systems - Written examination' (120 min., Part of modul grade 100 %)
- Seminar 'Advanced Control Methods for Adaptive Mechanical Systems - Seminar paper' (

Requirements for the award of credit points

- Passed seminar paper and passed final module examination

Module applicability

- M.Sc. Computational Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

DIV: The values can be taken from the table of contents.

Further Information

Advanced Discretization Methods					
Advanced Discretization Methods					
Module number CE-WP34/ADM	Credits 3 CP	Workload 90 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Advanced Discretization Methods (126512)			Contact hours a) 2 WLH (30 h)	Self-study a) 60 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr. Andreas Vogel a) Prof. Dr. Andreas Vogel, Assistants					
Admission requirements					
Learning outcome, core skills After successfully completing the module, the students • have acquired a solid foundation in the mathematical formulations, implementation aspects and application of advanced discretization methods for the solution of partial differential equations, such as the finite cell method (FCM) and isogeometric analysis (IGA), • understand the advantages and disadvantages of each method and can independently evaluate their suitability for a given situation, • can apply their knowledge to the solution of various engineering and scientific problems.					
Contents a) The lecture covers advanced discretization techniques beyond the conventional finite element methods for the solution of partial differential equations, such as the finite cell method (FCM) and isogeometric analysis (IGA). In each case the mathematical formulation as well as the implementation aspects of the method are discussed and contrasted with conventional methods. Furthermore, the strengths and shortcomings of each method are highlighted such that their suitability for a given problem can be evaluated.					
Educational form / Language a) Lecture with tutorial / English					
Examination methods • Written exam 'Advanced Discretization Methods' (120 min., Part of modul grade 100 %)					
Requirements for the award of credit points • Passed final module examination					
Module applicability • M.Sc. Computational Engineering					
Weight of the mark for the final score Percentage of total grade [%] = $3 \cdot 100 \cdot \text{FAK} / \text{DIV}$ FAK: The weighting factors can be taken from the table of contents. DIV: The values can be taken from the table of contents.					
Further Information					

Applied Finite Element Methods Applied Finite Element Methods					
Module number BI-WP06/CE-WP11	Credits 6 CP	Workload 180 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Applied Finite Element Methods (126519)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr. Roger A. Sauer a) Dr.-Ing. Gerrit E. Neu, Prof. Dr.Ing. habil. Izabela Lubowiecka					
Admission requirements Recommended previous knowledge: Finite Element Methods in Linear Structural Mechanics (CE-P05 respectively BI-P08) Basics knowledge in Mathematics, Programming, FEM and Structural Analysis					
Learning outcome, core skills After successfully completing the module, the students • have the ability to model structures using finite element software and to verify and assess the simulation results. • can generate simulation models for structures composed of different element types with static and dynamic loading and write reports. • can perform thermal, buckling and contact analyses of materials and structures. • are able to create simulations models of engineering problems under consideration of suitable abstractions, boundary conditions and definition of interactions between elements. • can handle digital interfaces between BIM and structural analysis software to convert building models into structural simulation models.					
Contents a) The course deals with the application of finite element simulations in structural engineering. This includes: • handling of commercial finite element software • modeling methods and sources of modeling errors • pre- and post-processing • BIM-FE interfaces					
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English					
Examination methods • Project report 'Applied Finite Element Methods' (60 h., Part of modul grade 100 %, Project work with a written report (90%) and a presentation, with oral examination (10%))					
Requirements for the award of credit points • Passed oral examination and project work					
Module applicability					

- M.Sc. Civil Engineering
- M.Sc. Computational Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

DIV: The values can be taken from the table of contents.

Further Information

optional Tutorial (2 WLH)

Automation in Design and Construction Automation in Design and Construction					
Module number BI-WP48/CE-WP36	Credits 6 CP	Workload 180 h	Semester[s] 3. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Automation in Design and Construction (129027)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr.-Ing. Markus König a) Dr.-Ing. Philipp Hagedorn, Prof. Dr.-Ing. Markus König					
Admission requirements					
Learning outcome, core skills The students • acquire skills for automating processes in the planning and execution of construction projects, • learn methods for generating as-built models, • apply additive manufacturing for prototyping, • acquire competencies in the application of sensors, data acquisition technologies, and robotics on construction sites, • work in small groups on selected problems related to the automation of processes in the planning and execution of construction projects, • learn about current research approaches to the use of artificial intelligence in the planning and execution of construction projects.					
Contents a) • Sensors and laser scanning on the construction site • Digital twins • Augmented and virtual reality • Additive manufacturing • Use of drones and robotics • Artificial intelligence in construction					
Educational form / Language a) Block seminar / Lecture (2 WLH) / Tutorial (2 WLH) / English					
Examination methods • Term paper 'Automation in Design and Construction' (90 h., Part of modul grade 100 %, with interim and final presentation)					
Requirements for the award of credit points • Passed final module examination: successful submission of the term paper with interim and final presentation					
Module applicability					

- M.Sc. Civil Engineering
- M.Sc. Computational Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

DIV: The values can be taken from the table of contents.

Further Information

Literature:

Borrmann, A., König, M., Koch, C., Beetz, J. (Ed.): Building Information Modeling – Technology Foundations and Industry Practice Springer International ISBN 978-3-319-92861-6

Case Study A Case Study A					
Module number CE-WP24/ CaStuA	Credits 3 CP	Workload 90 h	Semester[s] 2.+3. Sem.	Duration 1 Semester[s]	Group size 3
Courses a) Case Study A (126518)			Contact hours	Self-study a) 90 h	Frequency a) each sem.
Module coordinator and lecturer(s) Alle Professorinnen und Professoren des Studiengangs a) N.N.					
Admission requirements					
Learning outcome, core skills After completion of the project work, the students • will have gained experience in working on a problem individually or in small groups, • are able to organize and coordinate the assignment of tasks independently under the supervision of an advisor, • should have gathered new information and insights into the activities of practicing engineers while acquiring skills in innovative research fields, • will be able to present technical projects, and to develop problem solution strategies, hence obtaining worthwhile communication skills.					
Contents a) The project topic is usually determined by the respective lecturer or one of his/her assistants. In addition to this, students may also conduct project work on topics defined by companies from industry or official authorities. However, the project work must be completed under the supervision of one of the course's lecturers. The projects are usually devised so as to integrate interdisciplinary aspects such as • Noticing problems and describing them • Formulating envisaged goals • Team-oriented problem solutions • Organizing and optimizing one's time and work plan • Interdisciplinary problem solutions • Literature research and evaluation as well as the consultation of experts • Documentation, illustration and presentation of results The topic of a project paper is devised by a lecturer of the course or an assistant who supervises the exercises. The student - or a small group of students - conducts a project independently and presents the results in the form of a written report and optionally, an oral presentation (upon agreement with the respective lecturer).					
Educational form / Language a) Project / English					
Examination methods					

- Term paper 'Hausarbeit' (Part of modul grade 100 %, The project paper and presentation will be graded. For this purpose, the individual achievements of the students within the project groups are separately evaluated. The evaluation includes: Written project paper / 75% (100% without a final presentation) Final presentation / 25% (optional))
- Independent work in seminar rooms and computer labs; testing plants, where applicable.

Requirements for the award of credit points**Module applicability**

- M.Sc. Computational Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $3 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

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Further Information

Case Study B Case Study B					
Module number CE-W03/CaStu B	Credits 3 CP	Workload 90 h	Semester[s] 2.+3. Sem.	Duration 1 Semester[s]	Group size 3
Courses a) Case Study B (127512)			Contact hours a) 0 h	Self-study a) 90 h	Frequency a) each sem.
Module coordinator and lecturer(s) Alle Professorinnen und Professoren des Studiengangs a) N.N.					
Admission requirements					
Learning outcome, core skills After completion of the project work, the student • will have gained experience in working on a problem individually or in small groups, • are able to organize and coordinate the assignment of tasks independently under the supervision of an advisor, • should have gathered new information and insights into the activities of practicing engineers while acquiring skills in innovative research fields, • will be able to present technical projects, and to develop problem solution strategies and will hence also obtain worthwhile communication skills.					
Contents a) The project topic is usually determined by the respective lecturer or one of his/her assistants. In addition to this, students may also conduct project work on topics defined by companies from industry or official authorities. However, the project work must be completed under the supervision of one of the course's lecturers. The student - or a small group of students - conducts a project independently and presents the results in the form of a written report and optionally, an oral presentation (upon agreement with the respective lecturer). The projects are usually devised to as to integrate interdisciplinary aspects such as • noticing problems, describing them and formulating envisaged goals • team-oriented and interdisciplinary problem solutions • organizing and optimizing one's time and work plan • literature research and evaluation as well as the consultation of experts • documentation, illustration and presentation of results					
Educational form / Language a) Project / English					
Examination methods • Term paper 'Case Study B' (90 h., Part of modul grade 100 %, The project paper and presentation will be graded. For this purpose, the individual achievements of the students within the project groups are separately evaluated. The evaluation includes: written project paper with a final presentation)					
Requirements for the award of credit points					

Review of the project work and oral presentation
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Module applicability

- | |
|---|
| <ul style="list-style-type: none">• M.Sc. Computational Engineering |
|---|

Weight of the mark for the final score

Percentage of total grade [%] = $3 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

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Further Information

Computational Fluid Dynamics Computational Fluid Dynamics					
Module number CE-WP05/CFD	Credits 6 CP	Workload 180 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Computational Fluid Dynamics (126517)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr. Patrick Henning a) Prof. Dr. Patrick Henning					
Admission requirements Recommended previous knowledge: Basic knowledge of: partial differential equations and their variational formulation, finite element methods, numerical methods for the solution of large linear and non-linear systems of equations					
Learning outcome, core skills Students should become familiar with modern methods for the numerical solution of complicated flow problems. This includes: finite element and finite volume discretizations, a priori and a posteriori error analysis, adaptivity, advanced solution methods of the discrete problems including particular multigrid techniques. After successfully completing the module, the students shall • be familiar with the various equations describing fluid dynamics, in particular the Stokes equation, the compressible and incompressible Navier-Stokes equations and Euler, equations, as well as their scope and applicability, • be able to select stable finite element discretizations for each type of equations and know its advantages, disadvantages, limitations and practical realization, • know the convergence properties of the various methods and be able to describe when these convergence rates can be expected in practice, • be able to formulate a posteriori error estimators and know how to use them to improve the efficiency of finite element methods.					
Contents a) • 1) Modelization Velocity, Lagrangian / Eulerian representation; transport theorem, Cauchy theorem; conservation of mass, momentum and energy; compressible Navier-Stokes / Euler equations; nonstationary incompressible Navier-Stokes equations; stationary incompressible Navier-Stokes equations; Stokes equations; boundary conditions • 2) Notations and auxiliary results Differential operators; Sobolev spaces and their norms; properties of Sobolev spaces; finite element partitions and their properties; finite element spaces; nodal bases • 3) FE discretization of the Stokes equations, 1st attempt Stokes equations; variational formulation in $\{\text{div } u = 0\}$; non-existence of low-order finite					

element spaces in $\{\text{div } \mathbf{u} = 0\}$; remedies • 4) Mixed finite element discretization of the Stokes equations Mixed variational formulation; general structure of finite element approximation; an example of an instable low-order element; inf-sup condition; motivation via linear systems; catalogue of stable elements; error estimates; structure of discrete problem • 5) Petrov-Galerkin stabilization Idea: consistent penalty term; general structure; catalogue of stabilizations; connection with bubble elements; structure of discrete problem; error estimates; choice of stabilization parameter • 6) Non-conforming methods Idea; most important example; error estimates; local solenoidal bases • 7) Streamline formulation Stream function; connection to bi-Laplacian; FE discretizations • 8) Numerical solution of the discrete problems General structure and difficulty; Uzawa algorithm; improved version of Uzawa algorithm; multigrid; conjugate gradient variants • 9) Adaptivity Aim of a posteriori error estimation and adaptivity; residual estimator; local Stokes problems; choice of refinement zones; refinement rules • 10) FE discretization of the stationary incompressible Navier-Stokes equations variational problem; finite elements discretization; error estimates; streamline-diffusion stabilization; upwinding • 11) Solution of the algebraic equations Newton iteration and its relatives; path tracking; non-linear Galerkin methods; multigrid • 12) Adaptivity Error estimators; type of estimates; implementation • 13) Finite element discretization of the instationary incompressible Navier-Stokes equations Variational problem; time-discretization; space discretization; numerical solution; projection schemes; characteristics; adaptivity • 14) Space-time adaptivity Overview; residual a posteriori error estimator; time adaptivity; space adaptivity • 15) Discretization of compressible and inviscid problems Systems in divergence form; finite volume schemes; construction of the partitions; relation to finite element methods; construction of numerical fluxes
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English
Examination methods • Written exam 'Computational Fluid Dynamics' (120 min., Part of modul grade 100 %)
Requirements for the award of credit points • Passed final module examination
Module applicability • M.Sc. Computational Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

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Further Information

Computational Fracture Mechanics Computational Fracture Mechanics					
Module number CE-WP19/CFM	Credits 6 CP	Workload 180 h	Semester[s] 3. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Computational Fracture Mechanics (440108)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr. Alexander Hartmaier a) Prof. Dr. Alexander Hartmaier, Assistants					
Admission requirements Recommended previous knowledge: Basic knowledge about solid mechanics and plasticity is recommended					
Learning outcome, core skills After successfully completing the module, the students - remember the different types of brittle fracture and ductile failure of materials, - understand the theoretical background of the different types of fracture models, - are able to study the relevant literature independently, - are able to choose appropriate fracture models and to implement them in a finite element environment, - are able to independently simulate fracture including plasticity for a wide range of materials and geometries, - can assess situations where cracks in a structure or component can be tolerated or situations in which cracks are not admissible.					
Contents a) - Phenomenology and atomistic aspects of fracture - Concepts of linear elastic fracture mechanics - Concepts of elastic-plastic fracture mechanics - R curve behavior of materials - Concepts of cohesive zones (CZ), extended finite elements (XFEM) and damage mechanics - Finite element based fracture simulations for static and dynamic cracks - Application to brittle fracture & ductile failure for different geometries and loading situations					
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English					
Examination methods Portfolio exam 'Computational Fracture Mechanics' (120 h., Part of modul grade 100 %, Portfolio exam including reports on assignments, seminar and self-evaluation report)					
Requirements for the award of credit points Passed final module examination					
Module applicability - M.Sc. Computational Engineering - M.Sc. Mechanical Engineering					

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- M.Sc. Materials Science and Simulation

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

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Further Information**Teaching methods**

- lecture, hands-on classes, mini-project incl. seminar talk, assignments
- Lecture notes will be provided.

Computational Modeling of Membranes and Shells					
Computational Modeling of Membranes and Shells					
Module number BI-WP57/CE-WP16	Credits 6 CP	Workload 180 h	Semester[s] 3. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Computational Modeling of Membranes and Shells (127506)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr. Roger A. Sauer a) Prof. Dr. Roger A. Sauer					
Admission requirements Recommended previous knowledge: Basic knowledge of continuum mechanics (CE-P07) and linear Finite Element Methods (CE-P05) is strongly recommended.					
Learning outcome, core skills After successfully completing the module the students • can identify the elements of the numeric models for membranes and shells and explain their mathematic-physical background • are able to describe the presented numerical discretization methods • can transfer the formulations used for membranes and shells to other constitutive laws and implement them into an existing software application • are able to estimate the accuracy of those applications					
Contents a) The module includes the following topics: 1. Kinetics of membranes under large deformations 2. Constitutive laws for membranes 3. Membrane equilibrium for the strong form and the weak form 4. Summarization of the isogeometric finite element methods 5. Numerical discretization methods for membranes 6. Shell theory 7. Rotation-free discretization methods for Kirchhoff-Love Shells 8. Implementation of the presented discretization methods					
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English					
Examination methods • Oral exam 'Computational Modeling of Membranes and Shells' (30 min., Part of modul grade 100 %) • Term paper 'Computational Modeling of Membranes and Shells - Homework' (40 h., ungraded, Deadline will be announced at the beginning of the semester)					
Requirements for the award of credit points					

• Passed oral test • Passed Homework
Module applicability • M.Sc. Civil Engineering • M.Sc. Computational Engineering
Weight of the mark for the final score Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$ FAK: The weighting factors can be taken from the table of contents. DIV: The values can be taken from the table of contents.
Further Information

Computational Plasticity Computational Plasticity					
Module number CE-WP12/ CoPla	Credits 6 CP	Workload 180 h	Semester[s] 2. Sem.	Duration Semester[s]	Group size no limitation
Courses a) Computational Plasticity (440519)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr. Alexander Hartmaier a) Prof. Dr. Alexander Hartmaier					
Admission requirements Recommended previous knowledge: Basic knowledge of continuum mechanics (CE-P07) is required.					
Learning outcome, core skills After successfully completing the module, the students recall the definitions of different types of mechanical behavior into which materials can be classified. They understand the phenomenology and mechanisms of elastic and plastic behavior of crystalline materials and can outline the different types of plasticity models in solid mechanics. Furthermore, they can explain the basic concepts and the mathematical formulation of continuum plasticity and crystal plasticity. They discuss the basic concepts of the numerical implementation of plasticity models and identify the method which is most suited to solve a given mechanical problem. Students can implement and apply a numerical scheme for the solution of elasto-plastic problems within the finite element method.					
Contents a) - Basics of continuum mechanics and Finite Element Analysis - Phenomenology and atomistic origin of elastic and plastic deformation - Concepts of continuum plasticity (yield criterion, flow rule, isotropic and kinematic hardening) - Rate dependent and rate-independent formulations of continuum plasticity - Numerical solution schemes for elasto-plasticity (operator split, return mapping, consistent tangent modulus) - Computational aspects of small and large strain formulations - Concepts of crystal plasticity (dislocation slip, flow rule, hardening models, consistent tangent modulus) - Structure, implementation and application of an Abaqus UMAT					
Educational form / Language a) Lecture with tutorial / English					
Examination methods Portfolio exam 'Computational Plasticity' (120 h., Part of modul grade 100 %, Portfolio exam including reports on assignments, seminar and self-evaluation report)					
Requirements for the award of credit points Passed final module examination					

Module applicability

- M.Sc. Computational Engineering
- M.Sc. Mechanical Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

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Further Information**Teaching methods**

- lecture, hands-on classes, mini project incl. seminar talk, assignments
- Lecture notes will be provided.

Computational Structural Optimization Computational Structural Optimization					
Module number CE-WP35/BI-W74/SE-O-19	Credits 6 CP	Workload 180 h	Semester[s] 3. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Computational Structural Optimization (127517)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr. Roger A. Sauer a) Prof. Anupam Saxena					
Admission requirements Recommended previous knowledge: Basics knowledge in Mathematics, Programming, FEM and Structural Analysis					
Learning outcome, core skills After successfully completing the module, the students • have advanced knowledge regarding topology optimization and its integration in computational models • are able to independently implement topology optimization code in FE-Analysis frameworks • can perform computational topology optimization and apply it to any engineering problem • can critically interpret the results of a topology optimization					
Contents a) The course covers the basic knowledge of topology optimization and its implementation in computational frameworks. In particular, the following topics are taught in the course: • Introduction in finite-element theory and the development of code to perform FE-Analysis • Theory of topology optimization with code implementation • Application of topology optimization in computational models with different complexity levels					
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English					
Examination methods • Project report 'Computational Structural Optimization' (30 h., Part of modul grade 100 %, Project work with coding assignments and a written report (90%), optional presentation, with Oral examination (10%))					
Requirements for the award of credit points					
Module applicability • M.Sc. Computational Engineering • M.Sc. Subsurface Engineering • M.Sc. Civil Engineering					
Weight of the mark for the final score Percentage of total grade [%] = $6 \cdot 100 \cdot \text{FAK} / \text{DIV}$ FAK: The weighting factors can be taken from the table of contents.					

DIV: The values can be taken from the table of contents.

Further Information

Computational Wind Engineering Computational Wind Engineering					
Module number CE-WP14/CWE	Credits 3 CP	Workload 90 h	Semester[s] 3. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Computational Wind Engineering (127503)			Contact hours a) 2 WLH (30 h)	Self-study a) 60 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr.-Ing. Rüdiger Höffer a) Prof. Dr.-Ing. Rüdiger Höffer, Dipl.-Ing. Ulf Winkelmann					
Admission requirements Recommended previous knowledge: Modern Programming Concepts in Engineering (CE-P04), Fluid Dynamics (CE-P06), Recommended: Computational Fluid Dynamics (CE-WP05)					
Learning outcome, core skills The students acquire advanced skills of CFD methods for the computation of wind engineering problems such as • mean wind parameters and turbulence characteristics for the assessment of local wind climates (incl. wind farm locations), • wind pressures at surfaces for the determination of wind loads at structures, • gaseous transport in the atmospheric boundary layer for the prediction of the dispersion of exhausts and particles. After successfully completing the module, the students will be able to • understand the broad scope of computational fluid dynamics and the thematic integration of computational wind engineering within, • identify fluid dynamical mechanisms of observed flow phenomena and choose adequate and suitable CFD methods to explore and formulate engineering solutions for real flows, • solve relevant technical problems in the field of computational wind engineering by means of applying CFD simulations, • validate, verify, and assess the solutions and results of CFD simulations, • transfer learned skills in media literacy, and digital competence through the completion of supervised and supported self-studies to other engineering activities.					
Contents a) This course introduces the details and guidelines for the application of CFD methods in the field of wind engineering. Relevant problems for practical applications and solution procedures are investigated. The theoretical background is taught in the obligatory Fluid Dynamics course while this course aims at the practical application of CFD methods on various wind engineering problems. In general, the steady state RANS approach and the time dependent LES approach are used. The lectures and exercises include all necessary steps of a CFD simulation ranging from the creation of the geometry of the problem to the assessment and presentation of the results. During the semester, the commercial software package ANSYS CFX and the open source software OpenFOAM are used.					

The following working steps are explained and carried out:

- Generation of simple geometries and block structured grids and analysis of the influence of the quality of the mesh on the results of the simulation.
- Generation of complex geometries and unstructured numerical grids.
- Setting up simulations (Pre-Processing):
 - Choosing the right boundary conditions.
 - Choosing the correct turbulence models.
 - Deciding on the parameters of the finite volume method such as interpolation schemes for the convective term of the Navier-Stokes equation.
 - Adding source terms of exhaust for the investigation of pollution in the atmosphere.

Educational form / Language

a) Lecture (1 WLH) / Tutorial (1 WLH) / English

Examination methods

- Written exam 'Written examination' (75 min., Part of modul grade 100 %)

Requirements for the award of credit points

Passed final module examination

Module applicability

- M.Sc. Computational Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $3 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

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Further Information

Computer-based Analyses of Steel Structures					
Computer-based Analyses of Steel Structures					
Module number CE-P03/CbASS	Credits 6 CP	Workload 180 h	Semester[s] 1. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Computer-based Analyses of Steel Structures (125502)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr.-Ing Helen Bartsch a) Vertr.-Prof.'in Dr.-Ing. Rebekka Winkler					
Admission requirements Recommended previous knowledge: Fundamental knowledge in mechanics and strength of materials					
Learning outcome, core skills This course will introduce students to the fundamental structural behaviour of steel structures, numerical solution procedures and modelling details. The course aims to achieve a basic understanding of applied mechanics approaches to modelling member behaviour in steel structure problems. The course is addressed to young engineers, who will face the necessity of numerical analysis and applied mechanics more often in their design practice. The purpose of this course is to bridge the gap between applied mechanics and structural steel design using state-of-the-art tools. The students shall become familiar with computer-oriented analyses and design methods by using the example of steel constructions. The course will also convey to students the ability to use numerical tools and software packages for the solution of practical problems in engineering. After successfully completing the module, the students • have fundamental knowledge on structural and fatigue behavior of steel structures with the application of numerical procedures and modeling, • should be familiarized with basic principles of design and computer-oriented procedures in assessing steel structures, their stability behavior and durability, • will have gained experience in undertaking new concepts on their own and participate in inclass collaborative learning through the Inverted-classroom format, • will have gained skills in working on a problem individually and in groups, presenting their findings in interactive presentations as well as assessing the findings of their peers.					
Contents a) This course is introductory – by no means does it claim completeness in such a dynamically developing field as numerical analysis of slender steel structures. The course intends to achieve a basic understanding of applied mechanics approaches to slender steel structure modelling, which can serve as a foundation for the exploration of more advanced theories and analyses of different kind of structures. <i>Basics of the Analysis, Design and Fundamentals for Computer-Based Calculations</i> • Basic principles of structural design • Beam theory and torsion					

- Finite elements for beams and plates
- Software for analyses

Stability Behaviour of Slender Structures and Second Order Theory

- Geometric non-linear design of structures second order analysis
- Buckling of linear members and frames
- Lateral buckling and lateral torsional buckling
- Eigenvalues and –shapes
- Numerical methods for plate buckling

Structural Durability

- Fatigue
- Modern Concepts of Fatigue Strength Design
- Local Strain Concept
- Crack Propagation Concept

Educational form / Language

a) Lecture (2 WLH) / Tutorial (2 WLH) / English

Examination methods

- Written exam 'Klausur' (180 min., Part of modul grade 100 %)

Requirements for the award of credit points

- Passed final module examination

Module applicability

- M.Sc. Computational Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

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Further Information

Digital teaching within the meaning of the HDVO

Continuum Mechanics Continuum Mechanics					
Module number CE-P07/CM	Credits 6 CP	Workload 180 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Continuum Mechanics (126502)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr.-Ing. Johanna Waimann a) Prof. Dr.-Ing. Johanna Waimann					
Admission requirements Recommended previous knowledge: Mathematical Aspects of Differential Equations and Numerical Methods (CE-P01), Mechanical Modeling of Materials (CE-P02)					
Learning outcome, core skills Extended knowledge in continuum-mechanical modelling and solution techniques as a prerequisite for computer-oriented structural analysis. After successfully completing the module, the students • will possess extended knowledge of continuum mechanics • will be able to formulate problems of structural and material mechanics within the framework of continuum mechanics • will have mastered solution techniques for mechanical problems as a prerequisite for computer-oriented analysis • will be able to create mathematical models for engineering systems and processes • will be able to interpret modeling results and revise models accordingly					
Contents a) The course starts with an introduction to the advanced analytical techniques of linear elasticity theory, then moves on to the continuum-mechanical concepts of nonlinear elasticity and ends with the discussion of material instabilities and microstructures. Numerous examples and applications will be given. • Advanced Linear Elasticity • Beltrami equation • Navier equation • Stress-functions • Scalar- and vector potentials • Galerkin-vector • Love-function • Solution of Papkovitch - Neuber • Nonlinear Deformation • Strain tensor • Polar decomposition • Stress-tensors					

- Equilibrium
- Strain-rates
- Nonlinear Elastic Materials
- Covariance and isotropy
- Hyperelastic materials
- Constrained materials
- Hypoelastic materials
- Objective rates
- Material stability
- Microstructures

Educational form / Language

a) Lecture (2 WLH) / Tutorial (2 WLH) / English

Examination methods

- Written exam 'Klausur' (120 min., Part of modul grade 100 %)

Requirements for the award of credit points

- Passed final module examination

Module applicability

- M.Sc. Computational Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

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Further Information

Coupled Multiphysical Modeling and Simulations					
Coupled Multiphysical Modeling and Simulations					
Module number CE-WP15/ CMPMS	Credits 6 CP	Workload 180 h	Semester[s] 3. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Coupled Multiphysical Modeling and Simulations (127504)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each sem.
Module coordinator and lecturer(s) Dr.-Ing. Sergey Kozinov a) Dr.-Ing. Sergey Kozinov					
Admission requirements Recommended previous knowledge: Basic knowledge of continuum mechanics and mechanical modeling of materials is strongly recommended.					
Learning outcome, core skills Students should develop a strong understanding of coupled multiphysical systems and their modeling. After successfully completing the module, the students shall be able to - comprehend the properties and behavior of thermomechanical, electromechanical, and electromagnetic systems - develop mathematical and numerical models for coupled systems - implement and apply numerical methods for the computational solution of multiphysical systems - utilize software to solve coupled problems, with a clear understanding of the underlying methods, properties, and limitations - use machine learning techniques for surrogate modeling of complex multiphysical processes					
Contents a) - Constitutive laws for thermomechanics, electromechanics, and electromagnetics - Analytical methods for the mechanics of functional materials - Numerical techniques for multiphysics coupling and simulation - Non-linear electromechanical and electromagnetic material behavior - Size-dependent effects in electromechanical systems - Machine learning techniques applied to functional materials - Practical implementation of the numerical models - Simulation of real-world, industry-relevant problems					
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English					
Examination methods - Oral exam 'Coupled Multiphysical Modeling and Simulations' (30 min., Part of modul grade 100 %) - Bonus points for homework (40 h), Part of modul grade 0%					
Requirements for the award of credit points					

- Passed oral test

Module applicability

- M.Sc. Computational Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

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Further Information

Deep Learning for Engineers Deep Learning for Engineers					
Module number CE-WP33/DLE	Credits 6 CP	Workload 180 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Deep Learning for Engineers (126504)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr. Andreas Vogel a) Prof. Dr. Andreas Vogel, Assistants					
Admission requirements					
Learning outcome, core skills After successfully completing the module, the students • have acquired fundamental skills and knowledge in deep learning, including training concepts and neural network architecture designs, • are able to develop, train and employ deep learning models for scientific applications, • can assess the benefits and limitations of neural networks for their projects.					
Contents a) The lecture covers deep learning concepts and techniques, including: • general ideas and mathematical background • training and regularization methods • neural network architectures (feed-forward, convolutional, physics-informed, autoencoder, ...) • application to scientific and engineering problems • employment on modern computer hardware In hands-on sessions, practical exercises are used to discuss and illustrate the presented content.					
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English					
Examination methods • Written exam 'Deep Learning for Engineers' (120 min., Part of modul grade 100 %)					
Requirements for the award of credit points • Passed final module examination					
Module applicability • M.Sc. Computational Engineering					
Weight of the mark for the final score Percentage of total grade [%] = $6 \cdot 100 \cdot \text{FAK} / \text{DIV}$ FAK: The weighting factors can be taken from the table of contents. DIV: The values can be taken from the table of contents.					
Further Information					

Finite Element Methods in Linear Structural Mechanics					
Finite Element Methods in Linear Structural Mechanics					
Module number CE-P05/BI-P08/SE-C-2/ FEM-I	Credits 6 CP	Workload 180 h	Semester[s] 1. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Finite Element Methods in Linear Structural Mechanics (125507/127012)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr. Roger A. Sauer a) Prof. Dr. Roger A. Sauer					
Admission requirements Recommended previous knowledge: Basics in Mathematics, Mechanics and Structural Analysis (Bachelor level)					
Learning outcome, core skills After successfully completing the module, the students • have basic knowledge of the Finite Element Method (FEM), • are able to transfer initial boundary value problems of structural mechanics into discretized calculation models based on FEM and thus to solve simple tasks of structural mechanics independently (e.g. calculation of truss structures, disc-like or volume structures), • have advanced knowledge to understand the functionality of calculation programs based on FEM and to critically evaluate their results, • are able to independently implement corresponding user-defined elements in FE programs and perform numerical analyses of beam and shell structures.					
Contents a) The course covers the basic knowledge of linear FEM, which is based on the principle of virtual work. In particular, the following topics are taught in the course: • Isoparametric finite elements for trusses, two-dimensional elements, beams, three-dimensional volume elements for application in statics and dynamics, • consistent explanation of the fundamentals (basic equations, principle of variation), • Numerical integration, assembly of the elements to a discretized structure and the solution of the static and dynamic structure equation, • Discussion of stiffening effects ("locking") and their avoidance.					
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English					
Examination methods					

- Written exam 'Finite Element Methods in Linear Structural Mechanics' (120 min., Part of modul grade 100 %)
- Optional tasks to be solved at home and announced during the course, to get the bonus points for the exam.

Requirements for the award of credit points

- Passed final module examination

Module applicability

- M.Sc. Computational Engineering
- M.Sc. Subsurface Engineering
- M.Sc. Civil Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

DIV: The values can be taken from the table of contents.

Further Information

Fluid Dynamics Fluid Dynamics					
Module number CE-P06/FD	Credits 3 CP	Workload 90 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Fluid Dynamics (126501)			Contact hours a) 2 WLH (30 h)	Self-study a) 60 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr.-Ing. Rüdiger Höffer a) Prof. Dr.-Ing. Rüdiger Höffer					
Admission requirements Recommended previous knowledge: Mathematical Aspects of Differential Equations and Numerical Methods (CE-P01), Mechanical Modeling of Materials (CE-P02), Fluid Mechanics (Bachelor level)					
Learning outcome, core skills The students shall acquire consolidated skills of the basic laws of hydraulics, potential theory, flow dynamics and turbulence theory. The students shall be enabled to assess and to solve technical problems related to flow dynamics in hydraulics and in aerodynamics. After successfully completing the module, the students will be able to • understand the broad scope of fluid dynamics and the thematic integration of computational fluid dynamics within, • identify fluid dynamical mechanisms of observed flow phenomena and recognize the governing physical laws, • choose and apply adequate engineering models to explore and formulate engineering solutions for real flows, • solve fluid dynamical problems of acceptable complexity tailored to the student's study status, • validate and assess these solutions and the achieved results, • acquire skills in numeracy, media literacy, and digital competence through the completion of supervised and supported self-studies and other activities.					
Contents a) The technical basics of dynamic fluid flows are introduced, studied and recapitulated as well as related problems which are relevant for practical applications and solution procedures with an emphasis put on computational aspects. The lectures and exercises contain the following topics: Short review of hydrostatics and dynamics of incompressible flows involving friction (conservation of mass, energy and momentum, Navier-Stokes equations) Potential flow Isotropic turbulence and turbulence in a boundary layer flow Flow over streamlined and bluff bodies The students are guided in the exercises to working out assessment and solution strategies for related, typical technical problems in fluid dynamics.					

Educational form / Language
a) Lecture (1 WLH) / Tutorial (1 WLH) / English
Examination methods
• Written exam 'Klausur' (75 min., Part of modul grade 100 %)
Requirements for the award of credit points
• Passed final module examination
Module applicability
• M.Sc. Computational Engineering
Weight of the mark for the final score
Percentage of total grade [%] = $3 * 100 * \text{FAK} / \text{DIV}$ FAK: The weighting factors can be taken from the table of contents. DIV: The values can be taken from the table of contents.
Further Information

- Written exam 'Klausur' (75 min., Part of modul grade 100 %)

- Passed final module examination

- M.Sc. Computational Engineering

Percentage of total grade [%] = $3 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

DIV: The values can be taken from the table of contents.

German A1 German A1					
Module number CE-W13/SE-O-23	Credits 5 CP	Workload 150 h	Semester[s] Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) German A1 (125510)			Contact hours a) 4 WLH (60 h)	Self-study a) 30 h	Frequency a) each winter
Module coordinator and lecturer(s) M.A. Julia Salzinger a) M.A. Julia Salzinger					
Admission requirements Recommended previous knowledge: This course is aimed at beginners without any previous knowledge (Common European Framework of Reference for Languages)					
Learning outcome, core skills Students • can understand and use familiar everyday expressions. • engage in simple spoken communication. • read and understand short written texts. • write short personal messages and texts. • use basic grammar structures and vocabulary accurately. • develop listening comprehension for everyday contexts. • gain confidence in using German in real-life situations.					
Contents a) This course introduces students to the basics of the German language and helps them build essential communication skills for everyday situations. Through engaging activities, students learn to understand and use familiar expressions, ask and answer simple questions, and describe themselves and their surroundings. The course covers key topics such as personal information, family and hobbies, shopping, food and drink, daily routines, travel, and health. Emphasis is placed on listening and speaking, with integrated reading and writing tasks. Basic grammar, vocabulary, and pronunciation are taught in context to support meaningful communication.					
Educational form / Language a) Seminar / German / English					
Examination methods • Written exam 'German A1' (70 min., Part of modul grade 100 %, Written exam (percentage of the overall grade 75%) with Oral exam (20 minutes/pair, percentage of the overall grade 25%)) • Compulsory attendance 'German A1 - Course attendance' (OPart of modul grade 0 %, Preliminary work for the exam) • Course attendance (75%)					
Requirements for the award of credit points					

- Course attendance (75%)
- Passing the final written and oral exam

Module applicability

- M.Sc. Computational Engineering
- M.Sc. Subsurface Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $5 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

DIV: The values can be taken from the table of contents.

Further Information

Course registration by email with the instructor before the beginning of the class: Julia.salzinger@rub.de

Exam registration with the instructor in class

German A2 German A2					
Module number CE-W14/SE-O-24	Credits 5 CP	Workload 150 h	Semester[s] Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) German A2 (126508)			Contact hours a) 4 WLH (60 h)	Self-study a) 90 h	Frequency a) each summer
Module coordinator and lecturer(s) M.A. Julia Salzinger a) M.A. Julia Salzinger					
Admission requirements Recommended previous knowledge: This course is aimed at beginners who have finished A1 (Common European Framework of Reference for Languages)					
Learning outcome, core skills Students can • communicate in simple everyday situations (e.g., shopping, travel, work) • describe personal background, daily routines, and surroundings • talk about past events using the Perfekt tense • understand simple spoken German when it is clear and slow • read and understand short, practical texts (emails, signs, schedules) • write short messages, emails, and basic descriptions • use basic grammar structures (present tense, modal verbs, simple clauses) • ask and answer questions in familiar contexts • use common vocabulary for everyday topics (food, travel, health, etc.) • handle simple social interactions politely (<i>du</i> vs. <i>Sie</i>, requests, greetings)					
Contents a) This course introduces students to the basics of the German language and helps them build essential communication skills for everyday situations. Through engaging activities, students learn to understand and use familiar expressions, ask and answer simple questions, and describe themselves and their surroundings. The course covers key topics such as personal information, family and hobbies, shopping, food and drink, daily routines, travel, and health. Emphasis is placed on listening and speaking, with integrated reading and writing tasks. Basic grammar, vocabulary, and pronunciation are taught in context to support meaningful communication.					
Educational form / Language a) Seminar / German / English					
Examination methods • Written exam 'German A2' (70 min., Part of modul grade 100 %, Written exam (percentage of the overall grade 75%) with Oral exam (20 minutes/pair, percentage of the overall grade 25%))					

- Compulsory attendance 'German A2 - Course attendance' (0Part of modul grade 0 %, Preliminary work for the exam)
- Course attendance (75%)

Requirements for the award of credit points

- Course attendance (75%)
- Passing the final written and oral exam

Module applicability

- M.Sc. Computational Engineering
- M.Sc. Subsurface Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $5 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

DIV: The values can be taken from the table of contents.

Further Information

Course registration by email with the instructor before the beginning of the class: Julia.salzinger@rub.de

Exam registration with the instructor in class

High-Performance Computing on Clusters High-Performance Computing on Clusters					
Module number CE-WP26/ HPCC	Credits 6 CP	Workload 180 h	Semester[s] 3. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) High-Performance Computing on Clusters (127511)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr. Andreas Vogel a) Prof. Dr. Andreas Vogel					
Admission requirements					
Learning outcome, core skills After successfully completing the module, the students • are enabled to design and create programs for parallel computing clusters, • can critically evaluate distributed-memory systems and programming patterns, • can assess the mathematical properties of iterative solvers and their scalability.					
Contents a) The lecture deals with the parallelization on cluster computers. Distributed-memory programming concepts (MPI) are introduced and best-practice implementation is presented based on applications from scientific computing including the finite element method and machine learning. Special attention is paid to scalable solvers for systems of equations on distributed-memory systems, focusing on iterative schemes such as simple splitting methods (Richardson, Jacobi, Gauß-Seidel, SOR), Krylov-methods (Gradient descent, CG, BiCGStab) and, in particular, the multigrid method. The mathematical foundations for iterative solvers are reviewed, suitable object-oriented interface structures are developed and an implementation of these solvers for modern parallel computer architectures is developed. Numerical experiments and self-developed software implementations are used to discuss and illustrate the theoretical results.					
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English					
Examination methods • Written exam 'High-Performance Computing on Clusters' (120 min., Part of modul grade 100 %)					
Requirements for the award of credit points • Passed final module examination					
Module applicability • M.Sc. Civil Engineering • M.Sc. Computational Engineering • M.Sc. Angewandte Informatik					
Weight of the mark for the final score					

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

DIV: The values can be taken from the table of contents.

Further Information

- Beamer, computer lab, numerical experiments

High-Performance Computing on Multicore Processors					
High-Performance Computing on Multicore Processors					
Module number BI-WP56/CE-WP25/SE-O-8	Credits 6 CP	Workload 180 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) High-Performance Computing on Multicore Processors (126509)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr. Andreas Vogel a) Prof. Dr. Andreas Vogel					
Admission requirements					
Learning outcome, core skills After successfully completing the module, the students • are enabled to design and create programs for multicore processors, • can critically evaluate multi-threaded programs and shared-memory access patterns, • can assess the benefits and challenges of multicore programming techniques.					
Contents a) The lecture addresses parallelization on multicore processors. Thread-based programming concepts and techniques, including pthreads, C++11 threads, OpenMP and SYCL, are introduced and best practices are highlighted using applications from scientific computing. An overview of the relevant hardware aspects including multicore architectures and memory hierarchies is provided. An in-depth introduction to multi-threaded programming on multicore systems with special emphasis on shared-memory parallelization is given and parallelization patterns, thread management and memory access strategies are discussed. In hands-on sessions, programming exercises are used to discuss and illustrate the presented content.					
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English					
Examination methods • Written exam 'High-Performance Computing on Multicore Processors' (120 min., Part of modul grade 100 %)					
Requirements for the award of credit points • Passed final module examination					
Module applicability • M.Sc. Computational Engineering • M.Sc. Civil Engineering • M.Sc. Applied Computer Science • M.Sc. Subsurface Engineering					

Weight of the mark for the final score
Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$ FAK: The weighting factors can be taken from the table of contents. DIV: The values can be taken from the table of contents.
Further Information

Inelastic Finite Element Methods for Structures					
Inelastic Finite Element Methods for Structures					
Module number BI-WP59/CE-WP06/SE-CO-20	Credits 6 CP	Workload 180 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Inelastic Finite Element Methods for Structures (127518)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr. Roger A. Sauer a) Dr.-Ing. Vladislav Gudzulic, Prof. Dr. Roger A. Sauer					
Admission requirements Recommended previous knowledge: Basic knowledge of tensor analysis, continuum mechanics and linear Finite Element Methods. Previous participation in the course Nonlinear Finite Element Method for Structures is recommended and participation Object-Oriented Modeling and Implementation of Structural Analysis Software is advantageous.					
Learning outcome, core skills After successfully completing the module the students will • understand the fundamentals of dissipative processes in the context of modeling inelasticity in quasi-brittle materials, using concrete as the main example. • learn the computational approaches for modeling elastoplastic, damage and friction behavior. • be familiar with the concept of strain localization and localized failure, including their mathematical and numerical implications, as well as strategies to address them. • gain practical experience with implementation and algorithmic treatment of inelasticity in the context of incremental-iterative nonlinear structural analysis. • develop skills to select appropriate numerical methods and material models, including multi-scale approaches, for practical problems and critically assess their limitations. • be able to perform incremental analyses of progressive structural failure, critically evaluate the results, and assess the key design parameters such as load and deformation at the onset of inelasticity and structural redundancy (plastic reserve/residual strength).					
Contents a) The course is concerned with inelastic material models including their algorithmic formulation and implementation in the framework of nonlinear finite element method. Strain localization and localized failure will be explored in detail, focusing on their mathematical and numerical implications, as well as the strategies to address them. Further, the course covers the fundamental theory and implementation aspects of frictional contact. Special attention will be given to efficient algorithms for physically nonlinear structural analyses, including elastoplastic and damage models for quasi-brittle materials, as well as friction algorithms. While concrete serves as a primary example, these modeling approaches are equally applicable to other materials such as rocks, fiber composites, sea ice, bone, stiff soils, and wood. The course includes					

coding exercises and a final assignment, where students implement a selected inelastic model into a finite element program and apply it to nonlinear structural analysis.

Educational form / Language

a) Lecture with tutorial / English

Examination methods

- Term paper 'Inelastic Finite Element Methods for Structures' (90 h., Part of modul grade 100 %, Project work (implementation of an inelastic model into FE code) with final student presentation / bonus points for homework assignments)

Requirements for the award of credit points

- Passed final module examination

Module applicability

- M.Sc. Civil Engineering
- M.Sc. Computational Engineering
- M.Sc. Subsurface Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

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Further Information

Machine Learning: Supervised Methods Machine Learning: Supervised Methods					
Module number CE-WP28/ ML:SM	Credits 6 CP	Workload 180 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Machine Learning: Supervised Methods			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr. Tobias Glasmachers a) Prof. Dr. Tobias Glasmachers					
Admission requirements Recommended previous knowledge: The course requires basic mathematical tools from linear algebra, calculus, and probability theory. More advanced mathematical material will be introduced as needed. The practical sessions involve programming exercises in Python. Participants need basic programming experience. They are expected to bring their own devices (laptops).					
Learning outcome, core skills The participants understand statistical learning theory. They have basic experience with machine learning software, and they know how to work with data for supervised learning. They are able to apply this knowledge to new problems and data sets. After successfully completing the module, the students • understand the basics of statistical learning theory, • know the most relevant algorithms of supervised machine learning, and are able to apply them to learning problems, • know and understand the strengths and limitations of various learning models and algorithms, • can apply standard machine learning software for solving learning problems.					
Contents a) The field of machine learning constitutes a modern approach to artificial intelligence. It is situated in between computer science, neuroscience, statistics, and robotics, with applications ranging all over science and engineering, medicine, economics, etc. Machine learning algorithms automate the process of learning, thus allowing prediction and decision making machines to improve with experience. This lecture will cover a contemporary spectrum of supervised learning methods. All lecture material will be in English. The course will use the flipped classroom concept. Students work through the relevant lecture material at home. The material is then consolidated in a 4 hours/week practical session.					
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English					
Examination methods • Written exam 'Written examination' (90 min., Part of modul grade 100 %)					
Requirements for the award of credit points					

- Passed final module examination

Module applicability

- M.Sc. Computational Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

DIV: The values can be taken from the table of contents.

Further Information

The course applies a flipped classroom format. The sessions plan is largely based on the following caltech lectures: <http://work.caltech.edu/telecourse.html>

Master Thesis Masterarbeit CE					
Module number CE-M	Credits 30 CP	Workload 900 h	Semester[s] 4. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Master's Thesis			Contact hours a) 0 h	Self-study a) 900 h	Frequency a) each sem.
Module coordinator and lecturer(s) Alle Professorinnen und Professoren des Studiengangs a)					
Admission requirements Students can start their Master's thesis if six from seven compulsory courses have successfully been completed and a minimum of 70 credits has been collected.					
Learning outcome, core skills With the completion of the Master's thesis, - the students acquire the ability to plan, organize, develop, operate and present complex problems in Computational Engineering, - qualifies students are qualified to work independently in the field of Computational Engineering under the supervision of an advisor, - the associated presentation serves to promote the students' ability to deal with subject-specific problems and to present them in an appropriate and comprehensible manner, Further, it serves to prove whether the students have acquired the profound specialised knowledge, which is required to take the step from their studies to professional life, whether they have developed the ability to deal with problems from their in-depth subject by applying scientific methods, and to apply their scientific knowledge.					
Contents a) The Master's thesis can either be theoretically-, practically-, constructively- or organisationally oriented. Its topic is determined by the respective supervisor. The results should both be visualised and illustrated in writing in a detailed manner. This particularly includes a summary, an outline and a list of the references used within a specific thesis and obligatorily, an oral presentation.					
Educational form / Language a) Final thesis / English / German					
Examination methods Final thesis 'Masterarbeit' (6 mth., Part of modul grade 100 %, Review of the Master thesis report and oral presentation)					
Requirements for the award of credit points Successful evaluation (grade not lower than 4.0) of Master's thesis and oral presentation					
Module applicability M.Sc. Computational Engineering					
Weight of the mark for the final score					

Percentage of total grade [%] = $30 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

DIV: The values can be taken from the table of contents.

Further Information

Independent work in seminar rooms and computer labs; testing plants, where applicable. The topic of the Master's thesis is issued by a lecturer of the course. The student conducts research independently and presents the results in the form of a final written report and an oral presentation / English or German

Materials for Aerospace Applications Materials for Aerospace Applications					
Module number CE-WP20/MAA	Credits 6 CP	Workload 180 h	Semester[s] 3. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Materials for Aerospace Applications			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr. rer. nat. K. Hackl a) Dr.-Ing. Marion Bartsch, Prof. Dr. rer. nat. Klaus Hackl					
Admission requirements					
Learning outcome, core skills After successful completion of the module, students can - recapitulate which high performance material systems are used for aerospace applications, how they are manufactured, and which microscopic mechanisms control their properties, - explain and apply procedures for selecting and developing material systems for aerospace components, considering the specific requirements, - decide which characterization and test methods to apply for qualifying materials and joints for aerospace applications and know how lifetime assessment concepts work, - communicate, using technical terms in the field of aerospace engineering in English.					
Contents a) The substantial requirements on materials for aerospace applications are „light and reliable“, which have to be fulfilled in most cases under extreme service conditions. Therefore, specifically designed materials and material systems are in use. Furthermore, joining technologies play an important role for the weight reduction and reliability of the components. Manufacturing technologies and characterization methods for qualifying materials and joints for aerospace applications will be discussed. Topics are: - Loading conditions for components of air- and spacecrafts (structures and engines) - Selecting and developing materials and material systems for service conditions in aerospace applications (e.g. for aero-engines, rocket engines, thermal protection shields for reentry vehicles, light weight structures for airframes, wings, and satellites) - Degradation and damage mechanisms of aerospace material systems under service conditions - Characterization and testing methods for materials and joints for aerospace applications - Concepts and methods for lifetime assessment					
Educational form / Language a) Lecture (3 WLH) / Tutorial (1 WLH) / English					
Examination methods Written exam 'Written examination' (120 min., Part of modul grade 100 %, exceptions approved by examination office: oral exam/ 30 min)					

Requirements for the award of credit points
• Passed final module examination
Module applicability
• M.Sc. Computational Engineering • M.Sc. Mechanical Engineering
Weight of the mark for the final score
Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$ FAK: The weighting factors can be taken from the table of contents. DIV: The values can be taken from the table of contents.
Further Information
• Recommended are basics in materials science and solid mechanics • Script in English, additional literature announced during lecture

Mathematical Aspects of Differential Equations and Numerical Mathematics					
Mathematical Aspects of Differential Equations and Numerical Mathematics					
Module number CE-P01/SE-C-1/MADENM	Credits 6 CP	Workload 180 h	Semester[s] 1. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Mathematical Aspects of Differential Equations and Numerical Mathematics (125500)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr. Martin Kronbichler a) Prof. Dr. Martin Kronbichler					
Admission requirements Recommended previous knowledge: No prior knowledge or preliminary modules. Basic calculus and experience with matrices.					
Learning outcome, core skills The course will focus on the mathematical formulation of differential equations with applications to elastic theory and fluid mechanics. It gives an introduction to geometric linear algebra with emphasis on function spaces, coupled with the elementary aspects of partial differential equations. The students should learn to understand the mathematics side of the Finite Element Method (FEM) for elliptic PDE in low dimensions, appropriate Sobolev geometries, the FEM for Dirichlet and Neumann problems. For that reason, the basic principles in methods of error estimation are described to realize the understanding of fast and efficient solvers for the resulting matrix equations. As overall learning goal, the students should attain familiarity with modern methods and concepts for the numerical solution of complicated mathematical problems. After successfully completing the module, the students • should understand the mathematics side of the Finite Element Method for elliptic PDE in low dimensions, appropriate Sobolev geometries, the FEM for Dirichlet and Neumann problems, should attain familiarity with modern methods and concepts for the numerical solution of complicated mathematical problems.					
Contents a) Linear algebra: Basic concepts and techniques for finite- and infinite-dimensional function spaces stressing the role of linear differential operators. Numerical algorithms for solving linear systems. The mathematics of the finite element method in the context of elliptic partial differential equations (model problems) in dimension two.					
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English					
Examination methods • Written exam 'Mathematical Aspects of Differential Equations and Numerical Mathematics' (120 min., Part of modul grade 100 %)					
Requirements for the award of credit points					

- Passed final module examination

Module applicability

- M.Sc. Computational Engineering
- M.Sc. Subsurface Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

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Further Information

Remark: Due to the mixed background of the students, the exercise sessions often amount to additional lectures.

Mechanical Modeling of Materials Mechanical Modeling of Materials					
Module number CE-P02/SE-CO-19/MMoM	Credits 6 CP	Workload 180 h	Semester[s] 1. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Mechanical Modelling of Materials (125501)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr.-Ing. Daniel Balzani a) Prof. Dr.-Ing. Daniel Balzani					
Admission requirements Recommended previous knowledge: Basic knowledge in Mathematics and Mechanics (Statics, Dynamics and Strength of Materials)					
Learning outcome, core skills The objective of this course is to present advanced issues of mechanics and the continuum-based modelling of materials starting with basic rheological models. The concepts introduced will be applied to numerous classes of materials. Basic constitutive formulations will be discussed numerically. After successfully completing the module, the students • should have a deep understanding of the theoretical basis of classical material models, • should know how to derive constitutive equations from rheological models, • should be able to implement a material model with a suitable algorithmic treatment in finite element software.					
Contents a) Several advanced issues of the mechanical behaviour of materials are addressed in this course. More precisely, the following topics will be covered: • Basic concepts of continuum mechanics (introduction) • Introduction to the rheology of materials • Theoretical concepts of constitutive modelling • Derivation of 1- and 3-dimensional models in the geometrically linearized setting for - Linear- and nonlinear elasticity - Damage - Visco-elasticity - Elasto-plasticity • Aspects of parameter identification/adjustment • Algorithmic implementation in the context of the finite element method and analysis of simple boundary and initial value problems					
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English					

Examination methods

- Written exam 'Mechanical Modeling of Materials' (90 min., Part of modul grade 100 %)

Requirements for the award of credit points

- Passed final module examination

Module applicability

- M.Sc. Computational Engineering
- M.Sc. Subsurface Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

DIV: The values can be taken from the table of contents.

Further Information

Nonlinear Finite Element Methods for Structures Nonlinear Finite Element Methods for Structures					
Module number BI-WP05/CE-WP04/SE-CO-23	Credits 6 CP	Workload 180 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Nonlinear Finite Element Methods for Structures (126515)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr. Roger A. Sauer a) Assistants, Prof. Dr. Roger A. Sauer					
Admission requirements Recommended previous knowledge: Finite Element Methods in Linear Structural Mechanics (CE-P05/SE-C-2/FEM-I), Basic knowledge in Structural Mechanics					
Learning outcome, core skills After successfully completing the module, the students • understand the origins and implications of nonlinearities in structural mechanics • are able to formulate and solve nonlinear engineering problems with the finite element method accounting for geometrical and material nonlinearities • can perform structural analyses, where the linear (1st order) theory is not valid (e.g. cables, membrane structures, load bearing and stability analyses beyond limit loads), and they can assess the results.					
Contents a) The main topics of the course are: • formulation and finite element discretization of the basic equations for nonlinear materials and geometrically nonlinear analysis in structural mechanics • development of algorithms for the solution of the underlying nonlinear material and structural equations • application to analyze the structural behavior considering material nonlinearity and large deformations • nonlinear stability analysis of structures					
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English					
Examination methods • Written exam 'Nonlinear Finite Element Methods for Structures' (120 min., Part of modul grade 100 %)					
Requirements for the award of credit points • Passed final module examination					
Module applicability • M.Sc. Civil Engineering					

- M.Sc. Computational Engineering
- M.Sc. Subsurface Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

DIV: The values can be taken from the table of contents.

Further Information

Numerical Methods and Stochastics Numerical Methods and Stochastics					
Module number CE-WP08/SE-CO-8/NMS	Credits 6 CP	Workload 180 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Numerical Methods and Stochastics (126510)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr. Martin Kronbichler a) Assistants, Prof. Dr. Martin Kronbichler					
Admission requirements Recommended previous knowledge: Basic knowledge of: partial differential equations, numerical methods and stochastics					
Learning outcome, core skills Students should become familiar with modern numerical and stochastic methods After successfully completing the module, the students • should be able to formulate and analyze data from a probabilistic perspective, • should understand the theoretical aspects of FEM and FVM methods, • should be familiar with modern iterative solvers for large systems of linear equations and their necessity for numerical PDE solving, • should be familiar with standard methods for solving optimization problems.					
Contents a) Numerical Methods: • Boundary value problems for ordinary differential equations (shooting, difference and finite element methods) • Finite element methods (brief retrospection as a basis for further material) • Efficient solvers (preconditioned conjugate gradient and multigrid algorithms) • Finite volume methods (systems in divergence form, discretization, relation to finite element methods) • Nonlinear optimization (gradient-type methods, derivative-free methods, simulated annealing) Stochastics: • Fundamental concepts of probability and statistics, such as random variables, univariate distributions & densities, descriptive statistics, parameter estimation, & law of large no • Regression, such as univariate and multivariate linear regression, least-squares estimation, data transformations, qualitative predictors, and regularization • Exploratory data analysis, such as qq-plots and summary statistics					
Educational form / Language a) Lecture (3 WLH) / Tutorial (1 WLH) / English					

Examination methods

- Written exam 'Numerical Methods and Stochastics' (180 min., Part of modul grade 100 %)

Requirements for the award of credit points

- Passed final module examination

Module applicability

- M.Sc. Computational Engineering
- M.Sc. Civil Engineering
- M.Sc. Subsurface Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

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Further Information

Numerical Methods for Conservation Laws					
Numerical Methods for Conservation Laws					
Module number CE-WP17/ NMfCL	Credits 6 CP	Workload 180 h	Semester[s] 3. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Numerical Methods for Conservation Laws (127507)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr. Patrick Henning a) Prof. Dr. Patrick Henning					
Admission requirements Recommended previous knowledge: Basic knowledge about: ordinary differential equations, numerical integration, and numerical methods for the solution of large linear and non-linear systems of equations					
Learning outcome, core skills Students should attain familiarity with numerical methods for the solution of differential equations, in particular hyperbolic conservation laws. This includes understanding the notion of entropy solutions and being able to construct stable numerical schemes that are capable of finding such solutions. After successfully completing the module, the students shall be able to • design, implement and use numerical methods for computer solution of scientific problems involving differential equations, • understand properties of different classes of differential equations and their impact on solutions and proper numerical methods, • understand the different concepts of solutions to hyperbolic conservation laws and their physical interpretations, know how to select appropriate numerical methods that capture the physically correct solutions, • use software for solving differential equations with understanding of fundamental methods, properties, and limitations.					
Contents a) • Introduction to PDE's; classification of PDE's; well-posedness; outline of the course • Heat equation Setting; well-posedness; space discretization; properties of the discretization; finite volumes in 1D and 2D; stability of ODEs (repetition); time discretization • First order hyperbolic equations and characteristics; example: Burgers equation; crash of characteristics; discontinuous solutions; basic discretizations; characteristics for linear advective systems; linear Riemann problems • Basic discretizations finite volume methods; linearization of nonlinear conservation laws; boundary conditions					

- Convergence theory for linear methods notation; convergence, consistency and stability; verifying stability: CFL numbers; Von Neumann analysis
- Weak solutions and viscosity solutions weak solutions; viscosity limits and modified equations; Lax entropy condition; applications of entropy conditions; explicit entropy solutions to Riemann problems; weak entropy conditions; entropy pairs
- Monotone schemes, Consistent methods; idea of monotone schemes; properties of monotone schemes; the Godunov scheme
- Higher Order Finite volume methods for non-linear hyperbolic equations Lax-Wendroff scheme; TVD schemes, slope/flux limiters

Educational form / Language

a) Lecture (3 WLH) / Tutorial (1 WLH) / English

Examination methods

- Written exam 'Numerical Methods for Conservation Laws' (120 min., Part of modul grade 100 %)

Requirements for the award of credit points

- Passed final module examination

Module applicability

- M.Sc. Computational Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

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Further Information

Numerical Optimization Numerical Optimization					
Module number CE-W05	Credits 6 CP	Workload 180 h	Semester[s] 3. Sem.	Duration Semester[s]	Group size no limitation
Courses a) Numerical Optimization (212043)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr. Tobias Glasmachers a) Prof. Dr. Tobias Glasmachers					
Admission requirements Recommended previous knowledge: This course requires a solid grasp on various mathematical concepts for defining and analyzing optimization algorithms with mathematical tools, including a few proofs. Participants need a solid understanding of linear algebra (matrices, eigen decomposition, positive definiteness), analysis (sequences, convergence, convexity, gradient and Hessian matrix), and probability theory (multi-variate normal distribution). Prior knowledge of numerics is a plus, but not required. The exercise sessions as well as the exam require basic Python programming.					
Learning outcome, core skills The participants can explain important classes of optimization algorithms, like conjugate gradients (CG), BFGS, CMA-ES, and the simplex algorithm for linear programming. They understand properties of different types of search directions (sampling methods, gradient, conjugate gradient, Newton step and quasi Newton methods), as well step size control mechanisms (line search and trust region methods). They can relate these methods to convergence speed classes like linear and super-linear convergence. They understand Lagrangians and they can derive dual optimization problems. They can model real-world problems as mathematical optimization problems. They can pick suitable algorithms, apply them to actual optimization problems, and solve them efficiently.					
Contents a) This course offers a contemporary introduction to numerical optimization. Optimization algorithm find applications in many areas of engineering, economics, machine learning, and many more. This course covers the most prominent design principles and algorithm classes: gradient and Newton search directions • line search and trust region methods • conjugate gradients • quasi Newton algorithms • constraint handling, duality • linear programming, including the mixed integer case • direct search (gradient-free) methods Methods are presented and analyzed in the lecture, and implemented and tested in the exercise sessions. During the practical sessions, participants work on a mix of conceptual and practical exercises. Many practical exercises involve programming in Python.					

Educational form / Language

a) Lecture (2 WLH) / Tutorial (2 WLH) / English

Examination methods

- Written exam 'Numerical Optimization' (90 min., Part of modul grade 100 %, likely an electronic exam)

Requirements for the award of credit points

- Passing the final exam

Module applicability

- M.Sc. Computational Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

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Further Information

Recommended Literature:

1. "Numerical Optimization", Nocedal and Wright
2. "Convex Optimization", Boyd and Vandenberghe
3. "Introduction to derivative-free optimization", Conn, Scheinberg and Vicente
4. "The CMA evolution strategy: A tutorial", Hansen

Current information such as lecture dates, rooms or current lecturers and trainers can be found in the Ruhr University course catalog <https://vvz.rub.de/> and in the eCampus <https://www.rub.de/ecampus/ecampus-webclient/>.

More information about the organization of the course can be found in the Moodle course: please enter the link to the Moodle course if you already know it.

Numerical Simulation in Geotechnics and Tunneling					
Numerical Simulation in Geotechnics and Tunneling					
Module number BI-WP24/CE-WP09/SE-CO-3	Credits 6 CP	Workload 180 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Numerical Simulation in Geotechnics and Tunneling (128018)			Contact hours a) 4 WLH (60 h)	Self-study a) 60 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr.-Ing. Torsten Wichtmann a) Dr.-Ing. Mohammad Salimi					
Admission requirements					
Learning outcome, core skills After successfully completing the module, the students are able to • implement numerical models of complex boundary value problems in geotechnical engineering and tunneling, creating the adequate geometrical models, • evaluate numerical models and their results in a critical way, • acquire adequate knowledge in fundamentals of the finite element method to be able to adopt numerical simulation in design and control of geotechnical or tunneling problems with focus on the interactions between the soil and structures.					
Contents a) The course deals with the numerical modeling of various geotechnical structures and tunnels: • Overall insight to the numerical simulation of geotechnical problems by using the finite element method and concise review of simple constitutive models • Introduction to Hardening Soil (HS) and Hardening Soil Small Strain (HSS) model and calibration of constitutive parameters of the HS and HSS model • Simulation of lab tests and optimization of constitutive parameters • Details for proper simulation in geotechnics by addressing constructional details, optimum discretization, boundary and initial conditions • Fundamentals of contact elements and their applications in geotechnical modeling • Considering water pressures in numerical simulations: soil-water interactions in drained, undrained, consolidation, and fully coupled hydromechanical analyses • Creation of models, execution of calculations and analysis of results for various geotechnical boundary value problems: shallow foundations, retaining walls, excavation, embankments, consolidation, slope failure, tunneling • Methods to validate and verify the reliability of numerical models by exploring the numerical outputs in space and time and the evaluation of numerical results • Introduction to FE simulations with Plaxis 2D and numgeo • Introduction to Finite Element Limit Analysis (FELA) and the FE software OptumG2 • Comparison of Plaxis2D, numgeo and OptumG2 for different boundary value problems • Brief overview of other numerical methods (e.g. DEM, MPM, boundary element method)					

Educational form / Language
a) Lecture (4 WLH) / English
Examination methods
• Written exam 'Numerical Simulation in Geotechnics and Tunneling' (180 min., Part of modul grade 100 %)
Requirements for the award of credit points
• Passed final module examination
Module applicability
• M.Sc. Civil Engineering • M.Sc. Subsurface Engineering • M.Sc. Computational Engineering
Weight of the mark for the final score
Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$ FAK: The weighting factors can be taken from the table of contents. DIV: The values can be taken from the table of contents.
Further Information

Programming the Finite Element Method Programming the Finite Element Method					
Module number BI-W39/CE-WP10	Credits 3 CP	Workload 90 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Programming the Finite Element Method (128047)			Contact hours a) 2 WLH (30 h)	Self-study a) 60 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr. Roger A. Sauer a) Prof. Dr.-Ing. Matthias Baitsch, Prof. Dr. Roger A. Sauer					
Admission requirements Recommended previous knowledge: Finite Element Methods in Linear Structural Mechanics and Modern Programming Concepts in Engineering					
Learning outcome, core skills The seminar connects the theory of finite element methods (FEM) and object-oriented programming. After successfully completing the module, the students • can implement the theories and methods of the course 'Finite Element Methods in Linear Structural Mechanics' in an object-oriented finite element program and apply this program for the analysis of engineering structures, • have developed a program for the computation of spatial truss structures, • can verify the program using benchmark examples, • gained deep insight into the most relevant aspects for the implementation within the FEM and possibilities of using object-oriented programming for numerical approaches.					
Contents a) The main topics of the course are: • short summary of the basics of FEM and project-oriented programming • preparing a project with two parts - Part 1: students individually develop and verify an object-oriented finite element program for the linear analysis of spatial truss structures - Part 2: students can choose between different options, either, the application developed in the Part 1 is extended to more challenging problems (nonlinear analysis, other element types, etc.) or students switch to an existing object-oriented finite element package (e.g. Kratos) and develop an extension of that software (e.g. material models, element formulations)					
Educational form / Language a) Seminar / English					
Examination methods • Term paper 'Object-oriented Modelling and Implementation of Structural Analysis Software' (60 h., Part of modul grade 100 %, with final student presentation)					
Requirements for the award of credit points					

- Passed project work and final student presentation

Module applicability

- M.Sc. Civil Engineering
- M.Sc. Computational Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $3 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

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Further Information

Quantum Computing Quantum Computing					
Module number CE-WP21/QC	Credits 6 CP	Workload 180 h	Semester[s] 3. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Quantum Computing (127513)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr. Andreas Vogel a) Prof. Dr. Andreas Vogel					
Admission requirements					
Learning outcome, core skills After successfully completing the module the students • are enabled to design and create programs for quantum computers • can critically evaluate quantum systems and quantum algorithms • can assess the benefit of using quantum effects in computations					
Contents a) The lecture covers the theory and application of quantum computing from a computer science perspective with a focus on the usage of today's quantum hardware. The relevant basics of quantum mechanics including superposition, measurement, interference, entanglement and mathematical notation are introduced. The characteristics of quantum bits and registers are discussed, and the construction and properties of quantum gates and quantum circuits presented. Prominent examples for quantum algorithms are surveyed including algorithms based on quantum Fourier transformation (e.g. Shor's factoring), quantum search (e.g. Grover) and quantum solution of linear systems of equations (e.g. HHL). Current quantum computer hardware, including gate-based and adiabatic quantum computers, as well as quantum error correction are discussed. An introduction to quantum programming languages and environments will be provided. Hands-on programming exercises and self-implemented quantum circuits in study projects are used to discuss and illustrate the theoretical content. Implementations are tested on quantum simulators and cloudbased quantum hardware.					
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English					
Examination methods • Exercises 'Quantum Computing' (80 h., Part of modul grade 100 %, Study project with oral examination)					
Requirements for the award of credit points • Passed final project and passed oral examination					
Module applicability • M.Sc. Computational Engineering					
Weight of the mark for the final score Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$					

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Further Information

Recent Advances in Numerical Modelling and Simulation					
Recent Advances in Numerical Modelling and Simulation					
Module number BI-W35/CE-W04	Credits 2 CP	Workload 60 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Recent Advances in Numerical Modelling and Simulation (129224)			Contact hours a) 2 WLH (30 h)	Self-study a) 30 h	Frequency a) each sem.
Module coordinator and lecturer(s) Prof. Dr. Roger A. Sauer a) Prof. Dr. Roger A. Sauer					
Admission requirements Recommended previous knowledge: Finite Element Methods in Linear Structural Mechanics (CE-P05)					
Learning outcome, core skills After successfully completing the module, the students • gain insight into the current research in the field of numerical methods in structural mechanics based on selected research topics, • have skills on selected numerical simulation approaches and its application in engineering, • have tested research-oriented working					
Contents a) During the course, selected topics in the field of numerical modeling and simulation in structural mechanics will be presented. The range of topics will be continuously updated to fit with the relevance of current research topics, e.g.: • the Extended Finite Element Method • Finite Cell methods • Isogeometric Analysis • Peridynamics For each topic, the theory will be offered in the compact form with emphasis on the algorithms and specific numerical methods. Selected application examples will be demonstrated					
Educational form / Language a) Seminar / English					
Examination methods • Seminar 'Recent Advances in Numerical Modelling and Simulation' (30 h., Part of modul grade 100 %, Seminar presentation)					
Requirements for the award of credit points • Passed seminar presentation					
Module applicability • M.Sc. Computational Engineering					

- M.Sc. Civil Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $2 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

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Further Information

Scientific C++ Programming (Advanced) Scientific C++ Programming (Advanced)					
Module number CE-WP32/ SCPA	Credits 3 CP	Workload 90 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Scientific C++ Programming (Advanced) (128516)			Contact hours a) 2 WLH (30 h)	Self-study a) 60 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr. Andreas Vogel a) Prof. Dr. Andreas Vogel, Assistants					
Admission requirements					
Learning outcome, core skills After successfully completing the module, the students • are familiar with advanced programming concepts and constructs in C++, • are able to design and develop modern C++ applications using latest language features, • can review and contribute to advanced C++ projects.					
Contents a) The lecture addresses advanced topics in C++ programming. Object-oriented programming concepts such as classes, inheritance and polymorphism as well as generic programming concepts such as templates are introduced. The standard template library (STL) and selected functionalities from C++14 and above are surveyed. Best practices as well as the organization and development of advanced C++ projects are discussed. In hands-on sessions, programming exercises are used to discuss and illustrate the presented content.					
Educational form / Language a) Block seminar / English					
Examination methods • Written exam 'Scientific C++ Programming (Advanced)' (120 min., Part of modul grade 100 %)					
Requirements for the award of credit points • Passed final module examination					
Module applicability • M.Sc. Computational Engineering					
Weight of the mark for the final score Percentage of total grade [%] = 3 * 100 * FAK / DIV FAK: The weighting factors can be taken from the table of contents. DIV: The values can be taken from the table of contents.					
Further Information					

Scientific C++ Programming (Basics) Scientific C++ Programming (Basics)					
Module number CE-WP31/ SCPb	Credits 3 CP	Workload 90 h	Semester[s] 1. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Scientific C++ Programming (Basics) (127516)			Contact hours a) 2 WLH (30 h)	Self-study a) 60 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr. Andreas Vogel a) Prof. Dr. Andreas Vogel					
Admission requirements					
Learning outcome, core skills After successfully completing the module, the students • are familiar with basic programming concepts and constructs in C++, • are able to design and develop C++ applications and to work with C++ environments, • can review and contribute to basic C++ projects.					
Contents a) The lecture provides an introduction to C++ programming. Basics programming concepts such as types, statements, functions, pointers, memory management and data structures are introduced. Best practices as well as the organization and development of C++ projects are discussed. An introduction to C++ compilers, debugging concepts and development tools is provided. In hands-on sessions, programming exercises are used to discuss and illustrate the presented content.					
Educational form / Language a) Block seminar / English					
Examination methods • Written exam 'Scientific C++ Programming (Basics)' (120 min., Part of modul grade 100 %)					
Requirements for the award of credit points • Passed final module examination					
Module applicability • M.Sc. Computational Engineering					
Weight of the mark for the final score Percentage of total grade [%] = 3 * 100 * FAK / DIV FAK: The weighting factors can be taken from the table of contents. DIV: The values can be taken from the table of contents.					
Further Information					

Scientific Programming Scientific Programming					
Module number CE-P04/SE-O-10/SP	Credits 6 CP	Workload 180 h	Semester[s] 1. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Scientific Programming (125504)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr. Andreas Vogel a) Prof. Dr. Andreas Vogel, Assistants					
Admission requirements					
Learning outcome, core skills After successfully completing the module, the students • have acquired the fundamental skills for the development of software solutions, including programming concepts and constructs, data structures and algorithms, • are able to analyze problems with respect to their structure and requirements and are capable of designing and implementing suitable software code, • can implement typical problems in scientific computing using the Python programming language and are able to quickly adapt the learned concepts to other programming languages.					
Contents a) The lecture covers programming concepts such as • procedural programming, including data types, statements and functions, • object-oriented programming, including encapsulation, polymorphism and inheritance, • generic programming. Furthermore, fundamental data structures as well as efficient algorithms are presented, relevant software libraries are surveyed, and the organization of software projects is discussed. In hands-on sessions, programming exercises are used to discuss and illustrate the presente					
Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English					
Examination methods • Written exam 'Scientific Programming' (120 min., Part of modul grade 100 %)					
Requirements for the award of credit points • Passed final module examination					
Module applicability • M.Sc. Computational Engineering • M.Sc. Subsurface Engineering					
Weight of the mark for the final score Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$ FAK: The weighting factors can be taken from the table of contents.					

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Further Information

Seminar Computing in Engineering Seminar Computing in Engineering					
Module number CE-W11	Credits 3 CP	Workload 90 h	Semester[s] 3./4. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Seminar Computing in Engineering (126516)			Contact hours a) 2 WLH (30 h)	Self-study a) 60 h	Frequency a) each sem.
Module coordinator and lecturer(s) Prof. Dr.-Ing. Markus König a) Assistants, Prof. Dr.-Ing. Markus König					
Admission requirements					
Learning outcome, core skills After successfully completing the module, the students • will have learned how to structure and write a scientific work, including formal requirements such as how to cite others work, and how to search for suitable literature • will have gained experience in reading and understanding research papers in-depth and are able to summarize papers while focusing on relevant points • will have practiced condensing others written work into a scientific presentation, considering audience relevance and expectations, and presenting the result in a suitable manner • are able to participate in scientific discussion, either answering questions about a topic they have recently studied or asking questions about a previously unknown topic • will have evaluated the correct usage of machine learning tools for academic work, such as summarizing, (re)-writing, and understanding scientific papers					
Contents a) The seminar covers four different main aspects of academic work with a focus on computing in engineering topics: • how to read scientific literature • how to write scientific literature • how to search for scientific literature • how to present scientific literature					
Educational form / Language a) Seminar / English					
Examination methods • Seminar 'Seminar Computing in Engineering' (60 h., Part of modul grade 100 %, Submission of paper summary ("extended abstract") and Oral presentation)					
Requirements for the award of credit points • Passing grade (at least 4.0) for submission and presentation. To achieve the learning objectives, it is necessary to attend 9 out of 10 seminar sessions. A doctor's note is required to excuse absence from more than one session.					
Module applicability					

- M.Sc. Computational Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $3 * 100 * \text{FAK} / \text{DIV}$

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Further Information

Training of Competences (Part 1) Training of Competences (Part 1)					
Module number CE-W01/SE-O-14/ToC I	Credits 4 CP	Workload 120 h	Semester[s] 1. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Training of Competences and German Language course			Contact hours a) 4 WLH (60 h)	Self-study a) 60 h	Frequency a) each winter
Module coordinator and lecturer(s) N.N. a) University Language Center (ZFA) of Ruhr-University Bochum					
Admission requirements					
Learning outcome, core skills After successfully completing the module, the students are able to employ at a minimum level all four skills (speaking, listening, reading and writing) in familiar universal contexts or shared knowledge situations such as greeting, small talk, shopping, making appointments, eating out, orientation, biography, healthcare etc.					
Contents a) The learning goals of this German language course fulfill the special requirements of foreign students majoring in a subject that uses English as a teaching language. On a basic level, the main focus of the course lies on action-oriented speaking, listening, reading and writing comprehension so that the students learn to cope with everyday situations of their life in Germany. The classes consist of small groups, ensuring that students have ample opportunities to speak as well as having their individual needs attended to. All of our instructors are university graduates experienced in teaching DaF (Deutsch als Fremdsprache - German as a foreign language) and have been selected for their experience in working with students and their ability to make language learning an active and rewarding process. An optional intensive block course after the winter semester helps to activate and to intensify the newly acquired language skills.					
Educational form / Language a) Lecture with tutorial / English / German					
Examination methods Written exam 'Training of Competences and German Language course' (120 min., Part of modul grade 100 %, and Homework (20 h) / German)					
Requirements for the award of credit points Passed final module examination					
Module applicability - M.Sc. Computational Engineering - M.Sc. Subsurface engineering - Special offer for foreign students of the course					
Weight of the mark for the final score					

Percentage of total grade [%] = $4 * 100 * \text{FAK} / \text{DIV}$

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Further Information

University Language Center (ZFA) of Ruhr-University Bochum

Training of Competences (Part 2)					
Training of Competences (Part 2)					
Module number CE-W02/SE-O-15/ToC II	Credits 4 CP	Workload 120 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Training of Competences (Part 2)			Contact hours a) 4 WLH (60 h)	Self-study a) 60 h	Frequency a) each summer
Module coordinator and lecturer(s) N.N. a) University Language Center (ZFA) of Ruhr-University Bochum					
Admission requirements Participation on CE-W01/SE-O14/ToC I is obligatory					
Learning outcome, core skills After successfully completing the module, the students are able to employ at an intermediate level all four skills (speaking, listening, reading and writing) in familiar universal contexts or shared knowledge situations such as greeting, small talk, shopping, making appointments, eating out, orientation, biography, healthcare etc.					
Contents a) The learning goals of this German language course fulfill the special requirements of foreign students majoring in a subject that uses English as a teaching language. The main focus of the course lies on intermediate level action-oriented speaking, listening, reading and writing comprehension so that the students learn to cope with everyday situations of their life in Germany. This course continues the learning goals of the module Training of Competences 1.					
Educational form / Language a) Lecture (4 WLH) / English / German					
Examination methods Written exam 'Training of Competences (Part 2)' (120 min., Part of modul grade 100 %)					
Requirements for the award of credit points Passed final module examination					
Module applicability - M.Sc. Computational Engineering - M.Sc. Subsurface engineering - Special offer for foreign students of the course					
Weight of the mark for the final score Percentage of total grade [%] = $4 * 100 * \text{FAK} / \text{DIV}$ FAK: The weighting factors can be taken from the table of contents. DIV: The values can be taken from the table of contents.					
Further Information University Language Center (ZFA) of Ruhr-University Bochum					

Transient Finite Element and Finite Difference Methods					
Transient Finite Element and Finite Difference Methods					
Module number BI-WP60/CE-WP30/TFEM	Credits 6 CP	Workload 180 h	Semester[s] 2. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Transient Finite Element and Finite Difference Method (126520)			Contact hours a) 4 WLH (60 h)	Self-study a) 120 h	Frequency a) each summer
Module coordinator and lecturer(s) Prof. Dr. Roger A. Sauer a) Dr.-Ing. Sahir N. Butt, Prof. Dr. Roger A. Sauer					
Admission requirements Recommended previous knowledge: Finite Element Methods in Linear Structural Mechanics					
Learning outcome, core skills After successfully completing the module the students • understand the mathematical formulations of transient problems, including ordinary differential equations (ODEs) and partial differential equations (PDEs) • understand principles of numerical time integration schemes, their stability and accuracy • learn to assess the validity of the simulations, and interpret physical implications • gain hands-on experience in implementing numerical methods for transient problems					
Contents a) a) Introduction to transient problems and analysis • Hamilton's principle and Euler-Lagrange differential equation • Classification of transient problems and applications in engineering • Overview of numerical approaches b) Time integration of ODEs • Explicit and Implicit methods • Time integration of first order ODEs • Stability and accuracy analysis • Time integration of second order ODEs • Error estimates and Adaptive time stepping c) Time integration of PDEs • Finite differences in space and time • Diffusion and wave equation d) Outlook on Advanced topics in transient analysis • Fluid flow problems • Multiphysics problems					

Educational form / Language a) Lecture (2 WLH) / Tutorial (2 WLH) / English
Examination methods • Exercises 'Transient Finite Element and Finite Difference Method' (120 h., Part of modul grade 100 %, Classroom quizzes (60h), Homework assignments (60h))
Requirements for the award of credit points • Passed all quizzes and assignments
Module applicability • M.Sc. Computational Engineering • M.Sc. Civil Engineering
Weight of the mark for the final score Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$ FAK: The weighting factors can be taken from the table of contents. DIV: The values can be taken from the table of contents.
Further Information Can NOT be combined with CE-WP11 "Applied Computational Simulations of Structures" or BI-WP06 "Angewandte statische und dynamische Tragwerkssimulationen"

Uncertainty Quantification in FE Analyses with Surrogate Modeling					
Uncertainty Quantification in FE Analyses with Surrogate Modeling					
Module number BI-WP58/CE-WP29/SE-O-17	Credits 6 CP	Workload 180 h	Semester[s] 3. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Uncertainty Quantification (127519) b) Surrogate Modeling (127519)			Contact hours a) 2 WLH (30 h) b) 2 WLH (30 h)	Self-study a) 60 h b) 60 h	Frequency a) each winter b) each winter
Module coordinator and lecturer(s) Prof. Dr. Roger A. Sauer a) Dr.-Ing. Gerrit E. Neu b) Dr.-Ing. Ba Trung Cao					
Admission requirements Recommended previous knowledge: Fundamental knowledge in structural analysis, Finite Element Method, probability theory, and basic programming (MATLAB, Python)					
Learning outcome, core skills The course equips students with theoretical foundations and practical skills to model, propagate, and mitigate uncertainties in structural analysis. Students will be able to define an uncertainty quantification problem, evaluate the effect of aleatory, epistemic as well as polymorphic uncertainty onto computational models and to interpret the results. It delves into surrogate modeling methods that approximate high-fidelity simulations, enabling efficient uncertainty assessment in complex systems. Applications to structural reliability, optimization, and risk-informed decision-making are emphasized, with hands-on experience using state-of-the-art computational tools. After successfully completing the modules, the students are able to • Understand the role and significance of uncertainty in structural engineering and computational models. • Apply probabilistic and non-probabilistic methods for modeling uncertain parameters. • Develop and implement surrogate models for efficient uncertainty propagation and sensitivity analysis. • Use state-of-the-art tools and frameworks to solve real-world problems involving uncertain data.					
Contents a) The course deals with the uncertain data involving in structural analysis: • Fundamentals of uncertainty quantification: types and sources of uncertainty (aleatory vs. epistemic) • Sources of uncertainty in structural engineering: material properties, geometry, boundary conditions, and external loads • Computing with uncertainty models: stochastic model, interval analysis, fuzzy logic, and polymorphic model • Evaluation of model responses due to uncertain inputs: Quantification by statistical measures, sensitivity analysis and structural reliability b)					

The course deals with the development of numerical surrogate models to accelerate the computation with uncertain data:

- Surrogate models based on black-box machine learning techniques (Artificial Neural Network)
- Surrogate models based on reduced order methods (Proper Orthogonal Decomposition)
- Surrogate models based on hybrid combination (Physics-informed machine learning)
- Comparison of surrogate modelling techniques: accuracy vs. computational efficiency

Educational form / Language

a) Lecture (2 WLH) / English

b) Lecture (2 WLH) / English

Examination methods

- Term paper 'Uncertainty Quantification in FE Analyses with Surrogate Modeling' (90 h., Part of modul grade 100 %, Final project assignment + presentation of the results is used to determine the final grade Deadline will be announced at the beginning of the semester.)

Requirements for the award of credit points

- Passed final module examination

Module applicability

- M.Sc. Civil Engineering
- M.Sc. Subsurface Engineering
- M.Sc. Computational Engineering

Weight of the mark for the final score

Percentage of total grade [%] = $6 * 100 * \text{FAK} / \text{DIV}$

FAK: The weighting factors can be taken from the table of contents.

DIV: The values can be taken from the table of contents.

Further Information

Variational Calculus and Tensor Analysis Variational Calculus and Tensor Analysis					
Module number CE-WP01/SE-O-6/VCTA	Credits 5 CP	Workload 150 h	Semester[s] 1. Sem.	Duration 1 Semester[s]	Group size no limitation
Courses a) Variational Calculus and Tensor Analysis (125505)			Contact hours a) 3 WLH (45 h)	Self-study a) 105 h	Frequency a) each winter
Module coordinator and lecturer(s) Prof. Dr.-Ing. Johanna Waimann a) Prof. Dr.-Ing. Johanna Waimann, Dr.-Ing. Ulrich Hoppe					
Admission requirements Recommended previous knowledge: Mathematics					
Learning outcome, core skills After successfully completing the module, the students will be able • to read, write and interpret tensor expression in index and abstract notation, • to know and apply tools for formulating and manipulating the equations of continuum mechanics, • to understand and solve variational problems in mechanics.					
Contents a) • Tensor Analysis: Vector and tensor notation, vector and tensor algebra, dual bases, coordinates in Euclidean space, differential calculus, scalar invariants and spectral analysis, isotropic functions • Variational Calculus: First variation, boundary conditions, PDEs: weak and strong form, constrained minimization problems, Lagrange multipliers, applications to continuum mechanics					
Educational form / Language a) Lecture (2 WLH) / Tutorial (1 WLH) / English					
Examination methods • Written exam 'Variational Calculus and Tensor Analysis' (90 min., Part of modul grade 100 %, or Oral Examination (30 Min). Examination Methods will be defined at the beginning of the Semester due to the number of participants)					
Requirements for the award of credit points • Passed final written examination					
Module applicability • M.Sc Computational Engineering • M.Sc Subsurface Engineering					
Weight of the mark for the final score Percentage of total grade [%] = $5 * 100 * \text{FAK} / \text{DIV}$ FAK: The weighting factors can be taken from the table of contents. DIV: The values can be taken from the table of contents.					

Further Information
