Degree Program Documentation
Master's Program
Computational Mechanics

Part A

Department of Civil, Geo and Environmental Engineering
Technical University of Munich

General Information:

- Administrative responsibility: Department of Civil, Geo and Environmental Engineering
- Name of degree program: Computational Mechanics
- Degree: Master of Science (M.Sc.)
- Standard duration of study and credits:
  4 semester of enrollment and 120 credit points (CP)
- Form of study: full time
- Admission: Aptitude assessment (EV – Master's)
- Start: Winter semester (WiSe) 2000/2001
- Language(s) of Instruction: English
- Main Locations: Munich
- Additional information: Additional elite program at the Bavarian Graduate School of Computational Engineering possible
- Academic administrator (program design):
  Prof. Dr.-Ing. Gerhard Müller
- Contact for further questions (regarding this document):
  Felix Schneider, M.Sc.
  Email address: felix.w.schneider@tum.de
  Phone number: 089-289-28393
- Status as of: 19.05.2021

Table of Contents

1 Degree Program Objectives

1.1 Purpose

Computational mechanics (COME) is a constantly growing field with impact on both science and industry in all areas of engineering. It is concerned with solving mechanical problems on the basis of numerical approximation methods, involving discretization of the underlying equations in space and time. Nowadays, related skills are indispensable in civil and mechanical engineering, for the design of automobiles and spacecrafts, for developments in biomechanics and micro-electro-mechanical systems. Virtually all technical disciplines make use of the fast progress in this area.

Computational mechanics brings together highly sophisticated methods of theoretical, applied and structural mechanics, as well as computer science, software engineering and applied mathematics. Being familiar with the scientific background of this fascinating field opens the door to employment in all fields of engineering.

The rapid development of computers and the therewith connected technologies makes the practical computation of scientific phenomena possible which haven't been ascertainable yet. In the future an engineer, being familiar with Computational Mechanics, is demanded to have a consolidate knowledge in mechanics, mathematics and computer sciences more than today. A strong background in Computational Mechanics opens up a successful career in many fields of engineering. The interdisciplinary education conveys the ability to find innovative, creative and efficient solutions for the individual case and in consideration of the given time frame and budget. Computational modeling and simulation of physical processes as supplement to experimental methods are about to become an everyday tool, available at relatively low cost. The methods used in the field of Computational Mechanics are the future-oriented techniques a modern engineer needs.

Typical applications are for example, in

- Civil Engineering: new materials, nonlinear and dynamical structural behavior, interaction between building and environment, structural optimization and form finding, estimation of fatigue strength, transient behavior, flow-simulations, coupling of CAD and computing, information and internet technology.
- Mechanical and Automotive Engineering: 3-D-structural analysis, nonlinear dynamics, optimization, multibody dynamics, crash, acoustics, and airbags.
- Aerospace Engineering: fluid-structure-interaction, structural optimization, supersonic flight, high temperature exposure in the aerospace, active dampers, stratosphere balloons.
- Biomechanics and Medical Engineering: material models (e.g. bones, tissues), prostheses, implants, artificial blood vessels.

Therefore, the degree program aims at training engineers at the border between mechanical engineering, civil engineering, informatics and mathematics. The students shall be qualified as specialists in numerical analysis and simulation of complex engineering problems. For the solution of these problems, they can build a bridge between classical engineering disciplines, mathematics, informatics and software development. In order to achieve this goal, the degree program shall enable the students to develop own ideas and push the boundaries of their profession, and is thus research oriented.

1.2 Strategic Significance

In its mission statement, the Technical University Munich is committed to promoting innovation in all scientific fields that promise to improve the quality of life and cohabitation in the long term. The responsibility owed to future generations forms the basis for the interdisciplinary focal points of health & nutrition, energy & natural resources, environment & climate, information & communications, mobility & infrastructure.

The TUM Department of Civil, Geo and Environmental Engineering, including its central mission statements Construction – Infrastructure – Environment – Planet Earth, plays a leading role in covering interdisciplinary research fields and therefore contributes to the appeal and the international reputation of TUM.

Construction

The subject of construction plays a special role because building and living are one of the most basic of human requirements as well as being an important industrial sector and important cultural good. The aim is to use sustainable materials and techniques to apply construction methods that approach the ideal scenario: minimum consumption of resources with minimum emissions during the erection, operation, rebuilding and demolition of a construction. The main focal points are the optimization of construction principles, durability management, biogenic building substances and materials, reduction of emissions created during building work, and refurbishment and upgrading. Most of the constructions in civil engineering are prototypes. Therefore, simulation has always been a key issue for engineers in that field. The Master's Degree Program in Computational Mechanics focuses on modern numerical, mechanical simulation methods which help in the design process of constructions to reach the ideal scenario of the department. It deepens the knowledge and competences in these methods compared the Master's Degree Program in Civil Engineering.

Infrastructure

Today, the traffic issue is more than just the creation of a traffic infrastructure. Efficient, environmentally-friendly and safe operation of traffic systems is growing in importance. Traffic planning is increasingly becoming a design and management task within an overall complex system that comprises both passenger and freight traffic as well as all other carriers. A functional high-performing traffic system is a prerequisite for economic development. If traffic is considered as an overall system, it becomes apparent that this sector is immensely important for the economy (e.g. the traffic budget is the largest of the state's individual budgets).

The central theme 'Mobility, Transport and Traffic' reflects the department's mission statement well and is suitable for cross-faculty networking offering opportunities to publically present this engineering profession as a modern and interdisciplinary field. The central theme focusses on enhancing the classic traffic engineer training program to make traffic engineering an interdisciplinary and system-orientated profession; this also necessitates a shift in focus toward the basic and application research field. The structured approach is based on combining the network of teaching and research competence distributed among the various departments at the university to make use of the available resources, to serve the established professional degree programs and research fields, and to open up new combined teaching and research fields by procuring additional resources. One central element of this concept is the development of a knowledge network as a public-private partnership with participants from industry, public offices and science fields

Environment

One of the central issues addressed by the Technical University of Munich is the combined topic of environment and energy which is also one of the leading topics on the international agenda. Dealing with natural hazards and catastrophe prevention, i.e. the issue of "Preparedness" (more generally referred to as disaster and risk management) based on complex information, prevention and intervention is extremely important for the built-up and natural environment and is therefore a social, ecological and economic priority. This subject represents a precautionary contribution to sustainable environmental protection and the management of environmental problems.

Innovation results from the unique networking of the disciplines that previously merely existed alongside each other. In the foreseeable future this will greatly benefit the state, communes, the economy and society in general.

Inevitably, the socioeconomic aspects are pivotal for many essential research issues. The goal is to develop a continuous concept from one source for various risk areas such as flooding, food and water scarcity, landslides and mass movements etc. In this connection, the development of a dynamic system and handling concept in the shape of a complex expert system on the topic of environmental risk management is planned.

The simulation methods taught in the Master's Degree Program in Computational Mechanics are obligatory for the assessment of environmental risks.

Planet Earth

The task of the earth system sciences is to record dynamic changes and processes in and on the earth, the oceans and the atmosphere and to model their mutual interactions.

As these processes are global phenomena, it is essential to look at the system in a global way. To this end a growing number of earth observation satellites are used, e.g. the remote sensing satellite ENVISAT or the geodetic-geophysical satellites CHAMP and GRACE. These kinds of satellite observe the composition of the atmosphere, the sea level, the ice cover at the poles, the vegetation structure across the continents, the Earth's gravitation and magnetic field and lots more besides.

Earth science satellite missions are heavily influenced by geodesy. Firstly, by the photogrammetry measuring procedures, remote sensing and the visualization of the results (cartography), and secondly by establishing important basic principles for other disciplines. The realization of global coordinate systems and their interconnection with systems fixed in space (in which the satellite positions are defined) form the basis of all measurements and analyses.

Until the year 2019, the Institute for Astronomical and Physical Geodesy and the Institute of Photogrammetry and Cartography (both institutes are now part of the Department of Aerospace and Geodesy) have been working on realizing, analyzing and using various satellite missions at the TUM Department of Civil, Geo and Environmental Engineering – not just for observing the Earth but also for interplanetary missions e.g. to Mars. This involves close cooperation to applied subjects such as geophysics or oceanography, but also to engineering subjects such as mechanical engineering and electrical engineering that look at the orbit and position of the satellites, the sensors used or processing the collated raw data. Still, the simulation methods of Computational Mechanics are especially important in this field of engineering, because also satellites are usually prototypes or are produced at least at low quantities. Through application of elaborated numerical simulation tools, design and dimensioning of such systems can be done in a realizable time and cost frame, which might otherwise not be feasible.

Classification of the degree program

Orientated on its mission statement, the TUM Department of Civil, Geo and Environmental Engineering offers a wide range of degree programs that cover the individual aspects and allow the graduates to prepare in a targeted manner for their future work in science, research or commerce environments.

The degree program is positioned at the interface between various engineering disciplines and offers interested engineering graduates the opportunity to specialize in the interface subject of computer-aided mechanics. Merging the various engineering disciplines creates an interdisciplinary atmosphere which is of huge benefit to the students. Likewise, the shared element of computer-aided mechanics has a high appeal for international applicants. The inter-departmental element is very apparent in the curriculum. Anchoring the degree program in the TUM Department of Civil, Geo and Environmental Engineering, a department which focuses on transferring complex physical processes to models in many areas, allows students from other disciplines a general overview of the fundamental engineering processes, in particular the design of unique models that do not allow the preliminary production of prototypes or testing. In its particular focus on the implementation of a broad spectrum of solution strategies to various complex mechanical phenomena, this degree program is unique and differs from other master degree programs of the department (e.g. “Transportation Systems” or “Ressource-efficient and Sustainable Building”). In some parts there are overlaps with the two master’s programs “Civil Engineering” and “Environmental Engineering” offered at the Department of Civil, Geo and Environmental Engineering. Nevertheless, the master degree program “Civil Engineering” focusses on a more general engineering perspective, while the COME program allows a very specific approach to computer-aided mechanics. Also through its international orientation and accessibility for students with different backgrounds (comp. Section 3), the program creates a beneficial atmosphere for interdisciplinary exchange in between students but also with respect to the participating chairs and the department itself. The master degree program “Environmental Engineering” on the other hand has a stronger focus on developing and applying technologies to reduce the influence of human interaction on the environment. Typical field dealt with are in the field of water treatment, hydrology, water treatment or environmental hazards.

The COME program is embedded in the focus area “Modeling-Simulation-Processes”. Within this focus area it serves specially tailored interdisciplinary program that combines the departments expertise in the fields of numerical modeling and computer implementation. The degree program contributes to the development and transfer of knowledge and skills in this field as well as to the development and transfer of methods, strategies and good practice examples for computational mechanics.

2 Qualification Profile

After a successful finishing of his/her studies, a Master of Science of Computational Mechanics has developed a portfolio of knowledge skills and competences in the field of numerical simulation, modelling of engineering problems for a consequent numerical simulation and a profound understanding of mechanical problems. Overall, graduates are specialized in simulating structures or components thereof as well as fluids. They are able to translate complex physical systems into mechanical models and to predict the system behavior using highly elaborated numerical analysis tools.

For Master's programs, the following four areas of competence have been defined: Knowledge and understanding (1), Usage, application and generation of knowledge (2), Communication and cooperation (3), and Scientific self-understanding/ professionalism (4). [1]

Knowledge and Understanding

Based on the competences achieved during their individual Bachelor's program, graduates from the Master's Program in Computational Mechanics gain a deeper understanding during the course of the Master's program. As a part of that, they have the knowledge and a solid understanding of how to analyse structural-mechanical or fluid- mechanical engineering problems and how to transfer them into appropriate numerical models. They are able to interpret the particular terminology of their field of study and define and explain the underlying concepts. COME graduates are able to employ their knowledge and understanding in research or practical applications. Furthermore, they are able to critically reflect upon new research developments in the field of Computational Mechanics.

Besides, the graduates are able to evaluate the model assumptions linked with limitations of models, explain artefacts created during the modelling and evaluations process, give possible expansions of models for problems where the model assumptions might be violated and have detailed knowledge of numerical techniques to solve the engineering problems with the help of the developed models.

They derive ideas in engineering work as far as optimization of engineering products is concerned and are able to assess selected software tools. Therefore, they make scientifically founded decisions and can critically reflect on the consequences. The graduates are able to apply selected software tools and to get auto-didactically acquainted with new software products for numerical simulations.

COME graduates are able to apply complex principles in programming, including parallel computing, software development. They evaluate the underlying partial differential equations for various engineering problems, mainly from solid and fluid mechanics, know the assumptions for material description for a huge variety of different materials as well as those for the application of low and high frequency analysis.

Usage, application and generation of knowledge

---

[1] The qualification profile meets the requirements of the Qualifications Framework for German Higher Education Qualifications ("Hochschulqualifikationsrahmen" – HQR) from 16th February 2017.

The starting points of the study program Computational Mechanics are in-depth understanding of the foundations of continuum mechanics and fluid mechanics on the one hand, and the numerical solution of therefrom resulting complex differential equations. On the basis of these competences that go beyond the usual approaches of technical mechanics or technical fluid mechanics of a classical civil or mechanical engineer, so, the graduates of COME have a deeper knowledge in these topics and the ability to assess, optimize, and calculate system responses for concrete constructions and systems. This is largely independent from the specific application, may it be Civil, Aerospace or Automotive Engineering. On the basis of their sound knowledge of numerical methods and the underlying model boundaries for materials as well as system behaviour the students can universally assess simulation results with respect to numerical and mechanical artefacts. Thereby the students gain a deep fundamental knowledge in the basics of solid and fluid mechanics as well as numerical analysis and its computer implementation.

Through the connection of these fundamental competences in continuum mechanics and fluid mechanics and numerical analysis, the students develop competences to compute the response of complex structures and systems. Furthermore, they connect the learned methods to optimize a systems behaviour and evaluate the robustness of their predictions. The students then acquire the competences to critically reflect upon the obtained computation results with respect to underlying assumptions regarding the materials, chosen mechanical formulations, as well as the numerical discretization and solution strategy. These competences are especially important in practical applications in the industry to identify non-transparent artefacts in the numeric approximation and the modelling process that are usually not avoidable in the usage of black-box simulation software.

In the field of scientific innovation, the students pose current questions in the field of computational mechanics, numerical static and dynamic analysis and fluid mechanics, and solve these through application of appropriate research methods. They are finally able to critically reflect upon those ideas and communicate the approaches and results.

Communication and cooperation

After graduating from the Master's Program in Computational Mechanics, graduates are able to give presentations in front of an international academic audience. Along that they have the knowledge of how to prepare these presentations in a clear and concise way. COME graduates are able to work in an independent manner through their expertise to extract relevant problems by themselves. They have the expertise to to discuss their scientific findings with international experts.

COME graduates have good social and communication skills, enabling them to work together in a cooperative way. Furthermore, they are sensitive to issues arising in cross-cultural and interdisciplinary work environments. The graduates act in a responsible way and are tolerant and open-minded with respect to their fellow human beings and co-workers.

They enhanced their communication skills in groups with both academics and non-academics from various disciplines in the Computational Sciences as well as Engineering sciences. The Graduates are able to identify the conflict potential in a collaborative process and can develop solutions if conflicts arise. They are able to build a bridge between both professional communities and are thus able to discuss feasible alternatives for solving interdisciplinary and subject-related problems.

Scientific self-understanding/ professionalism

Graduates of the Master's Program in Computational Mechanics at TUM are able to justify their own professional actions in the field of Computational Mechanics based on their solid knowledge in the fields of mechanical modelling and computer implementation and critically reflect upon the results of their work. Through their studies they have develop a professional self-understanding based on the objectives and standards of professional action in academia and society. They assess their own abilities, know about the boundaries of their knowledge and make use of their freedoms of modelling and implementation choices independently. They are able to further develop them independently or under supervision. COME graduates recognize the limits of the applied theories and have learned to critically reflect their professional actions with regard to the predictability of these theories and methods. Thereby they always assess their own abilities and know how to develop their professional actions in the field of Computational Mechanics further.

3 Target Groups

3.1 Target Audience

The master's program of Computational Mechanics focuses on national and international bachelor's graduates in the fields of Civil or Mechanical Engineering who are especially interested in the link between the various fields of mechanics and engineering applications. It thus provides the possibility for students of civil engineering to obtain insights into other fields in engineering and to establish contact to other types of industries outside of civil engineering. On the other hand, it provides a link for students coming from mechanical engineering towards special topics in civil engineering, e.g. structural dynamics, hydromechanics. It thus can be considered as an interdisciplinary program bridging different engineering fields with the common basis of computational mechanics.

3.2 Prerequisites

The master's program Computational Mechanics requires a strong background in engineering, structural and/or applied mechanics and good skills in mathematics and informatics. Therefore, the program is open to students of engineering bachelor programs as long as these programs provide a comparable base in mathematics, mechanics and informatics as the TUM Bachelor programs in Civil or Mechanical Engineering. The selection of the students is done very carefully in the scope of an aptitude assessment of each application in order to reduce the number of drop-outs. A GPA above 2,5 (converted according to the so called Bavarian formula into the German grading system) gives an important benefit in the aptitude assessment, where a lower GPA will be more beneficial. Moreover, applicants need to prove their skills in English language through submitting one of the following: Test of English as a Foreign Language" (TOEFL) with at least 88 points, the „International English Language Testing System" (IELTS) with at least 6.5 points, the „Cambridge Main Suite of English Examinations" or a certificate stating that the applicants have taken modules of at least 30 credits in their Bachelors that are taught in English.They need to explain their motivation for the studies in Computational Mechanics with the help of a short letter and need to provide at least one recommendation of one of their professors. Furthermore, a student's aptitude is proven through having gained competences that are comparable to those taught in the Bachelor degree programs Civil Engineering and Mechanical Engineering. The details of the aptitude assessment are described in the study regulations. We specifically require the students to have a strong background in solid and fluid mechanics, mathematics and informatics. These are, inter alia, competences in Technical Mechanics, dynamics, flow mechanics, linear algebra, analysis, differential equations and programming. The quality of the selection process is proven by the very low dropout rate of around 5% per year during the last years.

3.3 Target Numbers

The degree program Computational Mechanics is designed for approximately 30 students per intake. The limiting elements are on the one hand side infrastructure as far as computer rooms are concerned (currently 35 working places) and the individual support of the students. Nevertheless, the number of students increases with the increasing number of applications. Currently approximately 35 students are enrolled, which sometimes unfortunately leads to crowded lecture rooms. There is an enormous interest for the degree program, which requires a competitive pre-selection out of more than 500 students among which approximately 35 are enrolled to the program. Illustration 1 shows the evaluation of the numbers of applications, the admitted students and the freshmen starting the program over time. In general, all numbers have grown, which emphasizes the growing popularity of the topic of the degree program. Due to the internet boom (esp. social media), information about this program gets spread faster around the world than in the beginning of the program. This fact attracts, together with the abolishment of study fees in Bavaria, more and more international applicants. Unfortunately, many of these additional applications cannot meet the challenging prerequisites of the program. Therefore, the number of applications have grown much faster than the number of additions and freshmen. Especially the number of applications of Indian, Iranian, Pakistani, Turkish, Chinese and German applicants grew in the last years.

Since the program's beginning in the winter semester 2000/2001 up to the winter semester 2019/2020, 564 students out of 56 different countries started the program. Based on the data starting from winter semester 2008/2009, the majority of the students come from Europe (44 %) and Asia (37 %). Additionally, 13 % of the students come from America, 4 % from Africa, and approximately 2 % of the students come from Oceania. Approx. 80 per-cent of the students enrolled are international, thus 20 % of the students come from Germany. Since the establishment of the Bachelor-Master system at TUM the number of German applicants has increased.

The most applications by far come from India. But also Pakistan, Iran, Turkey and China provide a remarkable amount of applications. Germany is on rank 6 regarding the number of applications.

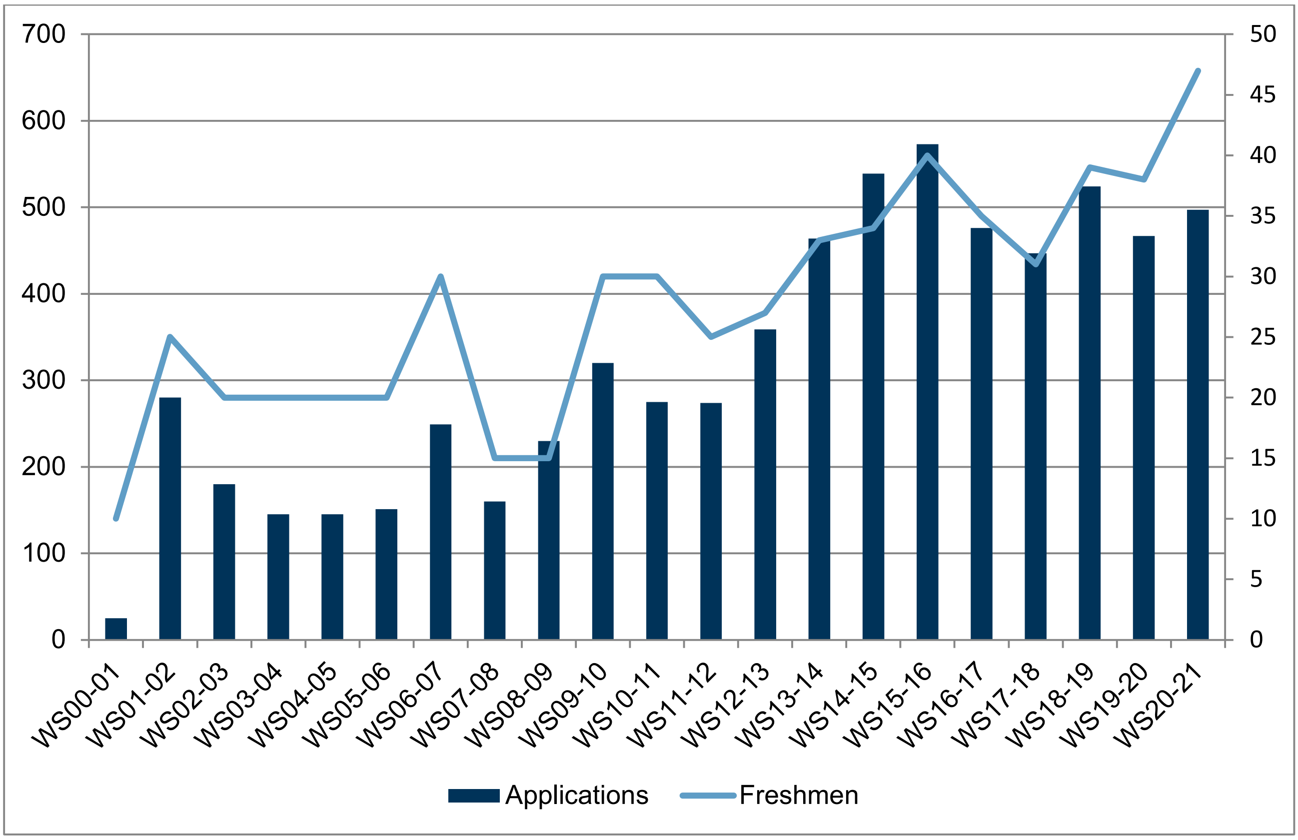

Illustration 1 Number of applications, admissions and freshmen. The number of applications (bars) links to the left axes, the number of freshmen (solid line) links to the right axes.

4 Analysis of Need

Graduates in Computational Mechanics should work as a new type of engineer on a borderline between various disciplines, as mechanical and civil engineering, informatics and mathematics, in engineering companies in the area of structural dynamics, acoustics, pollution control or in the classical fields of civil engineering with a special focus on structural analysis. Therein they are experts in numerical analysis and simulation of engineering problems and can provide a link between different classical engineering disciplines and software development. With their qualifications (see Section 2), the expected employment possibilities are Civil and Mechanical Engineering companies as well as research institutions and software developers. Because of their specific competences in the simulation of structures and fluids, and their fundamental understanding of modelling complex physical systems into mechanical models they are qualified for work as engineers in the automotive and aerospace industry and in engineering companies focussing on structural dynamics, acoustics or pollution control. In the classical field of civil engineering the main focus of their work lies on structural analysis. Due to their research competences in computational mechanics, they are also qualified for career paths in research institutions or universities focussing on computational mechanics.

In the extended quality management circle of 2019 it was stated by external experts that stem from the different COME relevant fields, such as civil or mechanical engineering and academia that the course content of COME is very relevant for the German labor market. They also see a high need for COME graduates. Furthermore, there was only positive feedback by the employers in Germany regarding their experience with hiring COME graduates. Also, a search on www.stepstone.de (an online job portal) on 22 July 2020 delivers around 320 open positions regarding “Mechanical Computational Engineer”.

The remainder of this analysis as well as the competitive analysis in section 5 is based on three surveys of in total 97 graduates of the program between 2002 and 2016. The surveys took place in March 2012 (74 participants), July 2018 (13 participants) and July 2020 (10 participants). In the following, mean values of the first two surveys are presented. The third survey verifies the findings of the first two surveys, but due to the low number of participants, we refrain from drawing detailed conclusions. Some questions haven’t been asked in 2018 and 2020 as compared to 2012. None of the graduates had problems in finding a job on the labour market.

The survey showed that the graduates find jobs in various companies from different sectors, such as Automotive and Aviation Industry, Civil Engineering, Simulation Engineering and Consulting, Mechanical and Plant Engineering and Software Development & Engineering. Another important part of the labour market which is relevant for COME alumni is research and development, as well in the private sector or at a large number of universities, where they often receive doctoral positions. Furthermore, the majority of the graduates, i.e. 67%, starts working in Germany after graduation while just 33% find a workplace in Europe or overseas. This is a great success in consideration of the fact that approx. 72% of the students come from abroad (survey 2012: 80%; survey 2018: 54%; survey 2020: 60%) and proofs the high demand of the graduates at the German labor market. Besides, 40% (survey 2012: 46%; survey 2018: 16%; survey 2020: 20%) of the 97 graduates who participated in the surveys stated that they continued with doctoral studies after graduation, among them 15 graduates at TUM.

The majority of students have Mechanical or Civil Engineering and Applied/Computational Mechanics as academic background from their bachelor’s. Other backgrounds are Aerospace or Automotive Engineering as well as Mechatronics and Naval Architecture. This can be compared with the fields of engineering in which the students were employed after graduation. The survey shows that the program’s curriculum attracts applicants from different fields of engineering as well as allows the graduates to work in various fields of engineering. Whereas approx. 90% of the students have a background in the traditional fields of engineering such as civil, mechanical, aerospace engineering and applied mechanics, the graduates are employed in even more various fields like Simulation, Develop Engineering or Multi Body Dynamics.

5 Competition Analysis

5.1 External Competition Analysis

In Germany, a continuously increasing number of international (English taught) Master's programs in the field of Computational Mechanics, Computational Engineering and Computational Sciences (www.hochschulkompass.de) exists. Apart from the Computational Mechanics program at Technical University of Munich, the following list gives a comprehensive overview over the various programs. The University of Stuttgart offers a program on Computational Mechanics of Materials and Structures and the University Duisburg-Essen offers a program on Computational Mechanics. Programs on Computational Engineering are offered at Ruhr-Universität Bochum, Technical University Darmstadt, Friedrich-Alexander-University Erlangen-Nürnberg, Technical University of Kaiserslautern. The program Computational Engineering Science is offered at RWTH Aachen. The program Computational Science and Engineering is offered at Technical University of Dresden, Technical University Bergakademie Freiberg and University Ulm. The program Computational Sciences and Engineering is offered at University of Rostock, and the program Computational Sciences in Engineering is offered at Technical University Carolo-Wilhelmina Braunschweig. The Bergische Universität Wuppertal offers a program on Computational Simulation in Science. All of the above programs can be studied full-time.

Internationally, programs on Computational Mechanics are rarely taught. Most of the programs that are offered, focus on Computational Science and Engineering, such as the program at MIT. Programs with a similar focus to COME at TUM are the Computational Mechanics program at Sorbonne University in Paris, which is in cooperation with La Sapienza University in Rome. Another joint degree is offered by Swansea University, Stuttgart University, Polytechnic University of Barcelona, École Centrale de Nantes, and University of Padova. Additionally, Duke University in the United States offers a Master's program on Computational Mechanics.

All the programs have in common that they have an interdisciplinary curriculum combining informatics and problems in science and engineering. However, contrary to most of the programs the master's program Computational Mechanics of TUM concentrates on a solid theoretic education in general mechanics which is needed for solving problems in different fields of engineering. This element is shared with the degree programs offered at the universities in Stuttgart and Duisburg-Essen. Another difference to other programs is the link to civil engineering which is very valuable as civil engineers have to deal with unique structures not permitting physical tests during their development. As already presented in Section 4 the program's curriculum attracts applicants from different fields of engineering and allows the graduates to work in various fields of engineering.

According to the graduate survey referred to in section 4 the most important reasons for choosing the master's program Computational Mechanics are the good reputation of TUM (46% of survey participants), the interest in the program's curriculum (39% of survey participants) and the uniqueness of the program (15% of survey participants). Furthermore, alumni of the program who are spread all over the world are excellent ambassadors for the master's program Computational Mechanics and recommend it to their compatriots.

5.2 Internal Competition Analysis

The degree program Computational Mechanics at the Department of Civil, Environmental and Geo Engineering aims at offering a highly specialized curriculum to train highly motivated students at the frontier of numerical analysis and software implementation. This requires a very well rounded curriculum that on the one hand side makes sure that each student gains basic competences while on the other hand allowing flexibility to ensure that the students can improve their individual skillset. Through its international orientation and broad range of applicable Bachelor studies as a prerequisite (comp. Section 3.2) the COME students support an interdisciplinary exchange and thus an atmosphere that promotes excellence in education and research.

The Department of Civil, Environmental and Geo Engineering offers the degree program Civil Engineering, which offers education in solid and fluid mechanics as well as computational aspects in engineering applications. The Master's Program in Civil Engineering has a quite broad curriculum. Students must select four specializations out of 22. Thus, they can choose the four specializations Structural Mechanics, Computation in Engineering, Hydromechanics and Structural Mechanics. The courses offered by the Chair of Computational Mechanics are not offered in one specific specialization, but can only be taken via an individually approved cross-sectional specialization. Furthermore, the structure of the COME program offers a larger flexibility for students with different prerequisites to follow their initial background and newly found interests through including courses from various institutes at TUM within their individual curriculum. Also, the COME program has a stronger international orientation as compared to the Civil Engineering program. Focusing on the methods of Computational Mechanics allows the students to reach higher competences in this field compared to civil engineering students. This is also emphasized by the curriculum, which contains modules which are either designed for this program (like "Software Lab") or are imported form the departments of mathematics, informatics or mechanical engineering (like "Bio Fluid Mechanics", "Scientific Visualization", "Functional Analysis"). Thus the outreach of the graduates to industries and research entities far beyond civil engineering is considerably enlarged.

The Department of Informatics at TUM offers the degree program Computational Science and Engineering (CSE) which combines applied mathematics with informatics and engineering to solve problems in science and engineering applications. In some parts both programs address the same issues, but CSE has a much stronger focus on computer science whereas the COME program addresses problems that require a deep understanding of the mechanic model at hand.

The Department of Mathematics at TUM offers the degree program Mathematics in Science and Engineering, which focusses on a solid education in applied mathematics, with focus on applied analysis or geometry, nonlinear optimization, numerical analysis or scientific computing). In parallel, the students are enabled to partly cover engineering tasks or work on problems in the natural sciences. As with the CSE program, there is some partial overlap in the addressed issues, but in contrast to COME the Master's in Mathematics in Science and Engineering has a much stronger focus on a sound theoretical mathematical education. All three programs complement each other, building a strong foundation for highly relevant and excellent research in education in computational engineering at TUM.

The Master of Science in Computational Mechanics at TUM thus is a unique international degree program without comparable degree programs at TUM. In spite of the partial overlap with specific specializations of the master’s program Civil Engineering, the curriculum of the master’s program Computational Mechanics is significantly complemented with specific offers.

The degree program profits enormously from the events held by the relevant specialization areas of the master´s programs Civil and Environmental Engineering. In the master´s program Civil Engineering, the relevant lectures are also taught in English. Therefore, a conscious decision was made to run the respective degree programs in joint groups, in order to encourage the students to mingle and get to know each other better (which is especially important for the high number of international students in COME). But still, as described above, the focus of the degree programs are different.

Altogether, the master’s program Computational Mechanics is a unique program at TUM, focussing on the frontier of applied mechanics and computational implementation. It addresses its own broad group of interests, reflected in the diverse accepted pre-requisites and has an own well-tailored curriculum that enables graduates to work in a specific market with a broad application spectrum and high demand.

6 Program Structure

The standard duration of study of the master’s program Computational Mechanics is four semesters consisting out of three semesters of course work and one semester for the master’s thesis. The program has in total 120 ECTS credit points (CP), the three semesters and the master´s thesis each worth 30 CP. The modular structure of the degree program includes required modules as well as elective modules. The 90 CP credits achieved through modules are divided into 36 CP credits of compulsory modules and 54 CP of elective modules. The elective modules are split into technical (fachspezifisch) elective modules (27 CP), general education modules (3CP) and two specialized elective modules, namely modules from the catalogues “Mechanical” and “Computational” (12 CP, each). A general degree chart is depicted in Illustration 2, where the two catalogues “Mechanical” and “Computation” are located in the second semester. The elective catalogues “Mechanical” and “Computational” could also be organized in such way that students can take these modules within the second and third semester. Either they can choose to take all “Mechanic” modules in one semester and all “Computation” modules in the other, see Illustration 3, or they could mix them during the semesters. Still, they have to choose modules worth 12 CP in total for each catalogue. This together with a wide variety of different possible elective modules gives the students the required flexibility to include a stay abroad into their studies.

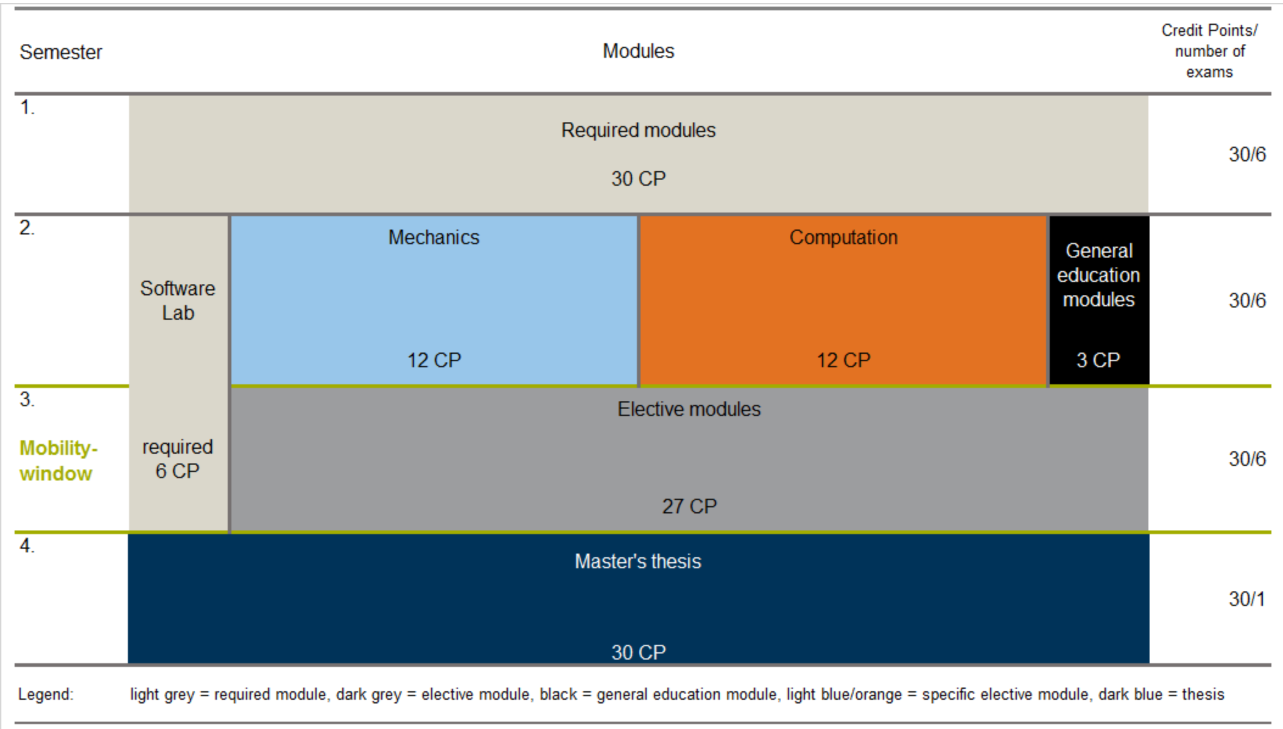

Illustration 2: Degree chart for Computational Mechanics

The academic background of the students of Computational Mechanics varies greatly. By means of the compulsory modules taught in the first semester the students are able to reach the same level of expertise required for successful studies and above all to tailor the needs of industry and research. After participating in the modules Computation in Engineering 1, Computational Material Modelling 1, Continuum Mechanics, Finite Element Method 1 and Advanced Fluid Mechanics the students learn about the most relevant theories, concepts and models and through that gain a solid background in mechanics (solid and fluid) and informatics (core competences). In Computation in

Engineering 1, the students learn about software engineering and object oriented implementation in C++. After participation in Computational Material Modeling 1, the students are able to understand and apply mechanical models for different materials, e.g. linear and non-linear elasticity or various models for plasticity. In Continuum Mechanics the students learn about Tensor Analysis, and formulate the differential equations that govern the deformation of continuous media. In Finite Element Method 1, the students work on the solution of partial differential equations using the Finite Element method and inter alia cover the theoretical formulation, implementation aspects and specific engineering problems. Finally in Advanced Fluid Mechanics, the students learn about the treatment of flow phenomena and how to apply higher mathematics to solve such problems. With this we ensure that the students obtain the necessary foundations in continuum mechanics and fluid mechanics on the one hand, and the numerical solution of therefrom resulting complex differential equations, as stated in Section 2.

The module Software Lab (6 CP) is taught in the second and third semester and builds upon the core fundamentals gained in the first semester. It is an interdisciplinary team project (3-4 students) which links the analysis and solution of engineering problems and the development of software components by processing a complex software project (industrial or research projects). To give the students the opportunity to make contacts in industry and introduce them to industrial issues, co-supervisors from industry are often involved in the assignment and supervision. Through implementing their own software code that solves a typical, yet advanced engineering problem, they gain very strong methodological competences. By requiring intermediate presentations, a realistic, project based work protocol is established, which prepares the students well for later work and research. Through the group-work in small teams, they gain experience in working together in multicultural groups and are sensitized to the importance of dealing with cultural differences.

The two-semester period is also based on the enormous computational effort. The computer clusters may require computing times between several days and weeks between the programming steps. In any case the students must always coordinate and discuss their own implementations in various iterations, which requires a longer project time. In addition, the students are given more time flexibility for processing. For example, they can reduce the workload for the SL during the regular examination phase of the second semester (usually in August and September) and then flexibly increase it again. Furthermore, through the parallel technical modules, students can gain valuable thematic links during the semesters.

The students can easily manage their projects using online tools and hold project meetings in digital form, so processing is also guaranteed during a stay abroad (So in the third semester mobility is possible without compromising the standard duration of study.)

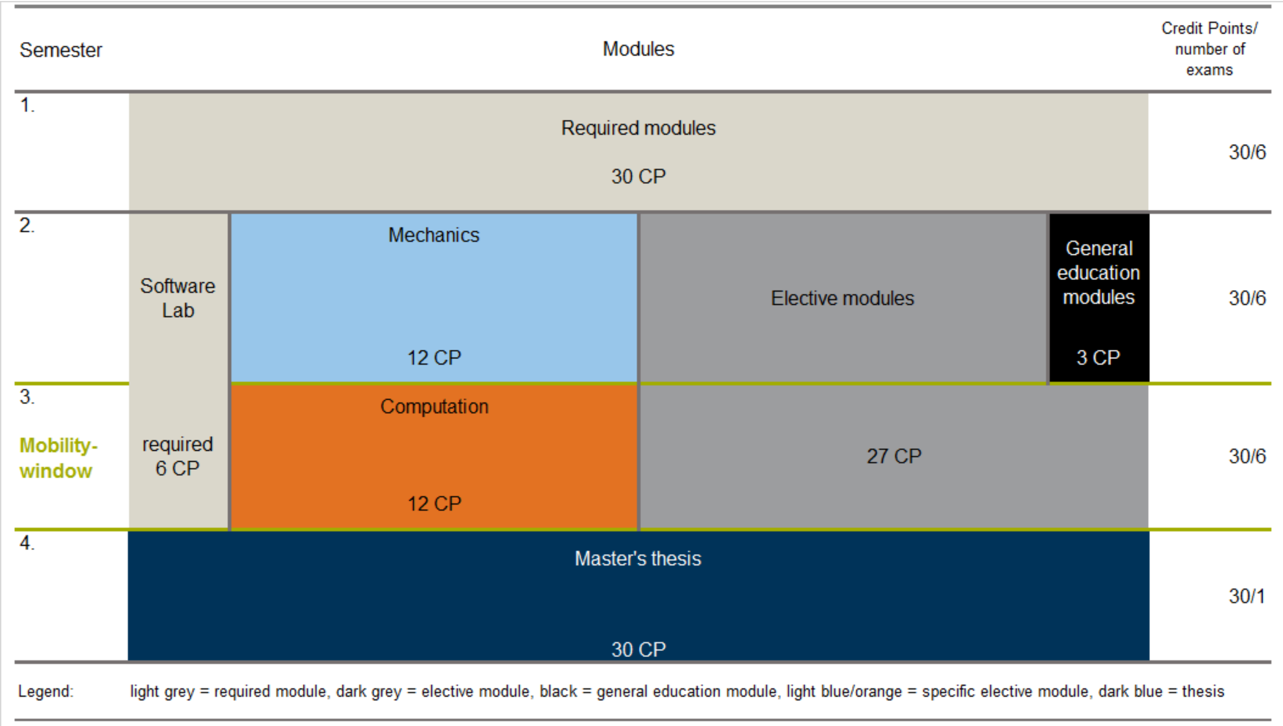

Illustration 3: Degree chart for Computational Mechanics - Alternative

In the second and third semester the students have to gain 12 CP out of the modules in each of the elective module catalogues “Mechanics” and “Computational” (see FPSO or direct link: http://www.bgu.tum.de/en/come/studying/curriculum/). These elective modules are required to specialize the student’s fields of interest and create their own professional profiles. Simultaneously, it maintains a clear degree program profile. These modules also potentially help in selecting an appropriate direction for a Master’s thesis. Furthermore, the students obtain the necessary competences to critically reflect on simulation results and identify numerical artefacts. Through modules in the elective catalogue ‘Mechanics’, the students obtain important competences in the mechanical modeling of engineering problems, whereas modules in the elective catalogue give a deeper understanding on the implementation and solution strategies that are required to solve the formulated mechanical problems. By requiring the students to choose subjects from both catalogues we enable the students to gain competences, that link the fields mathematics, informatics and mechanics. Through modules like ‘Computational Fluid Dynamics’, ‘Structural Dynamics’ or ‘Computational Material Modeling 2’, the students gain competences in the computation of various system responses for complex structures and loading scenarios. Through modules like ‘Finite Element Methods 2’, the students gain deeper fundamental knowledge in the basics of solid and fluid mechanics as well as numerical analysis and its computer implementation. Modules like ‘Artificial Intelligence in Computational Mechanics’ opens the field of Computational Mechanics to new research fields of ever increasing importance. The modules of both of these elective catalogues build upon the core competences taught in the compulsory modules.

Three exemplary degree charts for students with a focus on fluid mechanics or a focus on solid mechanics are shown in Illustration 2, Illustration 3 and Illustration 4.

Semester	Modules						Credits/ number of exams
1.	Computation in Engineering 1 (Required) Written exam + Coursework 6 CP	Computational Material Modeling 1 (Required) Written exam 6 CP	Continuum Mechanics (Required) Written exam 6 CP	Finite Element Methods 1 (Required) Written exam 6 CP	Advanced Fluid Mechanics (Required) Written exam 6 CP		30/6
2.	Software Lab	Finite Element Method 2 (Elective) Written exam + Project work 6 CP	Computational Fluid Dynamics (Elective) Practical requirement 6 CP	Modeling and Simulation of Turbulent Flows (Elective) Written exam 6 CP	Artificial Intelligence in Computational Mechanics (Elective) Written exam 6 CP	General education module (Elective) pass/fail credit requirement 3 CP	30/6
3. **Mobility window**	(Required) Project Work 6 CP	Computational Material Modeling 2 (Elective) Written exam 6 CP	Optimization (Elective) Written exam 6 CP	Risk Analysis (Elective) Project work 6 CP	Vibroaccoustics (Elective) Written exam 6 CP	Modeling and Simulation in Structural Mechanics (Elective) Project work 3 CP	30/6
4.	Master's thesis 30 CP						30/1

Legend: light grey = required module, dark grey = elective module, black = general education module, light blue/orange = specific elective module, dark blue = thesis

Illustration 4: Degree chart example 1, with broad elective spectrum

Altogether, the different degree charts show that the students can flexibly choose combinations of different modules, which is important to guarantee a stay abroad, while the two specialized elective catalogues make sure that all students gain specific required competences in industry and research.

Semester	Modules						Credits/ number of exams
1.	Computation in Engineering 1 (Required) Written exam + Coursework 6 CP	Computational Material Modeling 1 (Required) Written exam 6 CP	Continuum Mechanics (Required) Written exam 6 CP	Finite Element Methods 1 (Required) Written exam 6 CP	Advanced Fluid Mechanics (Required) Written exam 6 CP		30/6
2.	Software Lab	Computational Fluid Dynamics (Elective) Practical requirement 6 CP	Structural Dynamics (Elective) Written exam 6 CP	Modeling and Simulation of Turbulent Flows (Elective) Written exam 6 CP	Computation in Engineering 2 (Elective) Written exam + Project work 6 CP	General education module (Elective) pass/fail credit requirement 3 CP	30/6
3. Mobility window	(Required) Project Work 6 CP	Optimization (Elective) Written exam 6 CP	Functional Analysis & Computational Linear Algebra (Elective) Written exam 6 CP	Structural Wind Engineering (Elective) Project work 6 CP	Vibroacoustics (Elective) Written exam 6 CP	Modeling and Simulation in Structural Mechanics (Elective) Project work 3 CP	30/6
4.	Master's thesis 30 CP						30/1

Legend: light grey = required module, dark grey = elective module, black = general education module, light blue/orange = specific elective module, dark blue = thesis

Illustration 5: Degree Chart example 2, with focus on fluid mechanics

Semester	Modules						Credits/ number of exams
1.	Computation in Engineering 1 (Required) Written exam + Coursework 6 CP	Computational Material Modeling 1 (Required) Written exam 6 CP	Continuum Mechanics (Required) Written exam 6 CP	Finite Element Methods 1 (Required) Written exam 6 CP	Advanced Fluid Mechanics (Required) Written exam 6 CP		30/6
2.	Software Lab	Computational Fluid Dynamics (Elective) Practical requirement 6 CP	Structural Dynamics (Elective) Written exam 6 CP	Finite Element Method 2 (Elective) Written exam + Project work 6 CP	Artificial Intelligence in Computational Mechanics (Elective) Written exam 6 CP	General education module (Elective) pass/fail credit requirement 3 CP	30/6
3. Mobility window	(Required) Project Work 6 CP	Risk Analysis (Elective) Project work 6 CP	Functional Analysis & Computational Linear Algebra (Elective) Written exam 6 CP	Structural Wind Engineering (Elective) Project work 6 CP	Vibroacoustics (Elective) Written exam 6 CP	Modeling and Simulation in Structural Mechanics (Elective) Project work 3 CP	30/6
4.	Master's thesis 30 CP						30/1

Legend: light grey = required module, dark grey = elective module, black = general education module, light blue/orange = specific elective module, dark blue = thesis

Illustration 6: Degree chart example 3, with focus on structural mechanics

The elective modules allow getting a wide knowledge in different disciplines as they can be chosen also from other related TUM schools or departments as civil engineering, mechanical engineering or informatics up to 10 CP. The students are also free to deepen their knowledge within this catalogue and thus get even more knowledge in solid or fluid mechanics, programming or industrial applications, thus sharpening their individual professional profiles. The elective modules also tackle more research-oriented topics and enable the students to work on highly relevant problems, which opens them to identifying and articulating their own research questions. By this, they are prepared to continue their work in research and academia, where they can receive doctoral positions. The list of possible elective modules is subject to change in order to meet the requirements of the industry and the fields of interest of the students. It can be found (always up to date) on the webpage of the program, see https://www.bgu.tum.de/en/come/studying/curriculum/. Students are informed about the update prior to semester start. Furthermore, the students need to select a general education module with 3 CP during their studies to enhance the students' self-competences or soft skills. A catalogue with suitable and accepted modules, such as language courses or modules from Carl-von-Linde academy, is also published on the webpage of the program.

The master's thesis takes 6 months and can be written either at the chairs involved in Computational Mechanics or in cooperation with industry or other academic partners (i.e. Frauenhofer Institute). The students always need a supervisor at one of the chairs involved in Computational Mechanics. Often, the master's thesis opens the doors to a PhD-position at the university or a job offer in industry after graduation.

The examination types have a wide range in order to enable the students to gain all required competences within the Master's program. These include the competence to present their work, which is taught through smaller modules like "Modelling and Simulation in Structural Mechanics" and also through the Master's Thesis. Furthermore, through a couple of smaller project works, as within the module "Computation in Engineering 1" or the examination type "practical credit requirement" in the module "Computational Fluid Mechanics (CFD)" we make sure that the students have valuable hands-on experience in computer programming. The competence to critically reflect on the simulation results and structural or fluid system prediction is taught inherently within most of the modules in the curriculum.

Modules in the field of Computational Mechanics which are obtained during the master's program at another university (e.g. during an international exchange) can be recognized.

TUM is offering five different types of exchange programs for Computational Mechanics students:

- Erasmus-Program (studies within Europe)
- TUMexchange (studies outside Europe)
- EU Mobility Programs (studies in selected regions outside the European Union (EU))
- ATHENS (one-week courses within Europe)
- 1:1 MSc program in Computational Mechanics (jointly with DTU)

Especially the ATHENS program - which is offered twice a year - attracted many of the COME students in the last years. The compulsory module "Software lab" within the second and third semester is designed that way, that students are still able to go abroad or perform exchange studies within another German university. So the module can be done online and also the examination, a project work, can be handed in and be presented digitally. Thereby an unrestricted mobility without extended study times is made possible.

In the last years not many students were interested to go abroad since many of the students especially come to Germany to join the program. And so, there is not as much interest in studies abroad as in other degree programs. Still, a stay abroad or at another German university is supported and possible.

In 2006 Technical University of Denmark (DTU) and TUM entered the *European University Alliance in Science and Technology – a contract between universities of excellence*. Together the universities have developed a novel concept for English taught two-year Master of Science programs called 1:1 MSc programs because the students spend one year at each university (DTU and TUM). Since 2010 a 1:1 MSc program in Computational Mechanics is offered. Each Master of Science program consists of four semesters. This represents a workload equivalent to 120 CP. The DTU-TUM 1:1 MSc program is a single degree program where the graduate obtains a diploma from either TUM or DTU depending on where the student is enrolled. Starting at TUM the academic degree *"Master of Science"* (M.Sc.) is awarded upon successful completion of the Computational Mechanics degree program. Based on a recommended degree chart, each student admitted to the DTU-TUM 1:1 MSc degree program works out an individual curriculum together with the responsible supervisors at the partner universities. The final curriculum has to be approved by the respective DTU-TUM 1:1 Program Committee. The student composes a master's thesis of 30 CP. The thesis work is supervised by two researchers (one from each university). The thesis is presented at the university where the thesis work was done in the presence of both supervisors and an external examiner. Admission requirements to join the DTU – TUM 1:1 MSc program are:

- Students starting the 1:1 program at TUM must be enrolled in the COME master’s program.
- Eligibility must be demonstrated by a successful completion of the compulsory modules of the first semester and an above-average grade point average.

For the formal design of the degree program (module size, exam design) the Ländergemeinsame Strukturvorgaben ("Common Structural Guidelines") were considered. The study plans verify the ability to study the degree program. The modules, especially in the compulsory catalogue, mostly have an extent of a minimum of 5 CP. Deviations occur for the general education modules (3 CP) and in the technical modules. In the last, we explicitly also list smaller modules besides the modules with larger extent to give the students specialized insight into different areas of structural and fluid mechanics. Additionally, we aim at allowing for a higher degree of flexibility in the study design. In the exemplary study plans, we therefore enter a 3 CP elective module in the third semester, at the same time the maximum number of examinations of 6 exams per semester is not exceeded.

7 Organization and Coordination

The Master's Program in Computational Mechanics is offered at the Department of Civil, Geo and Environmental Engineering of the Technical University of Munich, where it is jointly taught by professors of the Focus Area "Modeling-Simulation-Processes". Following chairs (professors) are mainly involved in the teaching of the degree program:

- Computation in Engineering (Prof. Rank)
- Structural Analysis (Prof. Bletzinger)
- Computational Mechanics (Prof. Müller)
- Computational Mechanics (Prof. Duddeck)
- Hydromechanics (Prof. Manhart)

Several elective modules can be attended at the Department of Mechanical Engineering and the Department of Informatics. As it is an interdisciplinary degree program many other chairs and departments of the TUM are involved.

The following administrative tasks are performed by:

- Student Advising:
  TUM Center for Study and Teaching (TUM-CST),
  Student Advising and Prospective Student Programs
  Email: studium@tum.de
  Phone: +49 (0)89 289 22245
  Provides information and advising for
  prospective and current students
  (via hotline/service desk)
- Departmental Student Advising:
  Program Coordinators and Academic Advisors
  Corinna Schmaußer M. Sc.
  Felix Schneider M.Sc.
  Email: corinna.schmaußer@tum.de
  felix.w.schneider@tum.de
  Phone: +49 (0)89 289 22458
  +49 (0)89 289 28393
- Academic Programs Office:
  Examination Administration and Advising
  Christine Göppel
  Email: christine.goeppel@tum.de
  Phone: +49 (0)89 289 28194
- Study Abroad Advising/Internationalization:
  TUM-wide: TUM International Center,
  internationalcenter@tum.de
  Departmental: International Affairs Delegate
  Nadin Klomke, M.A.

Email: n.klomke@tum.de
Phone: : +49 (0)89 289 22427

- Gender Equality Officer: TUM-wide: Dr. Eva Sandmann
  Email: sandmann@tum.de
  Phone: +49 (0)89 289 22335
  Departmental: Dr.-Ing. Annette Spengler
  Email: annette.spengler@tum.de
  Phone: +49 (0)89 289 27102
  Prof. Dr.-Ing. Markus Disse
  Email: markus.disse@tum.de
  Phone: +49 (0)89 289 23916
- Advising – Barrier-Free Education: TUM-wide: Office for Disabled and Chronically Ill Students (TUM CST)
  Email: Handicap@zv.tum.de
  Phone: +49 (0)89 289 22737
  Departmental: Dipl.-Ing. Michaela Wenzel
  Email: m.wenzel@tum.de
  Phone: +49 (0)89 289 25261
- Admissions and Enrollment: Advising and Information (TUM CST), Admissions and Enrollment
  Email: studium@tum.de
  Phone: +49 (0)89 289 22245
  Admissions, enrollment
  StudentCard, leaves of absence,
  student fees payment, withdrawal
- Aptitude Assessment (EV): TUM-wide: Advising and Information (TUM CST), Admissions and Enrollment
  Departmental: Aptitude Assessment Commission,
  Chair: Prof. Dr.-Ing. Gerhard Müller
  Program coordinators:
  Corinna Schmaußer M.Sc.
  Felix Schneider M.Sc.
  Email: corinna.schmaußer@tum.de
  felix.w.schneider@tum.de
  Phone: +49 (0)89 289 22458
  +49 (0)89 289 28393
- Semester Fees and Scholarships: Advising and Information (TUM CST), Semester Fees Management
  Email: beitragsmanagement@zv.tum.de
- Examination Office: Central Examination Office (TUM CST)
  Campus Munich
  Graduation documents, notifications of examination results, preliminary degree certificates

- Departmental Examination Office: Christine Göppel
  Email: christine.goeppel@tum.de
  Phone: +49 (0)89 289 28194
- Examination Board: Prof. Dr.-Ing. Gerhard Müller (Chair)
  Christine Göppel (Secretary)
- Quality Management – Academic and Student Affairs:
  TUM-wide: Quality Management (TUM CST)
  www.lehren.tum.de/startseite/team-cst/
  Departmental: Consultants for Studies and Teaching
  Dr. Lars Fuchs, lars.fuchs@tum.de
  Dipl.-Ing. Sandra Spindler, sandra.spindler@tum.de
  Prof. Dr. Stephan Freudenstein (Dean of Studies)
  Organization QM Circle: Dipl.-Ing. Sandra Spindler,
  sandra.spindler@tum.de

8 Enhancement Measures

The program has been adapted to changing boundary conditions several times since its foundation in the year 2000. As the boundary conditions change, also the program has to be modified continuously. The boundary conditions are defined by the requisites of the Bavarian Universitisy Act (German: Bayerisches Hochschulgesetz, BayHSchG). The specifications enacted by the German Standing Conference of the Ministers of Education and Cultural Affairs (German: Kultusministerkonferenz, KMK) and the accreditation.

Examples for recently adapted boundary conditions are the maximum number of examinations per semester or minimum number of credits per module. Furthermore, issues formulated by students (and their representatives) in different boards of the department (Studienkommission, Fakultätsrat, Qualitätszirkel) are discussed and finally brought into the structure of the program. Furthermore, the curriculum was adapted and the required-elective catalogues were reorganized into elective catalogues representing mechanics and computational-oriented modules in order to implement a clearer structure. We introduced the module “Artificial Intelligence in Engineering” as a computational elective module to take account of this increasingly important aspect in computational science. Also, we made sure that the mobility window can be used without any barriers to increase student mobility.

Furthermore, we are constantly striving to include diverse, modern and innovative forms of teaching and examination within the program.