Operations Research with Engineering

Degrees Offered
- Master of Science in Operations Research with Engineering (Non-Thesis)
- Doctor of Philosophy in Operations Research with Engineering

Program Description
Operations Research (OR) involves mathematically modeling physical systems (both naturally occurring and man-made) with a view to determining a course of action for the system to either improve or optimize its functionality. Examples of such systems include, but are not limited to, manufacturing systems, chemical processes, socio-economic systems, mechanical systems (e.g., those that produce energy), and mining systems.

Program Requirements

Master of Science in Operations Research with Engineering (Non-Thesis)

Core Courses
- ORWE courses not taken as core courses 12.0
- Total 30.0

All Masters students are required to take a set of core courses (18 hours) that provides basic tools for the more advanced and specialized courses in the program as specified below.

- MATH530 INTRODUCTION TO STATISTICAL METHODS 3.0
- MATH531 THEORY OF LINEAR MODELS 3.0
- ORWE586 LINEAR OPTIMIZATION 3.0
  or ORWE585 NETWORK MODELS 3.0
- MATH438/538 STOCHASTIC MODELS 3.0
  Course may be substituted with Math 4XX Computational Linear Algebra
- ORWE587 NONLINEAR OPTIMIZATION 3.0
  or ORWE588 INTEGER OPTIMIZATION 3.0
- MEGN502 ADVANCED ENGINEERING ANALYSIS 3.0
  or CSCI406 ALGORITHMS 3.0
  or CEEN405 NUMERICAL METHODS FOR ENGINEERS 3.0
  or CEEN505 NUMERICAL METHODS FOR ENGINEERS 3.0

The remaining 12 hours of coursework can be completed with any ORWE-labeled course not taken as core. Or, specialty tracks can be added in areas, for example, including: (i) operations research methodology; (ii) systems engineering; (iii) computer science; (iv) finance and economics; and (v) an existing engineering discipline that is reflected in a department name such as electrical, civil, environmental, or mining engineering.

Examples of specialty tracks from various departments across campus are given below:

Energy Systems within Mechanical Engineering Track (12 hours from the course list below)
- MEGN461 THERMODYNAMICS II 3.0
- MEGN567 PRINCIPLES OF BUILDING SCIENCE 3.0
- MEGN583/AMFG501 ADDITIVE MANUFACTURING 3.0
- MEGN570 ELECTROCHEMICAL SYSTEMS ENGINEERING 3.0
- MEGN560 DESIGN AND SIMULATION OF THERMAL SYSTEMS 3.0

Additive Manufacturing Track (12 hours from the course list below)*

- Subject to approval by graduate council
- AMFG511 DATA DRIVEN ADVANCED MANUFACTURING 3.0
- MEGN583/AMFG501 ADDITIVE MANUFACTURING 3.0
- AMFG531 MATERIALS FOR ADDITIVE MANUFACTURING 3.0
- AMFG421/521 DESIGN FOR ADDITIVE MANUFACTURING 3.0

Applied Mathematics and Statistics Track (12 hours from the course list below)

- MATH500 LINEAR VECTOR SPACES 3.0
- MATH532 SPATIAL STATISTICS 3.0
- MATH536 ADVANCED STATISTICAL MODELING 3.0
- MATH537/538 MULTIVARIATE ANALYSIS 3.0
- MATH438/538 STOCHASTIC MODELS 3.0
- MATH551 COMPUTATIONAL LINEAR ALGEBRA 3.0
- EENG511 CONVEX OPTIMIZATION AND ITS ENGINEERING APPLICATIONS 3.0

Economics Track (12 hours from the course list below)

- EBGN509 MATHEMATICAL ECONOMICS 3.0
- EBGN510 NATURAL RESOURCE ECONOMICS 3.0
- EBGN530 ECONOMICS OF INTERNATIONAL ENERGY MARKETS 3.0
- EBGN535 ECONOMICS OF METAL INDUSTRIES AND MARKETS 3.0
- EBGN590 ECONOMETRICS I 3.0
- EBGN645 COMPUTATIONAL ECONOMICS 3.0
- CSCI555 GAME THEORY AND NETWORKS 3.0

Business Track (12 hours from the course list below)

- ORWE559 SUPPLY CHAIN MANAGEMENT 3.0
- EBGN560 DECISION ANALYTICS 3.0
- EBGN571 MARKETING ANALYTICS 3.0
- EBGN562 STRATEGIC DECISION MAKING 3.0

Students who do not wish to specialize in a track mentioned in the table below and do not wish to complete 12 additional hours of ORWE-labeled coursework can "mix and match" from the ORWE coursework and coursework mentioned in the tables below in consultation with and approval from their academic advisers.
### Computer Science Track (12 hours from the course list below)

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSCI542</td>
<td>SIMULATION</td>
<td>3.0</td>
</tr>
<tr>
<td>CSCI562</td>
<td>APPLIED ALGORITHMS AND DATA STRUCTURES</td>
<td>3.0</td>
</tr>
<tr>
<td>CSCI571</td>
<td>ARTIFICIAL INTELLIGENCE</td>
<td>3.0</td>
</tr>
<tr>
<td>CSCI575</td>
<td>ADVANCED MACHINE LEARNING</td>
<td>3.0</td>
</tr>
<tr>
<td>CSCI555</td>
<td>GAME THEORY AND NETWORKS</td>
<td>3.0</td>
</tr>
</tbody>
</table>

### Civil Engineering - Geotechnics Track (12 hours from the course list below)

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEEN506</td>
<td>FINITE ELEMENT METHODS FOR ENGINEERS</td>
<td>3.0</td>
</tr>
<tr>
<td>CEEN5XX</td>
<td>RISK ASSESSMENT IN GEOTECHNICAL ENGINEERING</td>
<td>3.0</td>
</tr>
<tr>
<td>CEEN510</td>
<td>ADVANCED SOIL MECHANICS</td>
<td>3.0</td>
</tr>
<tr>
<td>CEEN511</td>
<td>UNSATURATED SOIL MECHANICS</td>
<td>3.0</td>
</tr>
<tr>
<td>CEEN512</td>
<td>SOIL BEHAVIOR</td>
<td>3.0</td>
</tr>
<tr>
<td>CEEN515</td>
<td>HILLSLOPE HYDROLOGY AND STABILITY</td>
<td>3.0</td>
</tr>
</tbody>
</table>

### Civil Engineering-Structures Track (12 hours from the course list below)

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEEN506</td>
<td>FINITE ELEMENT METHODS FOR ENGINEERS</td>
<td>3.0</td>
</tr>
<tr>
<td>CEEN530</td>
<td>ADVANCED STRUCTURAL ANALYSIS</td>
<td>3.0</td>
</tr>
<tr>
<td>CEEN531</td>
<td>STRUCTURAL DYNAMICS</td>
<td>3.0</td>
</tr>
<tr>
<td>CEEN533</td>
<td>MATRIX STRUCTURAL ANALYSIS</td>
<td>3.0</td>
</tr>
<tr>
<td>CEEN543</td>
<td>CONCRETE BRIDGE DESIGN BASED ON THE AASHTO LRFD SPECIFICATIONS</td>
<td>3.0</td>
</tr>
<tr>
<td>CEEN545</td>
<td>STEEL BRIDGE DESIGN</td>
<td>3.0</td>
</tr>
</tbody>
</table>

### Electrical Engineering-Energy Systems and Power Electronics Track (12 hours from the course list below)

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EENG570</td>
<td>ADVANCED HIGH POWER ELECTRONICS</td>
<td>3.0</td>
</tr>
<tr>
<td>EENG580</td>
<td>POWER DISTRIBUTION SYSTEMS ENGINEERING</td>
<td>3.0</td>
</tr>
<tr>
<td>EENG581</td>
<td>POWER SYSTEM OPERATION AND MANAGEMENT</td>
<td>3.0</td>
</tr>
<tr>
<td>EENG583</td>
<td>ADVANCED ELECTRICAL MACHINE DYNAMICS</td>
<td>3.0</td>
</tr>
</tbody>
</table>

### Electrical Engineering-Information and Systems Sciences Track (12 hours from the course list below)

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EENG509</td>
<td>SPARSE SIGNAL PROCESSING</td>
<td>3.0</td>
</tr>
<tr>
<td>EENG511</td>
<td>CONVEX OPTIMIZATION AND ITS ENGINEERING APPLICATIONS</td>
<td>3.0</td>
</tr>
<tr>
<td>EENG515</td>
<td>MATHEMATICAL METHODS FOR SIGNALS AND SYSTEMS</td>
<td>3.0</td>
</tr>
<tr>
<td>EENG517</td>
<td>THEORY AND DESIGN OF ADVANCED CONTROL SYSTEMS</td>
<td>3.0</td>
</tr>
<tr>
<td>EENG519</td>
<td>ESTIMATION THEORY AND KALMAN FILTERING</td>
<td>3.0</td>
</tr>
<tr>
<td>EENG527</td>
<td>WIRELESS COMMUNICATIONS</td>
<td>3.0</td>
</tr>
<tr>
<td>EENG589</td>
<td>DESIGN AND CONTROL OF WIND ENERGY SYSTEMS</td>
<td>3.0</td>
</tr>
<tr>
<td>MEGN544</td>
<td>ROBOT MECHANICS: KINEMATICS, DYNAMICS, AND CONTROL</td>
<td>3.0</td>
</tr>
</tbody>
</table>

### Mining and Earth Systems Track (12 hours from the course list below)

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>MNGN5XX</td>
<td>Big Data Analytics for Earth Resources Sciences and Engineering</td>
<td>3.0</td>
</tr>
<tr>
<td>MNGN512</td>
<td>SURFACE MINE DESIGN</td>
<td>3.0</td>
</tr>
<tr>
<td>MNGN516</td>
<td>UNDERGROUND MINE DESIGN</td>
<td>3.0</td>
</tr>
<tr>
<td>MNGN536</td>
<td>OPERATIONS RESEARCH TECHNIQUES IN THE MINERAL INDUSTRY</td>
<td>3.0</td>
</tr>
<tr>
<td>MNGN539</td>
<td>ADVANCED MINING GEOSTATISTICS</td>
<td>3.0</td>
</tr>
</tbody>
</table>

### Doctor of Philosophy in Operations Research with Engineering


### Specialty Requirements

Doctoral students develop a customized curriculum to fit their needs. The degree requires a minimum of 72 graduate credit hours that includes coursework and a thesis. Coursework is valid for nine years towards a PhD degree; any exceptions must be approved by the Director of the ORwE program and by the student's adviser.
Credit requirements

Core Courses 24.0
Area of Specialization Courses 12.0
Any Combination of Specialization Courses or Research 12.0
Research Credits 24.0
Total Semester Hrs 72.0

Research Credits

Students must complete at least 24.0 hours of research credits. The student's faculty adviser and the doctoral thesis committee must approve the student's program of study and the topic for the thesis.

Qualifying Examination Process and Thesis Proposal

Upon completion of the appropriate core coursework, students must pass Qualifying Exams I (written, over four courses) and II (oral, consisting of a report and research presentation) to become a candidate for the PhD, ORwE specialty. Qualifying Exam I is generally taken no later than three semesters after entry into the PhD program, and Qualifying Exam II follows no more than two semesters after having passed Qualifying Exam I. The proposal defense should be completed within ten months of passing Qualifying Exam II.

Transfer Credits

Students may transfer up to 24.0 hours of graduate-level coursework from other institutions toward the PhD degree subject to the restriction that those courses must not have been used as credit toward a Bachelor's degree. The student must have achieved a grade of B or better in all graduate transfer courses and the transfer must be approved by the student's doctoral thesis committee and the Director of the ORwE program.

Although most doctoral students will only be allowed to transfer up to 24 credits, with approval from the student’s doctoral committee, exceptions may be made to allow students who have earned a specialized thesis-based master’s degree in operations research or other closely related field from another university to transfer up to 36 credits in recognition of the degree. Students should consult with their academic advisors and ORwE director for details.

Unsatisfactory Progress

In addition to the institutional guidelines for unsatisfactory progress as described elsewhere in this bulletin: Unsatisfactory progress will be assigned to any full-time student who does not pass the following prerequisite and core courses in the first three semesters of study:

CSCI262 DATA STRUCTURES 3.0
ORWE586 LINEAR OPTIMIZATION 3.0
MATH530 INTRODUCTION TO STATISTICAL METHODS 3.0
CSCI406 ALGORITHMS 3.0

Unsatisfactory progress will also be assigned to any students who do not complete requirements as specified in their admission letters. Any exceptions to the stipulations for unsatisfactory progress must be approved by the ORwE committee. Part-time students develop an approved course plan with their advisor.

Prerequisites

Students must complete the following undergraduate prerequisite courses with a grade of B or better:

CSCI261 PROGRAMMING CONCEPTS 3.0
CSCI262 DATA STRUCTURES 3.0

Required Course Curriculum

All PhD students are required to take a set of core courses that provides basic tools for the more advanced and specialized courses in the program.

Core Courses

CSCI406 ALGORITHMS 3.0
MEGN502 ADVANCED ENGINEERING ANALYSIS 3.0
ORWE586 LINEAR OPTIMIZATION 3.0
MATH530 INTRODUCTION TO STATISTICAL METHODS 3.0
MATH438 STOCHASTIC MODELS 3.0
ORWE585 NETWORK MODELS 3.0
ORWE588 INTEGER OPTIMIZATION 3.0
ORWE587 NONLINEAR OPTIMIZATION 3.0
Total Semester Hrs 24.0

Students are required to take four courses from the following list:

Area of Specialization Courses

EBGN528 INDUSTRIAL SYSTEMS SIMULATION 3.0
or MATH542 SIMULATION 3.0
or CSCI542 SIMULATION 3.0
CSCI555 GAME THEORY AND NETWORKS 3.0
MATH532 SPATIAL STATISTICS 3.0
MATH537 MULTIVARIATE ANALYSIS 3.0
MATH582 STATISTICS PRACTICUM 3.0
MEGN592 RISK AND RELIABILITY ENGINEERING 3.0
ANALYSIS AND DESIGN
ORWE688 ADVANCED INTEGER OPTIMIZATION 3.0
MTGN450/MLGN550 STATISTICAL PROCESS CONTROL AND 3.0
DESIGN OF EXPERIMENTS
EBGN560 DECISION ANALYTICS 3.0
EENG517 THEORY AND DESIGN OF ADVANCED 3.0
CONTROL SYSTEMS
CSCI562 APPLIED ALGORITHMS AND DATA 3.0
STRUCTURES
ORWE686 ADVANCED LINEAR OPTIMIZATION 3.0
MNGN536 OPERATIONS RESEARCH TECHNIQUES IN 3.0
THE MINERAL INDUSTRY
MNGN538 GEOSTATISTICAL ORE RESERVE ESTIMATION 3.0
EBGN509 MATHEMATICAL ECONOMICS 3.0
EBGN575 ADVANCED MINING AND ENERGY ASSET 3.0
VALUATION
MATH531 THEORY OF LINEAR MODELS 3.0
5XX/6XX Special Topics (Requires approval of the advisor 3.0
and ORwE program director)
Mines’ Combined Undergraduate / graduate Degree Program

Students enrolled in Mines’ combined undergraduate/graduate program may double count up to six hours of credits which were used in fulfilling the requirements of their undergraduate degree at Mines, towards their graduate program. Any 400+ level courses that count towards the undergraduate degree requirements as “Elective Coursework” or any 500+ level course, may be used for the purposes of double counting at the discretion of the graduate advisor. These courses must have been passed with a "B-" or better, not be substitutes for required coursework, and meet all other University, Department, Division, and Program requirements for graduate credit.

Courses

ORWE559. SUPPLY CHAIN MANAGEMENT. 3.0 Semester Hrs.
(I) Due to the continuous improvement of information technology, shorter life cycle of products, rapid global expansion, and growing strategic relationships, supply chain management has become a critical asset in today’s organizations to stay competitive. The supply chain includes all product, service and information flow from raw material suppliers to end customers. This course focuses on the fundamental concepts and strategies in supply chain management such as inventory management and risk pooling strategies, distribution strategies, make-to-order/make-to-stock supply chains, supplier relationships and strategic partnerships. It introduces quantitative tools to model, optimize and analyze various decisions in supply chains as well as real-world supply chain cases to analyze the challenges and solutions. 3 hours lecture; 3 semester hours.

ORWE585. NETWORK MODELS. 3.0 Semester Hrs.
(I) We examine network flow models that arise in manufacturing, energy, mining, transportation and logistics: minimum cost flow models in transportation, shortest path problems in assigning inspection effort on a manufacturing line, and maximum flow models to allocate machine-hours to jobs. We also discuss an algorithm or two applicable to each problem class. Computer use for modeling (in a language such as AMPL) and solving (with software such as CPLEX) these optimization problems is introduced. 3 hours lecture; 3 semester hours.

ORWE586. LINEAR OPTIMIZATION. 3.0 Semester Hrs.
(I) We address the formulation of linear programming models, linear programs in two dimensions, standard form, the Simplex method, duality theory, complementary slackness conditions, sensitivity analysis, and multi-objective programming. Applications of linear programming models include, but are not limited to, the areas of manufacturing, energy, mining, transportation and logistics, and the military. Computer use for modeling (in a language such as AMPL) and solving (with software such as CPLEX) these optimization problems is introduced. Offered every other year. 3 hours lecture; 3 semester hours.

ORWE587. NONLINEAR OPTIMIZATION. 3.0 Semester Hrs.
(I) This course addresses both unconstrained and constrained nonlinear model formulation and corresponding algorithms (e.g., Gradient Search and Newton’s Method, and Lagrange Multiplier Methods and Reduced Gradient Algorithms, respectively). Applications of state-of-the-art hardware and software will emphasize solving real-world engineering problems in areas such as manufacturing, energy, mining, transportation and logistics, and the military. Computer use for modeling (in a language such as AMPL) and solving (with an algorithm such as MINOS) these optimization problems is introduced. Offered every other year. 3 hours lecture; 3 semester hours.

ORWE588. INTEGER OPTIMIZATION. 3.0 Semester Hrs.
(I) This course addresses the formulation of integer programming models, the branch-and-bound algorithm, total unimodularity and the ease with which these models are solved, and then suggest methods to increase tractability, including cuts, strong formulations, and decomposition techniques, e.g., Lagrangian relaxation, Benders decomposition. Applications include manufacturing, energy, mining, transportation and logistics, and the military. Computer use for modeling (in a language such as AMPL) and solving (with software such as CPLEX) these optimization problems is introduced. Offered every other year. 3 hours lecture; 3 semester hours.

ORWE686. ADVANCED LINEAR OPTIMIZATION. 3.0 Semester Hrs.
(II) As an advanced course in optimization, we expand upon topics in linear programming: advanced formulation, the dual simplex method, the interior point method, algorithmic tuning for linear programs (including numerical stability considerations), column generation, and Dantzig-Wolfe decomposition. Time permitting, dynamic programming is introduced. Applications of state-of-the-art hardware and software emphasize solving real-world problems in areas such as manufacturing, mining, energy, transportation and logistics, and the military. Computers are used for model formulation and solution. Offered every other year. Prerequisite: MEGN586. 3 hours lecture; 3 semester hours.

ORWE688. ADVANCED INTEGER OPTIMIZATION. 3.0 Semester Hrs.
(II) As an advanced course in optimization, we expand upon topics in integer programming: advanced formulation, strong integer programming formulations (e.g., symmetry elimination, variable elimination, persistence), in-depth mixed integer programming cuts, rounding heuristics, constraint programming, and decompositions. Applications of state-of-the-art hardware and software emphasize solving real-world problems in areas such as manufacturing, mining, energy, transportation and logistics, and the military. Computers are used for model formulation and solution. Prerequisite: MEGN588. 3 hours lecture; 3 semester hours.

Director and Professor
Alexandra Newman