Operations Research with Engineering

Program Description

Operations Research 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: manufacturing systems, chemical processes, socioeconomic systems, mechanical systems (e.g., those that produce and utilize energy and materials), and mining systems. The ORwE Program allows students to complete an interdisciplinary master's (non-thesis) or doctoral-level degree by taking courses and conducting research in the following departments and divisions: Applied Mathematics and Statistics, Civil and Environmental Engineering, Electrical Engineering, Computer Science, Economics and Business, Mining Engineering, Mechanical Engineering, and Metallurgical & Materials Engineering. Operations Research presence at Mines is ubiquitous, especially in Mines' focus areas of earth, energy and the environment.

Student Learning Outcomes

- Apply principles of optimization, stochastic modeling and simulation to real-world engineering situations.
- Mathematically formulate operations research models.
- Use state-of-the-art software to determine solutions to optimization, stochastics and simulation models.

Contact

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Program Website

Program Requirements

Master of Science in Operations Research with Engineering (non-thesis)

Core Courses	18.0
ORWE courses not taken as core courses	12.0
Total	30.0

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

MEGN502	ADVANCED ENGINEERING ANALYSIS	3.0
or ORWE598	ALGORITHMS FOR OPERATIONS RESEARCH	
or CEEN505	NUMERICAL METHODS FOR ENGINEERS	
EBGN526	STOCHASTIC MODELS IN MANAGEMENT SCIENCE	3.0
or MATH538	STOCHASTIC MODELS	
EBGN528	INDUSTRIAL SYSTEMS SIMULATION	3.0
MATH530	INTRODUCTION TO STATISTICAL METHODS	3.0
ORWE586	LINEAR OPTIMIZATION	3.0
or ORWE585	NETWORK MODELS	

ORWE587	NONLINEAR OPTIMIZATION	3.0
or ORWE588	INTEGER OPTIMIZATION	

The remaining 12 credits 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: 1) operations research methodology, 2) systems engineering, 3) computer science, 4) finance and economics, and 5) an existing engineering discipline that is reflected in a department name such as electrical, civil, environmental, or mining engineering.

Students who do not wish to specialize in a track mentioned in the table below and do not wish to complete 12 additional credits of ORWElabeled 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.

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

Energy Systems within Mechanical Engineering Track (12 credits from the course list below)

MEGN567	PRINCIPLES OF BUILDING SCIENCE	
AMFG501	ADDITIVE MANUFACTURING	3.0
MEGN570	ELECTROCHEMICAL SYSTEMS ENGINEERING	
MEGN560	DESIGN AND SIMULATION OF THERMAL SYSTEMS	3.0
MEGN561	ADVANCED ENGINEERING THERMODYNAMICS	3.0

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

*Subject to approval by graduate council

AMFG511	DATA DRIVEN ADVANCED MANUFACTURING	3.0
AMFG521	DESIGN FOR ADDITIVE MANUFACTURING	3.0
AMFG531	MATERIALS FOR ADDITIVE MANUFACTURING	3.0
AMFG501	ADDITIVE MANUFACTURING	3.0

Applied Mathematics and Statistics Track (12 credits 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
MATH551	COMPUTATIONAL LINEAR ALGEBRA	3.0
EENG511	CONVEX OPTIMIZATION AND ITS ENGINEERING APPLICATIONS	

Economics Track (12 credits from the course list below)

EBGN509	MATHEMATICAL ECONOMICS	3.0
EBGN510	NATURAL RESOURCE ECONOMICS	3.0
EBGN530	ECONOMICS OF INTERNATIONAL ENERGY	3.0
	MARKETS	

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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 credits 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

Computer Science Track (12 credits from the course list below)

CSCI542	SIMULATION	3.0
CSCI562	APPLIED ALGORITHMS AND DATA STRUCTURES	3.0
CSCI571	ARTIFICIAL INTELLIGENCE	3.0
CSCI575	ADVANCED MACHINE LEARNING	3.0
CSCI555	GAME THEORY AND NETWORKS	3.0

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

CEEN506	FINITE ELEMENT METHODS FOR ENGINEERS	3.0
CEEN510	ADVANCED SOIL MECHANICS	3.0
CEEN519	RISK ASSESSMENT IN GEOTECHNICAL ENGINEERING	3.0
CEEN511	UNSATURATED SOIL MECHANICS	3.0
CEEN512	SOIL BEHAVIOR	3.0
CEEN515	HILLSLOPE HYDROLOGY AND STABILITY	3.0

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

CEEN506	FINITE ELEMENT METHODS FOR ENGINEERS	3.0
CEEN530	ADVANCED STRUCTURAL ANALYSIS	3.0
CEEN531	STRUCTURAL DYNAMICS	3.0
CEEN533	MATRIX STRUCTURAL ANALYSIS	3.0
CEEN543	ADVANCED DESIGN OF STEEL STRUCTURES	3.0
CEEN545	STEEL BRIDGE DESIGN	3.0

Nuclear Engineering Track (12 credits from the course list below)

	NUGN506	NUCLEAR FUEL CYCLE	3.0
	NUGN510	INTRODUCTION TO NUCLEAR REACTOR	3.0
		PHYSICS	
	NUGN520	INTRODUCTION TO NUCLEAR REACTOR	3.0
		THERMAL-HYDRAULICS	
	NUGN580	NUCLEAR REACTOR LABORATORY	3.0
	NUGN590	COMPUTATIONAL REACTOR PHYSICS	3.0
	NUGN585/586	NUCLEAR REACTOR DESIGN I	2.0

Electrical Engineering-Antennas and Wireless Communications Track (12 credits from the course list below)

EENG525	ANTENNAS
EENG527	WIRELESS COMMUNICATIONS
EENG530	PASSIVE RF & MICROWAVE DEVICES
EENG526	ADVANCED ELECTROMAGNETICS
EENG528	COMPUTATIONAL ELECTROMAGNETICS

Electrical Engineering-Energy Systems and Power Electronics Track (9 credits from the course list below)

EENG570	ADVANCED HIGH POWER ELECTRONICS	3.0
EENG580	POWER DISTRIBUTION SYSTEMS ENGINEERING	3.0
EENG581	POWER SYSTEM OPERATION AND MANAGEMENT	3.0

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

EENG509	SPARSE SIGNAL PROCESSING	3.0
EENG511	CONVEX OPTIMIZATION AND ITS ENGINEERING APPLICATIONS	
EENG515	MATHEMATICAL METHODS FOR SIGNALS AND SYSTEMS	3.0
EENG517	THEORY AND DESIGN OF ADVANCED CONTROL SYSTEMS	3.0
EENG519	ESTIMATION THEORY AND KALMAN FILTERING	3.0
EENG527	WIRELESS COMMUNICATIONS	
EENG589	DESIGN AND CONTROL OF WIND ENERGY SYSTEMS	3.0
MEGN544	ROBOT MECHANICS: KINEMATICS, DYNAMICS, AND CONTROL	3.0

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

MNGN502	GEOSPATIAL BIG DATA ANALYTICS	3.0
MNGN512	SURFACE MINE DESIGN	3.0
MNGN516	UNDERGROUND MINE DESIGN	3.0
MNGN536	OPERATIONS RESEARCH TECHNIQUES IN THE MINERAL INDUSTRY	3.0
MNGN539	ADVANCED MINING GEOSTATISTICS	3.0

Doctor of Philosophy in Operations Research with Engineering

The ORWE PhD allows students to complete an interdisciplinary doctoral degree in Operations Research with Engineering by taking courses and conducting research in eight departments/divisions: Applied Mathematics and Statistics, Electrical Engineering, Computer Sciences, Civil and Environmental Engineering, Economics and Business, Mining Engineering, Mechanical Engineering, and Metallurgical and Materials Engineering.

Specialty Requirements

Doctoral students develop a customized curriculum to fit their needs. The degree requires a minimum of 72 graduate credits that includes coursework and a thesis. Coursework is valid for nine years toward a PhD degree; any exceptions must be approved by the director of the ORWE program and by the student's adviser.

Credit requirements

Total Semester Hrs	72.0
Research Credits	24.0
Any Combination of Specialization Courses or Research	12.0
Area of Specialization Courses	12.0
Core Courses	24.0
Core Courses	24

Research Credits

Students must complete at least 24 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 passing 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 credits 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 thesisbased 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

ORWE598	ALGORITHMS FOR OPERATIONS RESEARCH	3.0
EBGN526	STOCHASTIC MODELS IN MANAGEMENT	3.0
	SCIENCE	

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:

CSCI128	COMPUTER SCIENCE FOR STEM	3.0
CSCI200	FOUNDATIONAL PROGRAMMING CONCEPTS & DESIGN	3.0
CSCI220	DATA STRUCTURES AND ALGORITHMS	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

Total Semester Hrs		24.0
EBGN526	STOCHASTIC MODELS IN MANAGEMENT SCIENCE	3.0
ORWE587	NONLINEAR OPTIMIZATION	3.0
ORWE588	INTEGER OPTIMIZATION	3.0
ORWE585	NETWORK MODELS	3.0
MATH530	INTRODUCTION TO STATISTICAL METHODS	3.0
ORWE586	LINEAR OPTIMIZATION	3.0
MEGN502	ADVANCED ENGINEERING ANALYSIS	3.0
ORWE598	ALGORITHMS FOR OPERATIONS RESEARCH	3.0

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

Area	of	Specialization	Courses

CSCI555	GAME THEORY AND NETWORKS	3.0
CSCI562	APPLIED ALGORITHMS AND DATA STRUCTURES	3.0
EBGN509	MATHEMATICAL ECONOMICS	3.0
EBGN528	INDUSTRIAL SYSTEMS SIMULATION	3.0
or CSCI542	SIMULATION	
EBGN560	DECISION ANALYTICS	3.0
EBGN575	ADVANCED MINING AND ENERGY ASSET VALUATION	3.0
EENG517	THEORY AND DESIGN OF ADVANCED CONTROL SYSTEMS	3.0
MATH531	THEORY OF LINEAR MODELS	3.0
MATH532	SPATIAL STATISTICS	3.0
MATH537	MULTIVARIATE ANALYSIS	3.0
MATH582	STATISTICS PRACTICUM	3.0
MEGN592	RISK AND RELIABILITY ENGINEERING ANALYSIS AND DESIGN	3.0

MNGN536	OPERATIONS RESEARCH TECHNIQUES IN	3.0
	THE MINERAL INDUSTRY	
MNGN538	GEOSTATISTICAL ORE RESERVE ESTIMATION	3.0
ORWE688	ADVANCED INTEGER OPTIMIZATION	3.0
ORWE686	ADVANCED LINEAR OPTIMIZATION	3.0
5XX/6XX	Special Topics (Requires approval of the advisor and OrwE program director)	3.0

Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

Courses

ORWE559. SUPPLY CHAIN MANAGEMENT. 3.0 Semester Hrs.

(II) 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/maketo-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. **Course Learning Outcomes**

- Understand fundamental supply chain management concepts such as inventory management, supply chain planning, integration, distribution and coordination"
- Understand challenges that arise in supply chains
- Understand the role of optimization models that are used to model supply chain operations and solve them using AMPL
- Analyze supply chains of different businesses and discuss possible solutions to their problems.

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. **Course Learning Outcomes**

• 1. Understand how to differentiate spanning tree, shortest path, maximum flow and minimum cost flow models.

- 2. Understand how to graphically depict and mathematically model spanning tree, shortest path, maximum flow and minimum cost flow models.
- 3. Understand algorithms that solve model spanning tree, shortest path, maximum flow and minimum cost flow models.
- 4. Understand the difference between network and non-network optimization models

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. **Course Learning Outcomes**

· Understand how to formulate linear optimization models

- Understand how to solve linear optimization models, both by hand and with the computer through an algebraic modeling language and a state-of-the-art solver.
- Understand the special structure underlying linear optimization models and how this affects their ability to be solved.
- · Understand sensitivity and post-optimality analysis.

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.

Course Learning Outcomes

- Understand how to formulate nonlinear optimization models.
- Understand how to solve nonlinear optimization models, both by hand and with the computer through an algebraic modeling language and a state-of-the-art solver.
- Understand the special structure underlying nonlinear optimization models and how this affects their ability to be solved.

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.

Course Learning Outcomes

- · Understand how to formulate linear-integer optimization models.
- Understand how to solve linear-integer optimization models, both by hand and with the computer through an algebraic modeling language and a state-of-the-art solver.
- Understand the special structure underlying linear-integer optimization models and how this affects their ability to be solved.
- Understand decomposition techniques to aid in solution.

ORWE598. SPECIAL TOPICS. 0-6 Semester Hr.

ORWE598. ALGORITHMS FOR OPERATIONS RESEARCH. 0-6 Semester Hr.

Reasoning about algorithm correctness (proofs, counterexamples). Analysis of algorithms: asymptotic and practical complexity. Review of dictionary data structures (including balanced search trees). Priority queues. Advanced sorting algorithms (heapsort, radix sort). Advanced algorithmic concepts illustrated through sorting (randomized algorithms, lower bounds, divide and conquer). Dynamic programming. Backtracking. Algorithms on unweighted graphs (traversals) and weighted graphs (minimum spanning trees, shortest paths, network flows and bipartite matching); NP-completeness and its consequences. Prerequisite: CSCI220 with a grade of C- or higher or CSCI262 with a grade of C- or higher, MATH213 or MATH223 or MATH224, MATH300 or MATH358 or CSCI358.

Course Learning Outcomes

• Same as existing CSCI406.

ORWE598. SIMULATION FOR OPERATIONS RESEARCH. 3.0 Semester Hrs.

A first course in computer simulation using formal learning groups and emphasizing the rigorous development of simulation applications. Topics will include random number generation, Monte Carlo simulation, discrete event simulation, and the mathematics behind their proper implementation and analysis (random variates, arrival time modeling, infinite horizon statistics, batch means and sampling techniques). The course uses learning group assignments, quizzes, programming projects (using Linux) and exams for assessment. Prerequisite: (CSCI210 or CSCI274) AND CSCI306 AND (MATH201 or MATH334). **Course Learning Outcomes**

same as existing course CSCI423

ORWE599. INDEPENDENT STUDY. 0.5-6 Semester Hr.

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.

Course Learning Outcomes

- Understand how to formulate complicated linear optimization models.
- Dual Simplex Method and Interior Point Method
- Algorithmic Tuning
- · Column Generation and Dantzig-Wolfe Decomposition

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. Offered every other year.

Course Learning Outcomes

 Know how to formulate advanced integer optimization models 2. Be familiar with advanced algorithms to solve these models 3. Be able to use software, including scripting, to model and solve these models 4. Understand the theory behind and mathematical tenants of advanced integer optimization models

Program Director

Alexandra Newman, Professor, Mechanical Engineering