Principles of Biosystems Engineering: A Sophomore-Level Course

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Introduction

In 1906, the Agricultural Engineering program at Michigan State University was established. The program took the lead in education in production agriculture engineering and food process engineering in the State of Michigan and elsewhere. Recently, however, environmental issues have become a global concern in all sectors. Production agriculture will now have to be viewed in the context of the whole biological, ecological, and environmental system of which it is a part. While we need to increase and improve food production for the present generation, we also need to protect our natural environment upon which food production for the future generations depends. In 1995, the Biosystems Engineering (BE) program was launched to serve not only the production agriculture and food processing industries, but also the natural resources sector. The BE program is designed to train students to address the challenges imposed by a rapidly growing world population, expanding food and energy needs, increasing resource demands, and greater environmental problems[2]. Core courses in the BE program include biology, chemistry, mathematics, computer science, physics, systems science, engineering sciences, and principles of design. To fulfill an academic career goal, the student completes a cognate which can either be in agricultural engineering, food engineering, natural resources/environmental engineering, packaging, environmental studies, biotechnology, or biomedical engineering.

Course Objectives

Offered at the sophomore level, the three-credit course entitled “Principles of Biosystems Engineering” is the first required subject in the BE program. A knowledge of calculus is a prerequisite to enroll in the course. Knowledge in computer programming, physics, chemistry and biology are strongly recommended. Acquired skills in technical writing will be very helpful. The course is designed to introduce systems engineering concepts and systems engineering principles applicable to biologically-based systems. Specifically, the course objectives are: (1) to learn the systems concepts and properties related to biologically-based systems; (2) to understand and apply the principles of cybernetics, stability, and sustainability in biological systems; (3) to develop systems-oriented thinking and an integrated approach to problem solving; (4) to develop the skill of translating “word” problems into mathematical expressions (problem formulation), particularly in structuring a set of differential equations; (5) to use a mathematical type of software, in this case, *Mathematica*[6], to find solutions; and (6) to understand the environmental, economic, and technological factors affecting the performance of biologically-based systems through the use of mathematical dynamic models.

The course presents many disciplinary sciences and examines the interrelationships among them to enable students to learn, understand, and recognize the interconnections among technological advancement, environmental integrity, and economic development.

Classroom Mechanics

On a weekly basis, the class meets for two 50-minute "lecture" periods and another 50-minute computer laboratory session. A "lecture" period may consist of course material presentation by the instructor, student interactions among themselves facilitated by the instructor, and student teamwork. Cooperative learning[1] is used to convey the contents of the course to the students. Students work *individually* to accomplish assigned homework, exams, and project papers; work as a *team of two* to solve classroom problems and computer exercises, and work as a *team of three* to complete and present poster projects to the class.

Name Tags. Knowing each other well is an important factor in a successful classroom and in building teamwork. To facilitate the process, each student is requested to wear a name tag, provided by the instructor, during the first few weeks of class until everyone has learned everyone else's name.

Ad Hoc Teams During the Class Period. Teams of two members each are organized during any class period on an ad hoc basis. Members of the team may be asked to do one of the following: (1) identify key issues, (2) solve a problem, or (3) interpret results. Team answers are written up and submitted to the instructor. The ad hoc teams are also assigned several case studies to be analyzed outside the classroom and reported on during the class period. One member from the team, chosen randomly by the instructor during the class period, is asked to explain briefly the team output.

Project Teams for the Semester. A team of three students, preferably heterogeneous in composition, is organized for the semester. The project topic is chosen by each team and is worked on during the semester. During the semester, each team member has two major responsibilities: (1) learn the body of knowledge emphasized in the course in order to prepare and report on the team project and (2) ensure that all members in the team learn the body of knowledge emphasized in the course in order to prepare and report on the team project. At the end of the semester, each team finalizes the project, makes a poster presentation to the class for a grade, and discusses the poster with faculty during a faculty-student poster session. The posters get voted on by a selected group of faculty, with the "best" team receiving a plaque of recognition.

Grading. Students are graded on an absolute scale of 59-100%, with 59% or below resulting in a zero grade and 90-100% resulting in 4.0 (out of 4.0). They are graded for individual performance through homework, writing a technical paper, and exams (each weighted 20%). They are graded as a team through classroom teamwork and poster projects (each weighted 20% also). Bonus points are provided along the way to encourage team effort and comprise an additional 5% to supplement the final grade. An excellent student may achieve 105% in the class.

Course Contents

The course contains the following general topics: (1) biosystems and systems concepts, (2) properties of biosystems, (3) mathematical models and their classifications, (4) model development, (5) modeling population dynamics, (6) modeling biological and environmental systems, (7) stability analysis, (8) cybernetics or feedback analysis and (9) sustainability analysis of biologically-based systems.

Biosystems and Systems Concepts

This topic includes a discussion on issues related to the need for increasing food production, the reality of rapidly growing human population, and the stresses put on the environment. Students are made to understand the interactions among economic development, technological advancement and natural resource management. A major part of this topic is the definition of terms. Systems-related terms are defined and the concepts are introduced through problem sets. For example, the concept of a system, controllable input, exogenous input, desired output, undesired by-products, state variables, system parameters, system boundary, and system environment are presented through the well-known problem "how the three strangers and three headhunters got to cross the river on a two-person boat satisfying the condition that the three headhunters could not be allowed to outnumber the three strangers at any time in any place under any circumstances." Also included in the definition of terms are biosystems engineering, analysis, control and design processes, cybernetics, stability and sustainability analyses.

Biosystems Engineering is defined here as the analysis, design, and control of natural, biological and human-made physical system components and their interconnections for the sustainable production and processing of food, feed, fiber and shelter materials through the efficient utilization of natural and biological resources in a manner that is harmonious to the natural environment. A biosystems engineer should be able to design and control a sustainable biologically-based system that will be compatible with, and able to accommodate, change, complexity and growth.

Cybernetics is introduced as the science of how systems are regulated. Stability is concerned with how the system handles perturbations or disturbances. Sustainability is introduced as a philosophical paradigm that addresses economic growth and the improvement of social well-being within the limits set by ecology in the broadest sense—by the interrelationships of human beings and their works, the biosphere, and the physical and chemical laws that govern it[5]. Sustainable systems are described as those which are economically viable, environmentally benign, socially acceptable, and, whenever necessary, morally wholesome.

A 30-minute video entitled *Understanding Ecosystems*[3] is presented to provide a quick and brief introduction to ecological and biological terms.

Properties of Biosystems

The biosystem properties covered in this section are: hierarchy, modularity, network, wholeness, purpose, open system, feedback, stability, reproduction and stochasticity. Principles of system structure, organizational hierarchy, transitivity, asymmetry, seriality, interdependence, coherence, time and space orientations, and equifinality are presented through real-life examples. The properties are made explicit through a case study of the DDT pesticide in the Yakima River Basin[4]. This 24-page monograph by the U.S. Geological Survey provides a medium through which to understand the properties of biosystems while at the same time illustrating how the natural environment, a precious natural resource, can be so damaged by a seemingly "friendly" and breakthrough technology — pesticides.

Mathematical Models and Their Classifications

Different types of mathematical models are introduced and classified as to time and space distribution, involvement of stochastic variables, continuous or discrete nature of the system, linearity, stationarity and homogeneity of the system variables. Mathematical description of inputs (step, ramp, parabolic, and sinusoidal) and outputs (exponential in form) are presented as well. Data interpretation is part of this section.

Model Development

The procedure for developing a mathematical model is presented from problem definition to model validation. The students learn to develop a mathematical model from "word" problems. Models are limited to ordinary differential equations (ODE). Examples of word problems include biological processes, environmental pollution, species population and the food chain. Knowledge of the *Mathematica* software becomes very useful beginning at this stage.

Modeling Population Dynamics

For single species, the population dynamics are modeled using the Malthusian equation (exponential growth and decay), Verhulst equation (logistic growth), Allee effect equation, and the Gompertz equation. Predator-prey systems are modeled using the Lotka-Volterra equations and competition of species is modeled using the Lotka-Voterra-Gause equations. Variations of the models are also introduced. The principles learned in studying the population dynamics are related to similar behavior observed in political parties, business enterprises, and chemical compounds in natural systems. The skill to write mathematical equations from word problems continues in this section. *Mathematica* continues to be the medium for finding solutions.

Modeling Biological and Environmental Systems

The modeling process of biological and environmental systems follows the *law of conservation of mass* principle. The ODEs are expressed and solved in either continuous time or in discrete time. Algebraic models are generated from ODEs for steady-state conditions. At this stage, students learn to evaluate the validity of assumptions and explore the consequences of changing initial conditions. Computer exercises include pollution of a single lake and interconnected lakes, phosphorus cycling, deforestation, biomagnification of trace substances in the food chain and atmospheric pollution.

Stability Analysis

Oscillation is characteristic of biological systems. It is introduced as a phenomenon that occurs at all levels of the hierarchy in society, from the cell up to the universe. Newton's law of motion is fundamental in this section. Simple harmonic motion, damped motion, damped forced vibrations, forced free vibrations, and resonance in biological systems are among the topics covered. Stability is analyzed by the isocline method. Computer exercises include movement of a human leg, pest population, lake pollution, and antibody-tumor interactions.

Cybernetics or Feedback Analysis

The existence of a flow of information from the system "output" to the "controller" that regulates the input to maintain a stable set point is a commonly accepted emblem of a cybernetic system. Feedback flow is introduced in the form of information, material and energy. The idea of a population or ecological community being perturbed from equilibrium is presented. The students learn that the balance of negative and positive feedback mechanisms in the system to counteract the perturbation and restore the system to equilibrium may or may not be conspicuous. Feedback loops may drive the perturbed system to extinction or restore it to equilibrium population. Computer exercises include population dynamics, pest outbreak and algae bloom.

Sustainability Analysis

One major reason for understanding the behavior of biological dynamic systems is to be able to control and manage the system for sustainability. Sustainable development is development that satisfies the needs of the present generation without compromising the ability of future generations to satisfy their own needs. Management and control may be expressed in terms of harvesting or stocking. Students learn a mathematical algorithm to identify the optimum harvesting or stocking rate in order to sustain a population. Computer exercises include the sustainable management of game birds and fish.

Research Paper

Individually, students have an opportunity to analyze a technical paper in depth. They are asked to find a technical paper describing a biological system with at least two differential equations being solved simultaneously. The students are to accomplish the following tasks: (1) read the paper; (2) understand the objectives; (3) if the paper contains several research works, decide which work to further analyze; (4) extract all the differential equations (at least two) used in the section to be analyzed, including initial conditions and assumptions; (5) cross reference, if necessary, to understand or get model parameters; (6) solve the differential equations using *Mathematica*; (7) submit a write-up comparing and discussing student results and that of the paper. Table 1 presents a sample list of analyses, the number of differential equations being solved simultaneously during the analysis, and the reference of the original technical paper. The Table shows a broad range of topics on biologically-based systems.

Poster

The semester is capped with a poster presentation by student teams. The topics describe the dynamics of biological systems where two or more differential equations are solved simultaneously. The posters also relate how the technological, economic, and environmental factors affect the sustainability of the biological system being studied. A sample list of poster titles and the number of differential equations involved (enclosed in parenthesis) are listed as follows: *The Dynamics of Lake Pollution* (3), *Controlling Pest Population* (3), *Pest Management of the Spruce Budworm* (3), *The Development of a Sustainable Fisheries* (4), *Fishery Dynamics: Squid, Whale and Humans* (4), *Global Warming Due To Burning Fossil Fuels* (5), *The Economics of Elephant Poaching* (3), *Modeling Shell Patterns* (2), *Dynamics of the Ebola Virus* (3), *Measles* (3), *Consumer Population and Its Food Source* (3) and *Chaotic Behavior of the Food Chains* (3).

Expected Proficiencies

The output of the class can be summarized by the expected proficiencies, especially as those proficiencies are related to the ABET criteria 2000. The expected proficiencies after taking the class are: (1) an ability to identify, formulate and solve biologically-based engineering problems, (2) an ability to apply appropriate knowledge in mathematics, biology, chemistry and engineering, (3) an ability to analyze and interpret data, (4) an ability to function on teams, (5) an ability to communicate effectively, (6) understanding of the impact of engineering solutions in a global/societal context, (7) knowledge of contemporary issues and (8) an ability to develop mathematical models and to use a well-known and powerful mathematical software (*Mathematica*) to find model solutions.

Additional proficiencies from preparing the technical paper and poster include: (1) literature search (article referencing and information sourcing), (2) information sharing, (3) exposure to scientific journals, (4) technical writing, (5) deeper knowledge of the paper and poster subject matter, (6) poster preparation, (7) oral presentation, (8) use of overhead projector and transparencies, (9) leadership skills, (10) time management, (11) coordination among members (12) student interaction and (13) faculty interaction.

References

1. Alocilja, E.C. 1995. Cooperative Learning in the Biosystems Engineering Program. *In* 1995 Annual Conference Proceedings, American Society for Engineering Education. Anaheim, California. Pp.1373-1380.

2. Biosystems Engineering Program, Department of Agricultural Engineering, Michigan State University. 8pp.

3. Educational Video Network, Inc., 1401 19th Street, Huntsville, Texas 77340.

4. Rinella, J.F., P.A. Hamilton, and S.W. McKenzie. 1993. *Persistence of the DDT Pesticide in the Yakima River Basin Washington*. U.S. Geological Survey Circular 1090. 24 pp.

5. Ruckelhaus, W.D. 1989. Toward a Sustainable World. *Scientific American*, A Special Issue on Managing Planet Earth. 261(3).

6. Wolfram, S. 1991. *Mathematica, A System for Doing Mathematics by Computer*. Addison-Wesley Publishing Co., Reading, Massachusetts. 961 pp.

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Table 1. Sample list of individual papers: analyses, number of ODEs and references.

Title of Analysis	No. of ODE	Original Paper
Biological behavior of pest populations	3	Bor, Y.J. 1995. Optimal Pest Management and Economic Threshold. Agricultural Systems 49:113-133.
The effect of decreasing system size in open-access fisheries	2	McGarvey, R. 1995. The Effect of Decreasing System Size on the Birth and Death Models of Open-Access Fisheries and Predator-Prey Ecosystems. Natural Resource Modeling. 9(2):121-145.
Lotka-Volterra competition model	2	Pascual, M. and P. Kareiva. 1996. Predicting the Outcome of Competition Using Experimental Data: Maximum Likelihood and Bayesian Approaches. Ecology, 77(2):337-349
Stunted growth and stepwise die-off in animal cohorts	3	Scheffer, M., J.M. Baveco, D.L. DeAngelis, E.H.R.R. Lammens, and B. Shuter. 1995. Stunted Growth and Stepwise Die-Off in Animal Cohorts. The American Naturalist. 145(3):376-388.
Temporal patterns in terrestrial carbon storage	8	Townsend, A.R., B.H. Braswell, E.A. Holland, and J.E. Penner. 1996. Spatial and Temporal Patterns in Terrestrial Carbon Storage Due To Deposition of Fossil Fuel Nitrogen. Ecological Applications. 6(3):806-814.
Earth's human carrying capacity	2	Cohen, J.E. 1995. Population Growth and Earth's Human Carrying Capacity. Science 269:341-345.
Modeling the temporal pattern of teeth primordia in the alligator	3	Kulea, P.M., G.C. Cruywagen, S.R. Lubkin, M.W.J. Ferguson, and J.D. Murray. 1996. Acta Biotheoretica 44:153-164.
Chaos in a three-species food chain	3	Ruxton, G.D. 1996. Chaos in a Three-Species Food Chain with a Lower Bound on the Bottom Population. Ecology, 77(1):317-319.
How populations persist	2	Nee, S. 1994. How Populations Persist. Nature, 367:123-124.
Effects of mass extinctions on biodiversity	1 (with 15 initial conditions & parameters)	Courtillot, V. and Y. Gaudemer. 1996. Effects of Mass Extinctions on Biodiversity. Nature 381:146-148.