COMPUTER-BASED COURSEWARE FOR SYSTEMS ENGINEERING EDUCATION AND TRAINING

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Abstract. Systems engineering is an integration activity which is difficult to teach by conventional means alone. Education and training efforts should be supported with computer-based courseware to augment textbooks, technical articles, case studies, and other written materials. The purpose of this paper is twofold: to describe the approach adopted at Virginia Tech in the instruction of systems engineering courses and to describe the development and utilization of computer-based courseware in these courses. While this courseware is applicable in teaching systems engineering generally, three academic courses and their continuing education counterparts will be featured as examples. These courses are: The Systems Engineering Process, Logistics Engineering, and Economic Evaluation of Projects.

INTRODUCTION

Systems engineering is a process involving a series of structured steps with the objective of translating an identified need into an effective and efficient product or system [Blanchard and Fabrycky 1990]. This process subsumes the activities of the traditional engineering disciplines such as mechanical engineering, electrical engineering, and civil engineering because engineering specialists acting alone are often unable to ensure functional and developmental compatibility between the various sub-elements of the system being developed. Given the iterative, multi-discipline, and complex nature of the process, computer-based courseware can be an invaluable aid to instruction.

Several insightful studies have been conducted to investigate and develop a curriculum for effective education and training in systems engineering and concurrent engineering [Blanchard 1991, Fabrycky 1991, Report 1984]. On the other hand, little, if any, effort has been expended towards the development of supporting and equally important courseware. Systems engineering courseware, in the context of this paper, refers to computer-based models used to support the relevant concepts addressed during traditional classroom lectures. The focus of this paper will be such courseware, its development and implementation at Virginia Tech.

COURSEWARE DEVELOPMENT

The Systems Engineering Design Laboratory (SEDL) was organized at Virginia Tech in 1990. It serves as the central focus for research and development activities supporting the interdepartmental Systems Engineering Graduate Program. The laboratory also supports the Manufacturing Systems Engineering Option within the Department of Industrial and Systems Engineering. The various research projects being conducted led to the development of a number of useful computer-based models and tools. These models and tools have been adapted for classroom use to facilitate working with realistic case studies. The tools also permit complex "what-if" analyses in real time. Such exercises are of significant importance to fully comprehend the myriad interactions inherent in the courses that constitute an inter-disciplinary program like systems engineering.

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Over the past few years, research relationships have been forged with certain commercial software developers. This has also resulted in the development of systems engineering courseware in the form of university/student editions of commercially available software packages. These university editions are abridged versions of the full-blown tools but yet adequate to convey all the underlying concepts and to work on hypothetical case studies.

Development of university/student editions is of mutual interest. Needless to say, the computer programs utilized are tested and validated very comprehensively. Our contribution, thus far, has included a set of recommendations for further improving the tools. From the vendors' perspective, using their models in a classroom environment is an extremely effective verification opportunity. From an instructional perspective, this courseware is of the highest quality and gives the students an opportunity to interact with models and tools now being used extensively in the real world.

Table 1 lists certain selected computer-based tools and models that are presently being used to support three courses that will be discussed in further detail in the following sections.

COURSE / COURSEWARE INTERACTION

In order to maximize the benefits of the supporting computer-based courseware, its interface with course topics should be carefully planned. The three courses presented in the following sections have had the benefit of exposure to industry in the form of short courses of varying lengths and numerous seminars. The courses are in a constant state of evolution, and, while all the course objectives have not been met, much has been accomplished relative to the integration of the courseware within the structure of the overall course. Moreover, the assignments performed on the computer are not standalone or independent of one another. In order to convey the link and relationship between different analyses, effort is made such that each computer-based assignment lead into the next. This overall strategy also facilitates trade-off and sensitivity analyses.

It is important to realize that the computer-based models used in the instruction of the systems engineering courses at Virginia Tech represent but a subset of the relevant analyses that ultimately need to be performed and integrated into the systems engineering process. The students are introduced to the vision of an integrated design workstation. Moreover, as mentioned above, the computer-based assignments are designed to convey the iterative nature of the overall process and the necessity of communications and feedback between the various analyses.

All three courses, The Systems Engineering Process, Logistics Engineering, and Economic Evaluation of Projects, have evolved from a traditional classroom "lectures only" scenario to a classroom "lectures interspaced with computer laboratory modules" scenario. The lectures focus on the theory and concepts that lead into each laboratory module.

COURSEWARE IMPLEMENTATION

The general course in systems engineering at Virginia Tech is The Systems Engineering Process. Various other courses play a supporting role. Two of the more important supporting courses are Logistics Engineering and Economic Evaluation of Projects. The computer-based systems engineering courseware utilization in the three systems engineering courses will be addressed. In each case, the course outline will be delineated and the utilization of the relevant courseware made explicit. The objective is to show how computer-based models and tools have been integrated into the instructional process and their significance in the overall course evaluation. When possible, a flow chart to depict the relationship between the various course topics, homework and computer assignments, and the examinations is also shown for the course.

The Systems Engineering Process. This is a graduate level course (a required course in the Systems Engineering Graduate Program). Students are introduced to systems engineering as the application of scientific and engineering efforts to transform an operational need into a defined system configuration through the iterative process of functional analysis, synthesis, optimization, and design integration. The systems engineering process is shown to include consideration of reliability,maintainability, human factors, logistic support, safety, producibility, economic, and related parameters as they apply to the total engineering

Table 1. Selected courseware developed to support systems engineering courses.

TOOL	TOOL DEVELOPER	TOOL DESCRIPTION
ECONOMY	SEDL Virginia Tech, VA.	ECONOMY consists of 12 programs covering most topics in engineering economy .
EDCAS-UE	Systems Exchange Los Angeles, CA.	Equipment Designer's Cost Analysis System (University Edition) (EDCAS), includes life-cycle cost and level of repair analysis, etc.
FME	Powertronic Systems, Inc. New Orleans, LA	Failure Modes, Effects, and Criticality Analysis Program (FME). A university edition is being developed, and like the commercial version, separate worksheets exist for failure modes and effects, criticality analysis, maintainability analysis, and damage modes/effects.
LCCC	SEDL Virginia Tech., VA	The Life-Cycle Cost Calculator (LCCC) is based on the cost breakdown structure concept. Objectives and activities are linked with resources in a logical subdivision of cost by functional activity area.
MPF	SEDL Virginia Tech., VA	The Manufacturing Progress Function (MPF) addresses adjustments in resource consumption based on learning concepts. It provides item cost for a manufactured item based on empirical data or on knowledge of direct labor hours, a learning parameter, and cost inputs.
MPP	Powertronic Systems, Inc. New Orleans, LA	Maintainability Prediction Program (MPP) facilitates prediction of mean corrective maintenance times, mean maintenance manhours per repair, per maintenance action, and per operating hour, and maximum active maintenance corrective times. A university edition of this program is available.
RDD System Designer	Ascent Logic Corporation San Jose, CA	Requirements Driven Development (RDD) System Designer is a tool to analyze and process system requirements and to model the expected system behavior. A database maintains complete traceability of the requirements for consistency and completeness.
REPS-INT	SEDL Virginia Tech., VA	Repairable Equipment Population System(Interactive Version)(REPS-INT) is a design evaluator for repairable equipment with respect to the number of equipment that need to be deployed, the number of repair channels needed, and the economic life of the system for each design dependent parameter set.
REPS-OPT	SEDL Virginia Tech., VA	Repairable Equipment Population System (Optimizer Version)(REPS-OPT) performs the same function as the interactive version, with the exception that the system is automatically optimized with respect to the three system design variables.
RPP	Powertronic Systems, Inc. New Orleans, LA.	Reliability Prediction Program (RPP) provides system reliability predictions for parallel and series components. Predictions are made for electronic components in terms of mean time between failure (MTBF) and failure rate. A university edition of this program is available.

Table 2. Systems Engineering Courseware Usage.

SYSTEMS ENGINEERING	
Course Title: The Systems Engineering Process (one semester or 15 weeks) **Course Materials:** Text - Blanchard, B. S. and W. J. Fabrycky, **"Systems Engineering and Analysis"**, 2nd. Edition, Prentice-Hall, Englewood Cliffs, N. J., 1990; Computer-based tools to include LCCC, REPS (Interactive Version), REPS(Optimizer Version), RDD, RPP, MPP, FME, EDCAS; and class notes.	
Course Outline	**Courseware Support**
1. The systems engineering process; system terms and definitions.	
2. Conceptual system design; customer requirements; operational requirements; maintenance concept; design criteria; system specification.	
3. Preliminary system design; functional analysis; functional block diagrams; allocation of requirements.	RDD System Designer
4. Detail design and development; system synthesis; analysis; trade-offs; detail design; design review.	
5. New technologies in design; CAD; related methodologies.	
6. System test and evaluation; requirements; formal T & E; data collection, analysis, feedback, and corrective action.	
7. Alternatives and models in decision making; tools for system analysis; decision evaluation theory; decisions under risk and uncertainty; models in design and operations.	ECONOMY REPS-INT
8. Models for economic evaluation; interest formulas and equivalence; evaluating multiple alternatives; break-even evaluations.	
9. Optimization in design and operations; classical optimization theory; unconstrained and constrained optimization; LP/DP.	
10. Queuing theory and analysis; Monte Carlo analysis; queuing models and optimization; finite population queuing models.	
11. Control concepts and technologies; SPC; project control; total quality control.	
12. Design for reliability; definitions; measures; requirements; models; FMECA; derating; predictions and analysis; test and evaluation.	RPP FME
13. Design for maintainability; definitions; measures; requirements; predictions and analysis; level of repair analysis; reliability centered maintenance; maintenance task analysis; demonstration.	MPP EDCAS
14. Human factors requirements; definitions; requirements; task analysis; operational sequence diagrams; personnel and training requirements; test and evaluation.	
15. Design for supportability; logistics definitions; measures of logistics; design requirements; LSA; computer-aided acquisition and logistic support.	EDCAS
16. Design for economic feasibility; life-cycle costing terms and definitions; design to cost; LCC analysis process; cost breakdown structure; evaluation of alternatives; high-cost contributors: break-even analysis; areas of risk.	LCCC
17. PC tools for life-cycle costing; communication system design application.	
18. PC tools for system optimization; Repairable Equipment Population System design application.	REPS-INT REPS-OPT
19. Computer-integrated systems engineering.	
20. Systems engineering management; program requirements; system engineering management plan; organization for systems engineering; program tasks; leadership characteristics; program implementation and control; supplier requirements; reporting; documentation requirements; risk management plan.	

Table 3. Economic Evaluation of Projects Courseware Usage.

ECONOMIC EVALUATION	
Course Title: Economic Evaluation of Projects (one semester or 15 weeks) **Course Materials:** Text - Fabrycky, W. J. and B. S. Blanchard, **"Life-Cycle Cost and Economic Analysis"**, Prentice-Hall, Englewood Cliffs, N. J., 1991; Journal - **"Engineering Costs and Production Economics"**, Elsevier Science Publishers (selected articles); Computer-based models and tools to include ECONOMY, LCCC, REPS (Interactive), REPS (Optimizer), EDCAS, MPF. **Course Evaluation Criteria:** Midterm and final examinations; homework assignments; computer assignments and creative exercise.	
Course Outline	**Courseware Support**
1. System life-cycle concepts. Planning for economic competitiveness; the system life-cycle process; cost commitment over the life cycle; life-cycle economic analysis.	
2. Economic and cost concepts. The value and utility of goods; economic inputs and outputs; some classifications of cost; the cost breakdown structure; time value of money; the earning power of money; the purchasing power of money.	
3. Interest formulas and equivalence. Interest and economic equivalence; interest formula deviations; equivalence of money flows; inflation and equivalence.	ECONOMY
4. Alternatives and decision making. Elements of decision criteria; types of proposals; forming mutually exclusive alternatives; comparisons based on total investment; present equivalent and rate of return on incremental investment; alternatives with unequal lives.	ECONOMY
5. Decision evaluation theory. Evaluation by economic equivalence; the economic optimization function; the decision evaluation matrix; decisions under certainty, risk, and uncertainty; decision involving multiple criteria.	
6. Life-cycle costing methodology. The life-cycle costing situation; cost generated over the life cycle; life-cycle cost analysis; cost treatment over the life cycle; design to cost.	
7. Estimating cost and economic elements. Cost estimating methods; developing and adjusting cost data; cost estimating relationships; estimating manufacturing costs; accounting data and judgement in estimating.	MPF ECONOMY
8. Evaluating errors in estimating. Decisions based on estimates; allowing for errors in estimates; considering a range of estimates; sensitivity analysis; Monte Carlo simulation.	EDCAS
9. Life-cycle economic evaluations. Cost evaluation of two alternatives and multiple alternatives; profitability evaluation of alternatives; evaluation system design alternatives; break-even evaluation of alternatives; evaluation alternatives with multiple futures.	ECONOMY
10. Life-cycle Optimization of Alternatives. Optimizing first cost, life-cycle cost, and equipment life.	
11. Life-cycle cost in program evaluation. Program requirements and planning; organization for life-cycle costing; program review and control; consumer/producer/supplier interfaces; contractual implications; managerial implications.	
12. Case Studies: (1) Communication System Procurement and (2) REPS Design. Both these case studies make use of the courseware supporting the course.	LCCC, REPS- Optimizer and Interactive Versions

Table 4. Logistics Engineering Courseware Usage.

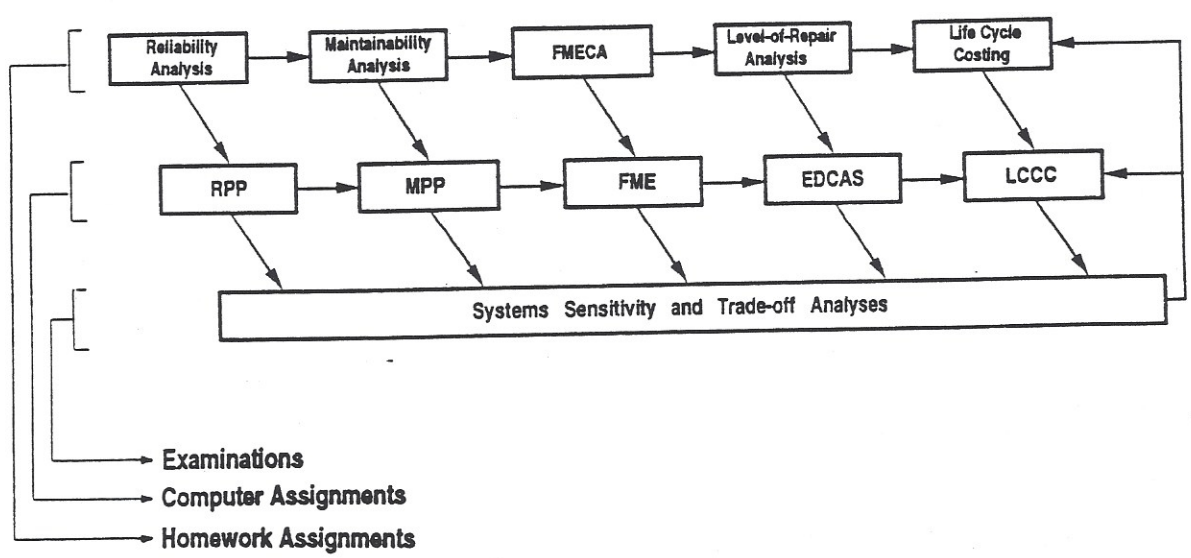
LOGISTICS ENGINEERING

Course Title: Logistics Engineering (one semester or 15 weeks)
Course Materials: Text - Blanchard, B. S., "**Logistics Engineering and Management**", 4th. Edition, Prentice-Hall, Englewood Cliffs, N. J., 1992; DEC LG02 Lineprinter; Computer-based models and tools to include RPP, MPP, EDCAS, LCCC, FME; and supporting notes.
Course Evaluation Criteria: Midterm and final examinations; homework assignments; computer assignments and laboratory exercise.

Course Outline

1. Introduction to logistics; terms and definitions; logistics in the system life cycle; logistics functions/tasks; logistics engineering.
2. Reliability concepts, measures, and models (reliability allocation and prediction using Powertronic Systems' RPP).
3. Maintainability concepts, measures, and models (maintainability prediction using Powertronic Systems' MPP).
4. Supply support factors, test and support equipment factors, organizational factors, facility factors, transportation factors, economic and life-cycle cost factors.
5. Logistics in the system life cycle; operational requirements; maintenance concept; functional analysis and requirements allocation; logistic support analysis (level of repair analysis using Systems Exchange's EDCAS; failure modes, effects, and criticality analysis using Powertronic Systems' FME; and life-cycle cost analysis using SEDL's LCCC).
6. Logistics in design; integration; design review; test and evaluation (using DEC LG02 line printer for maintainability demonstration).
7. Logistics in production/construction; logistics during system operational use; system retirement.
8. The management of logistics; planning and organization for logistics; program implementation and control.

Computer-Based Courseware Interface



effort. It is emphasized that the systems engineering process, in its evolving of functional detail and design requirements, has as its goal the achievement of balance between operational, economic, and logistics factors. The students are required to submit a project demonstrating knowledge of the systems engineering process and primary functions in each phase of the system life cycle and the many inter-relationships that exist among system parameters.

This course is currently being taught over the statewide cooperative TV satellite system (one-way video, two-way audio). This medium of instruction places constraints on the utilization of the computer-based courseware. Usage of this courseware is limited to demonstrations over the satellite system. The application of computer-based tools and models is further clarified through case studies. Moreover, these tools and models are made available and the students are strongly encouraged to use them during the course of their respective projects. This project offers the students an excellent opportunity to utilize the computer-based courseware and perform sensitivity and trade-off analyses to facilitate the comparison of feasible alternatives. The course outline, instruction materials, and the computer-based courseware demonstrated and made available to the students is delineated in Table 2.

Economic Evaluation of Projects. This is a graduate level course that presents a life-cycle based extension of engineering and engineering economics through all project life-cycle phases, design and development, production/ construction, utilization, support, phaseout, and disposal [Fabrycky and Blanchard 1991].

This course is divided into three phases. In the first phase the student is introduced to the basic concepts and the underlying theory. Methodologies are formulated from a life-cycle perspective and application areas are delineated in the second phase. In the third phase, hypothetical case studies are presented to the students utilizing the computer-based courseware. These case studies help in bringing together the topics addressed earlier during the course. The computer-based models and tools also facilitate sensitivity and trade-off analyses, providing an opportunity for further insight into the theory and concepts. The course outline, instruction materials, computer-based courseware, and the course evaluation criteria is shown in Table 3.

Logistics Engineering. This is a senior level course (although it can also be taken for graduate credit) that addresses the field of logistics in terms of the system life cycle, with a focus on the design and development process [Blanchard 1992]. The course objective is to provide the student with an introduction to logistics, an understanding of the elements of logistics, and knowledge pertaining to the "design for supportability". It is emphasized that the ultimate effectiveness of a system is not only dependent on the design of its prime elements but the design of its maintenance and support capability as well.

The course outline, instruction materials including the computer-based courseware, the evaluation criteria, and the integration of the courseware within the course topics via assignments and examinations is shown in Table 4. The flow chart within the table illustrates the effort to maintain a link between all computer assignments with emphasis on the communication and feedback between relevant analyses [Verma and Blanchard 1992].

SUMMARY AND CONCLUSIONS

The development of computer-based courseware outlined in this paper would not have been possible without the continued support of some of the commercial software developers named in Table 1. The systems engineering discipline would benefit significantly from improved communications between the tools presently in use. Over the past few years the authors have realized that useful research and courseware development are not necessarily mutually exclusive activities. The Systems Engineering Design Laboratory has served as a catalyst in adapting research results for instructional use.

Certain changes are currently being considered to better integrate the computer-based courseware with the lectures. Efforts are also under way to study and, if possible, incorporate into the curriculum computer-based tools to perform tasks such as requirements and functional analysis, and case studies based upon real systems.

Most computer-based models and tools developed within the Systems Engineering Design Laboratory (SEDL) at Virginia Tech have been made available upon request by interested parties (SEDL is now implementing a nominal handling and shipping charge to defray expenses). The courseware developed in conjunction with the commercial software vendors is available directly from the respective company.

Finally, the authors are very interested in learning of other courseware development experiences in systems engineering. Input would be appreciated. Please contact the authors at (Tel: 703-231-5458; Fax: 703-231-7248).

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BIOGRAPHICAL SKETCHES

Dinesh Verma is presently working towards a Ph.D. in Industrial and Systems Engineering from Virginia Polytechnic Institute and State University. He is a Graduate Project Assistant and Coordinator of the Systems Engineering Design Laboratory at Virginia Tech. Verma is currently Chairman of the Blue Ridge Chapter of the Society of Logistics Engineers. Prior to entering graduate school, he worked for a year with Fibreglass Pilkington Inc. as a Technical Support Engineer and for a year with Cimmco Heavy Machinery Inc. as a Manufacturing Engineer.

Alberto Sols obtained a Master of Science in Naval Architecture and Marine Engineering from Madrid Polytechnic University. He is employed by ISDEFE, a Madrid-based systems engineering firm. Sols has over seven years of industry experience and is currently enrolled as a M.S. student in the Systems Engineering Graduate Program at Virginia Tech where he is also employed as a Research Assistant. He was co-founder of the Spanish District of the Society of Logistics Engineers.

Wolter J. Fabrycky received the Ph.D. in Engineering in 1962 from Oklahoma State University, the M.S. in Industrial Engineering in 1958 from the University of Arkansas, and the B.S. in Industrial Engineering in 1957 from Wichita State University. Dr. Fabrycky taught at Arkansas and Oklahoma State and then joined Virginia Tech in 1965 where he served as Chairman of Systems Engineering, Associate Dean of Engineering, and then as Dean of Research for the University. He is the John L. Lawrence Professor of Industrial and Systems Engineering.

Dr. Fabrycky was elected to the rank of Fellow in the Institute of Industrial Engineers in 1978 and the rank of Fellow in American Association for the Advancement of Science in 1980. He is listed in Who's Who in Engineering and Who's Who in America. Fabrycky is a Registered Professional Engineer in Arkansas and Virginia.

Benjamin S. Blanchard received the B.S. in Civil Engineering in 1951 from the University of Maine and the M.B.A. in 1969 from the University of Rochester. Blanchard is Professor of Engineering and Assistant Dean, College of Engineering. He is Chairman of the Systems Engineering Program, responsible for the College's off-campus graduate engineering programs throughout Virginia, and teaches courses in Systems Engineering, Reliability and Maintainability, Life-Cycle Costing, and Logistics Engineering.

Prior to joining Virginia Tech in 1970, Blanchard was employed in industry for 17 years as design engineer, field service engineer, and engineering manager with Boeing, Sanders Associates, Bendix, and General Dynamics. Professor Blanchard is past president of the Society of Logistics Engineers.