AC 2009-220: A QRW PARADIGM FOR INDUSTRIAL ENGINEERING CURRICULA

Marlin Thomas, Air Force Institute of Technology

MARLIN U. THOMAS is Dean, Graduate School of Engineering and Management, Air Force Institute of Technology, past Professor and past Head of the School of Industrial Engineering at Purdue University. He received his BSE at the University of Michigan-Dearborn, and MSE and PhD at the University of Michigan. He has held other academic appointments at Lehigh University, Cleveland State University, University of Missouri-Columbia, University of Wisconsin-Milwaukee, and the Naval Postgraduate School. He has also served as a Program Director for the National Science Foundation; Manager, Reliability and Warranty Analysis, Chrysler Corporation; and Development Engineer, Owens-Illinois, Inc. He is past National Secretary of ORSA, Chairman of the Council of Industrial Engineering Academic Department Heads, and IIE Past-President and member of the Board of Trustees. His research interests are in operations research with applications in reliability and contingency logistics. He has served on several editorial boards and is currently Associate Editor for IIE Transactions and is a Fellow of IIE, ASQ, and INFORMS. He is also a Captain, Civil Engineer Corps, U.S. Navy Reserve (Retired).

A QRW Paradigm for the Industrial Engineering Curriculum

Abstract

Industrial engineers need to have a thorough understanding of how product and service quality are influenced through their design and development, production, and acceptance by customers. This paper proposes a core course for the basic curriculum that provides a modern broad view of quality as a vector of attributes that includes reliability and warranty concepts and methods. A notional course is developed by integrating topics from current courses using concept mapping to construct a platform that can be used to build and reinforce quality throughout the curriculum.

1. Introduction

Quality is much more broadly interpreted today than it was during the embryonic days of development of the industrial engineering (IE) discipline. Initially, it was treated more as a compliance process to ensure that processes and standards were being followed in producing products. This interpretation held for many year throughout the era of mass production when more often than not the pressures for high volume production out-weighed options for testing and inspection in cost tradeoff decisions. This all changed drastically with the onset of global competition and the explosion of new technologies in the early 1970s. This led to an almost immediate shift in management philosophies and to major change in attitudes and consciousness that ultimately altered the meaning of quality throughout the world.

Quality can be defined as the state of acceptance of a product or service relative to the expectations of customers or users of the product. These states depend on how the products are developed, produced, and used by customers. There are several factors that influence a quality state. Compliance with standards in manufacturing and production is still important but there are other important factors as well, one being reliability since it expresses the amount of failure-free time that can be expected of a product or system. When competition was weak or non-existent product manufacturers lacked incentives to focus on customer needs as we know them today. Though product guarantees and warranties were offered on many product lines they were commonly ignored and not taken seriously. Today, essentially all consumer products have warranty protection either directly or indirectly through consumer protection legislation. Moreover, warranty programs are essential for product manufacturers to remain competitive in global markets (see Kelley[5]).

The first industrial engineering curriculum was created by modifying a mechanical engineering curriculum to include a selection of courses from business, psychology, and statistics along with courses in time study and work methods. Production management, quality control, statistical testing and process control were soon to emerge as part of the core areas for entry level IE professionals (see Aldrich[1]). The focus of the discipline was on improvement of the efficiencies of the worker and the processes used in production to maximize productivity. Quality was certainly an important part of this focus and was particularly emphasized in the curriculum as the discipline matured. However, in the late 1960s U.S. engineering schools shifted bachelors level programs from five to four years. IE being the most diversified engineering field faces additional challenge in maintaining balance among the functional areas of the discipline. Consequently, in spite of the importance of quality and its role in the design and development of products and service systems the modern concept of quality is presented as a topic in selected courses but it is not treated as an integral part of the curriculum. Courses in quality control, statistical process control, and reliability are generally offered as a program option or elective courses, thus leaving some students completely void of the background.

The purpose of this paper is to propose a core industrial engineering course that will integrate quality, reliability, and warranty (QRW) concepts and methods. The objective is to provide a modern broader view of quality that is multidimensional with elements that relate to how products are developed, produced and accepted by customers, and to improve the integration of relevant IE courses. The approach is to construct a quality, reliability, and warranty paradigm that can provide a framework for integration. We start in Section 2 with a brief review of the history of how the IE curriculum evolved. Section 3 then provides discussion of the modern view of product quality and how the elements of quality are affected in production and manufacturing. In Section 4 a process is presented for developing or modifying a core course by selecting integration segments from other courses to create what will be defined as a learning platform. Guidelines are discussed for applying this approach to create a notional course in quality, reliability and warranty (QRW) that could become a core requirement for integrating quality in the IE core. Concluding remarks are provided in Section 5.

2. The IE Curriculum

Definition 2.1 *Industrial Engineering deals with the design and development of integrated systems of people, machines, and information resources for producing products and services.*

IE is the most diverse of the engineering disciplines. It evolved out of industry needs for efficient work systems and processes for better utilizing workers in factory operations in the early 1900s. The early focus was on time management and work simplification but soon included standards for conformance quality and extended beyond the factory floor. Today, IE is practiced throughout private and public sectors, including government and service industries. In all cases they are engaged in the development and management of systems and processes that best utilize people, equipment and other resources that will provide products or services at an optimum level of performance. For a complete review of the evolution of the IE discipline from inception to modern day practice and applications see Emerson and Naehring[3], Martin-Vega[8], and Billings et. al.[2].

The basic undergraduate core industrial engineering program today ranges from 120 to 136 semester credit hours, of which 6 to 10 courses are in industrial engineering, 10 to 14 in engineering science, with the remaining from mathematical, natural and social sciences and liberal arts. A typical curriculum is shown in Figure 1. This example was taken from Purdue University, where engineering students must complete a Freshman Engineering Program before they are admitted to a professional school. During the remaining three years they will complete the remaining physical and engineering science, humanities, and social science elective courses along with the required 12 IE courses listed. This program is typical of the standard Accreditation Board for Engineering and Technology (ABET) accredited programs in the U.S. (see Kuo[6]). While the contents of these courses have changed over time, through advances in research, new technologies and changing societal needs, the titles and basic course structures themselves have remained much the same over the past several decades. Pressures to keep engineering programs at four years add further challenge to implementing program changes. Faculties face hard decisions in deciding what to reduce or eliminate in order to make room for new concepts and methodologies. This is even more difficult for IE, being more diverse than other engineering disciplines. This has also led to much more deviation among IE programs across the country and abroad. The tendency has been to reduce the common core requirements; shifting some courses from core required to electives. Quality and reliability have fallen to this strategy.

Industrial engineering departments cope with the demands for change through three options: (1) have more diversity among IE programs – can impact the image of the discipline, (2) maintain a strong common core with diversity provided through strong program options, and (3) consolidate and integrate program concepts and topics. In this paper the third option is proposed for strengthening quality concepts in the core curriculum. There are several IE programs today that do not require these courses.

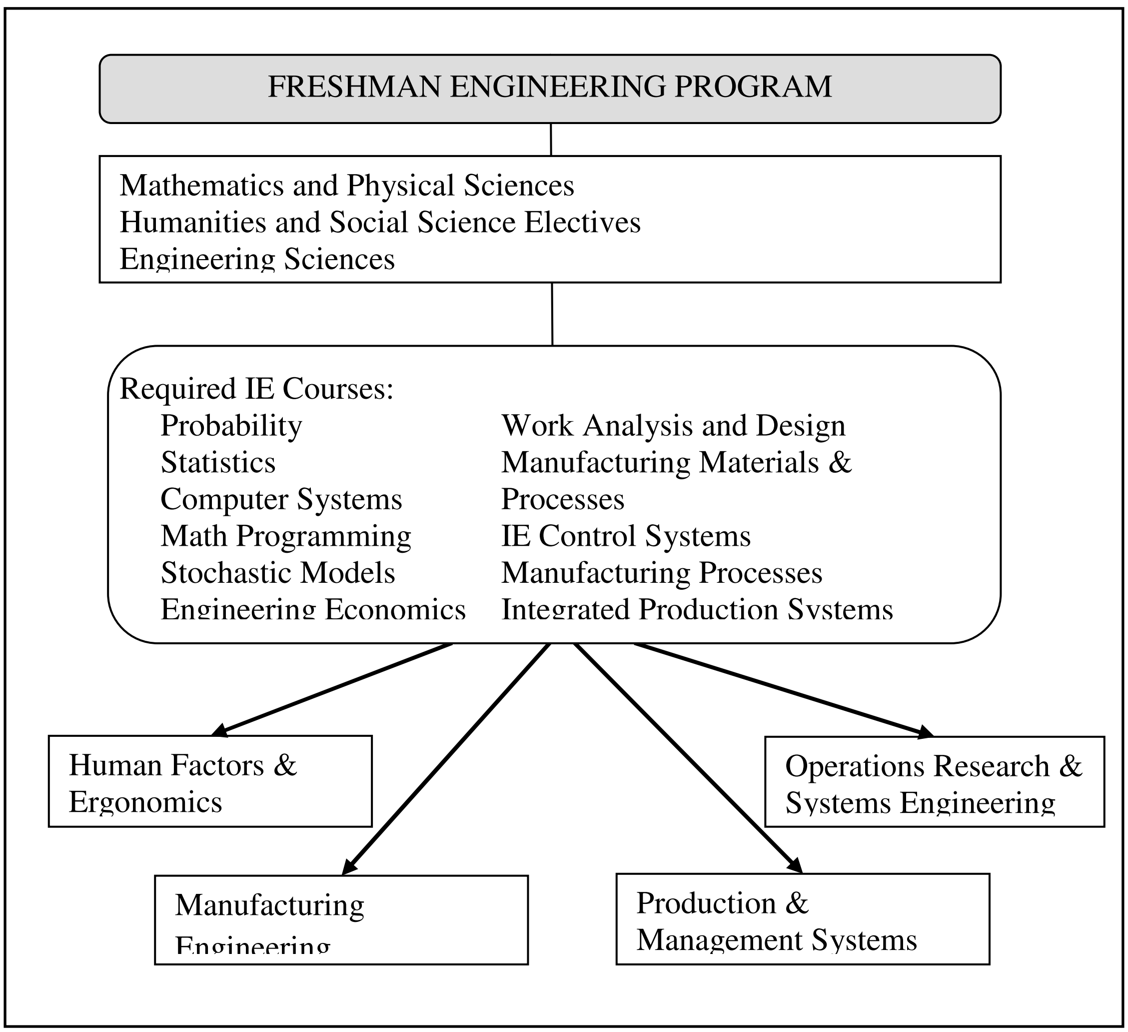


Figure 1. A Typical Industrial Engineering Curriculum (taken from Purdue University)

3. Quality, Reliability and Warranties

Definition 3.1 *Quality is the state of acceptance of products or services relative to how they are developed, produced, and utilized by customers.*

3.1 A Modern Interpretation of Quality

Quality is the resultant of a vector of factors and attributes that equate to the value of the way an item is developed, produced, and used by customers. Garvin[4] proposed eight dimensions for defining quality through characteristics relative to the manufacturer, customer, and a third party such as a product dealer. These are listed in Table 3.1.

Table 1. Product Quality Dimensions from Garvin[4]

	Dimension	Description
1	Performance	Operational performance of the product
2	Durability	Ultimate amount of use before deterioration or failure beyond repair
3	Reliability	Probability of product failing beyond a specified time having survived to that point
4	Conformance	Degree to which design and operating characteristics comply with established standards
5	Aesthetics	Way a product is sensed through appearance, feel, touch, sound, and smell
6	Perceived Quality	Overall image of the product among users and potential users
7	Features	Additional options and characteristics that distinguish a product from competition
8	Serviceability	Ease in servicing and maintaining a product

The first two of these dimensions, performance and durability relate to how well and how long a product will function. Vehicle fuel consumption, the output of a heater in BTU's, and the output of a pump in pounds/inch^2 are examples of product performance measures. Durability, is a product life measure, typically expressed in age or time of valued performance. Reliability is a probabilistic statement about the chances of an item surviving over time. Though it is formally a conditional probability, it is often expressed as a percentage or even on a subjective categorical scale such as low, medium, and high likelihood. It also relates directly to the amount of useful service a customer receives from a product. The fourth dimension, conformance, represents the level of compliance to standards in the production of a product. Conformance quality is tracked and assessed during the production and manufacturing processes through standard quality control methods and procedures. While the first four dimensions are readily quantifiable through objective measures, aesthetics and perceived quality are subjective and hence more difficult to assess on a consistent basis. Nonetheless, these dimensions are very important in expressing quality. Aesthetics represents the level of a product based on how it is sensed through appearance which also includes feel, sound, touch, taste, and smell, depending on the type of product. This is assessed through subjective scales, classification schemes, and relative rankings.

Perceived quality represents the overall image of a product and its producer among users and potential users. This is an indicator for consumer confidence. The last two dimensions, features and serviceability, are self explanatory and weigh heavily in customer attitude and satisfaction.

All of these quality dimensions affect the attitude of customers toward the value of a product. They are overlapping and interdependent but some are more dominating than others in contributing to the overall state of product quality. Conformance and reliability are two such dimensions. The impact from low conformance quality is generally due to manufacturing related issues found in early failures and malfunctions due to improper workmanship, assembly, or handling during final production. Reliability related failures generally occur later in the product lifetime and are the result of design and engineering problems. Consumers rely on warranties for protection against low quality products.

3.2 Reliability and Warranty

Definition 3.2 *Reliability is the probability of an item performing its intended function over its intended life and under specified operating conditions.*

A complete definition of product reliability further requires a description of what constitutes successful performance and the conditions of failure, the time period during which successful performance is to be sustained, and the user conditions and limitations for the particular operating environment. Producers have some liability for virtually any product, through direct or implicit warranties or by law. Warranties have been around in one form or another as far back in time that is known to mankind, Loomb[7], but as mentioned previously early product warranties carried little validity until government intervention led to the Magnuson-Moss Warranty and Federal Trade Commission Act of 1975 and subsequent uniform commercial codes that protect the public and holds producers accountable for low quality products. Since that time warranties have become extremely important to producers as well as customers, throughout our global economy.

Definition 3.3 *A warranty is a formal commitment to customers by a producer of products or services to assume certain responsibilities for the quality of their products or services following sale or delivery.*

It wasn't until the early 1970s that quantitative methods were used in quality and warranty planning, Thomas and Rao[10]. The literature has since developed considerably with numerous articles that deal with warranty policies and marketing strategies, cost and economic models, and maintenance and replacement decisions. Manufacturers have been using relative measures of warranty claims and costs as indicators of relative quality for many years, though data quality and availability have limited the capability of the analyses. With the modern perspective on quality and recognition and understanding of the importance of customers in the design and development of products, a product system view of manufacturing and producing products and services is essential. This is illustrated in its simplest form by the production control model shown in Figure 2. Input materials and resources are controlled through the management of planning and development of the product, which includes the product planning, design and development. The processer consists of the production and manufacturing processes that convert the materials into products that are sold and delivered as output to customers. The interior feedback loop provides information back on the conformance quality of the product as it progresses through the various production phases. This information is primarily to maintain control of the processes. The outward loop provides product feedback from customers and potential customers. Warranty claims are a major source of this information, along with customer surveys and consumer reports.

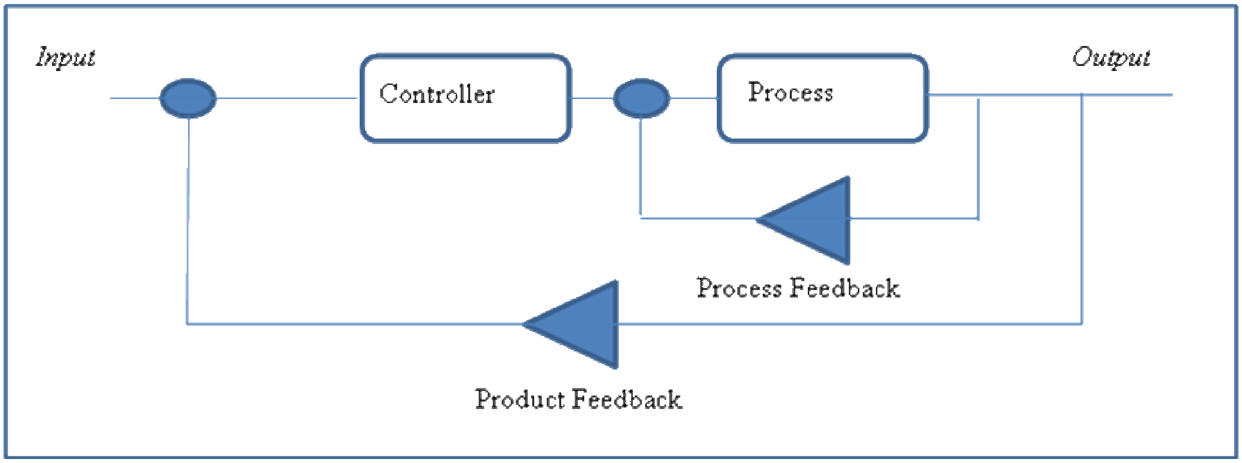


Figure 2. A production control model with warranty.

Continuous quality improvement planning has become fundamental throughout most industries today. It is widely accepted in service organizations and essential for product manufacturers to be competitive in global markets. The control model in Figure 2 depicts a conceptual view for treating the product development process systematically with warranty feedback information that is inclusive of all dimensions of quality and not isolated to standard conformance quality and reliability improvement approaches. Thomas[9] proposed a QRW paradigm based on using warranty feedback as an overall measure of effectiveness in developing and producing products. This paradigm can also serve as a useful approach to integrating important quality, reliability engineering, and warranty concepts.

4. Toward a Systems Approach to Course Development

In what follows we will consider a systems approach for developing and modifying courses and curricula by translating concepts and elements of learning into networks that represent their relationships and order. This is by no means a novel approach and in fact it is somewhat of a common sense approach to most IE's. The goal is to develop a set of relevant learning modules that will establish an overall higher concept that we will call a *learning platform*. Key topics are identified from quality control, reliability, and warranty methods using concept mapping[11], from which a notional QRW course and proposed learning platform is described.

__Definition 4.1__ A learning platform is a collection of concepts with strong connectivity relationships that: (1) facilitate retention of concepts, (2) provide reinforcement of learned materials, and (3) has high transference into other concepts and platforms.

A learning platform can be thought of as a higher level of integrated topics. Their development involves concepts in overlapping courses and they can be derived through multiple routes in curricula. There are varying opinions among engineering educators on the methods for accomplishing the three elements of learning in the above definition. Issues range from the amount of repetition of topics through course overlaps, review of materials from course to course, inclusion of projects, and case studies. The objective is to establish an efficient and effective routing for students to accomplish and build on the elements of learning through concept integration. Course prerequisites are very important in establishing the routes.

4.1. Example of a Learning Platform

The Poisson process is an example of a learning platform for industrial engineering. It is the fundamental stochastic process for the applications in queuing, inventory, and maintenance systems. It also serves as a building block for further studies of advanced processes such as renewal theory, semi-Markov processes, and generalized point processes.

The development of the Poisson learning platform requires the understanding of numerous concepts. A concept mapping of the Poisson process is illustrated in Figure 3. Students start with an understanding of probability theory, so they understand random events, sample spaces, random variables, and at least an axiomatic definition of probability. The four concepts shown on the left of Figure 3 are the events and random variables that are building blocks for the probability distributions that are involved in the construction of a Poisson process. Random events occurring independently over continuous time, and the corresponding random variables $X_i, i = 1, 2, \ldots$, representing the times between these events, lead to the development of the exponential distribution. The subtle but extremely important lack of memory property that is inherent with the exponential probability distribution has implications that carry forward to arrival processes to service systems in queuing and inventory, reliability theory, and Markov processes. The cumulative time to failure random variable involves summing independent exponential distributed random variables,

$$S_n = \sum_{i=1}^{n} X_i \ .$$

This involves the concept of convolving probability distributions and using probability transformation methods to derive k-Erlang distribution. To count the number of these failure events over a fixed period of time requires an understanding of the translation of continuous total time to event n, and discrete count of events in a fixed interval (0,t) through the probability equivalence identity,

$$N(t) \geq n, \text{if and only if } S_n \leq t \ .$$

The graph shown to the far right in Figure 3 is a sample realization of the Poisson process with events separated in time intervals $X_i, i = 1, 2, \ldots$, shown on the bottom axis which in turn generates an increase in the count at time t, $N(t), t \geq 0$ which is indicated on the vertical axis.

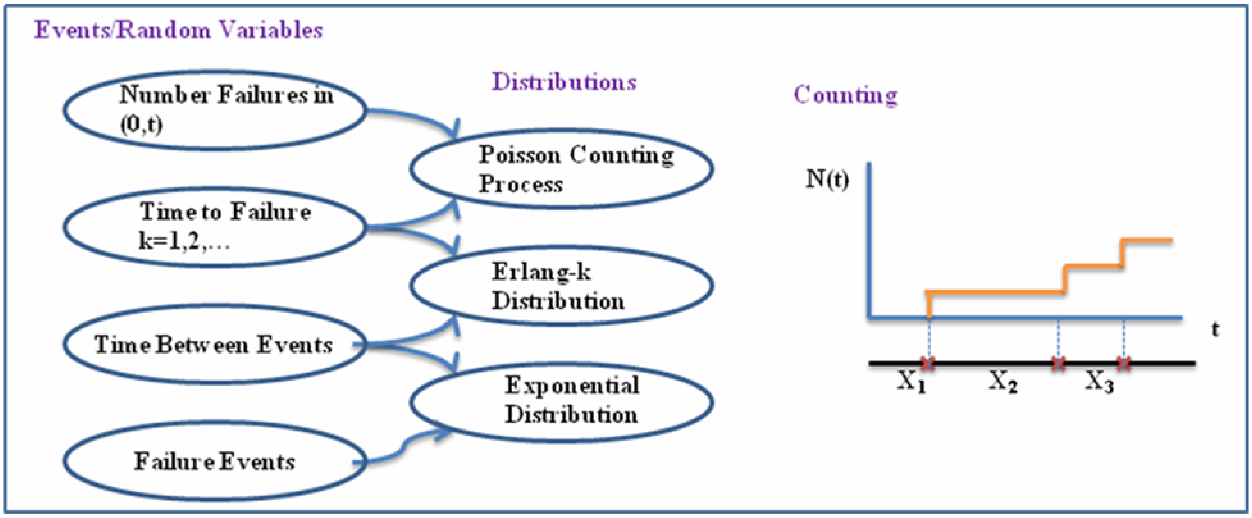


Figure 3. Concept map for a Poisson learning platform.

4.2. A Proposed QRW Learning Platform

The Poisson learning platform is an integrator for many concepts, methods, and applications in industrial engineering and operations research. A similar platform is needed to better integrate concepts from conventional courses in quality, reliability and related subjects into a single integrated framework that could serve as a core IE course and provide a foundation for advanced courses in quality related areas.

The QRW paradigm proposed by Thomas[9] is illustrated in Figure 4. The conceptual framework starts with the multidimensional definition of quality, $Q = f(Q_1, \ldots, Q_n)$ with the n elements that correspond to those factors and features that relate to how the products are designed, developed, produced, and used by customers. Functions involving design, production, and service have differing effects among the n dimensions, producing large impact on some and very little on others. This of course will depend on the particular type of product. The nature of the dimensions makes it difficult to establish an overall simple measure of the state of quality, with some dimensions being quantitative while others are very subjective. Warranty feedback, $W = h\left[g_1(Q_1, \ldots, Q_n), \ldots, g_m(Q_1, \ldots, Q_n)\right]$ does however, provide an overall weighting of the aggregate measure of the state of product quality. This provides not only important information for understanding and developing market strategy but also in developing quality improvement options.

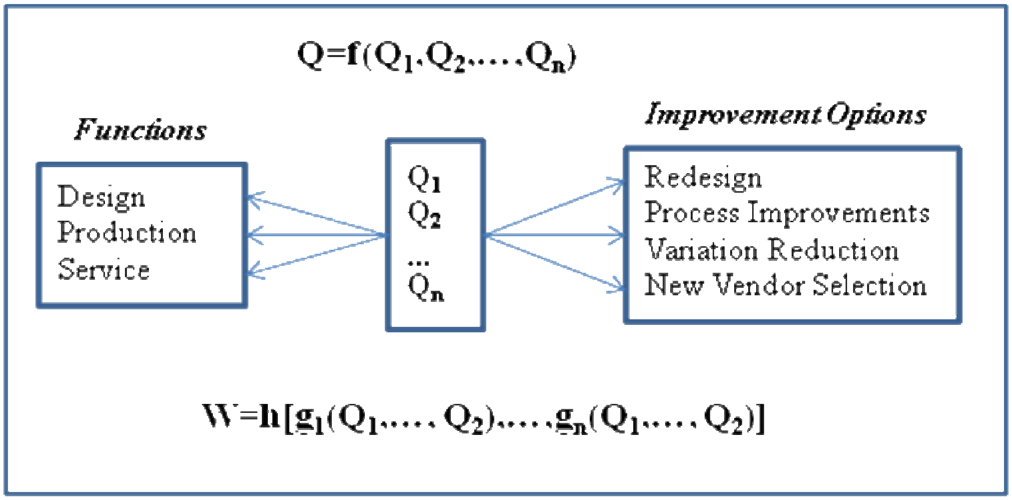


Figure 4. A Quality, Reliability, Warranty (QRW) paradigm.

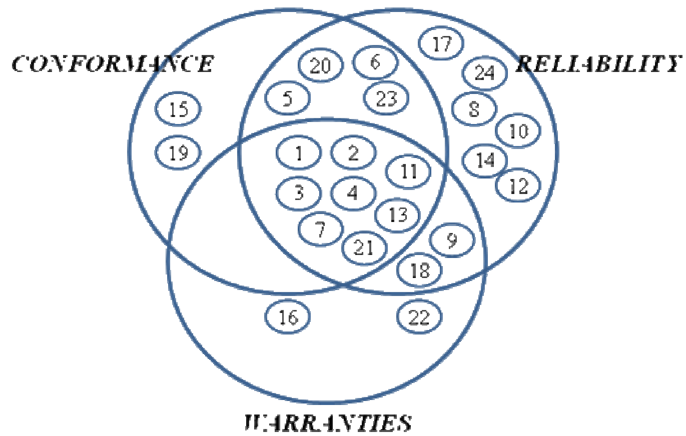
This paradigm can serve as a focus and starting point for the development of a learning platform. To this end let us develop a set of course topics for a course that could serve as a core IE course for introducing the QRW paradigm. A course description for this course is given in the Appendix. Since the content of quality related course offerings varies widely among IE programs a single approach is not likely to be applicable. The following approach should therefore be taken as guidelines for developing an integrated course. It is convenient to assume there are three existing sets of courses topics A, B, and C, from which the integrated course, I is to be developed. The procedure is as follows:

(1) Start with development of course objectives for I.
(2) Decompose each of A, B, and C into learning elements.
(3) Construct a concept map from the combined set of elements in (2) that will achieve the objectives in (1).
(4) Detail an outline and syllabus for the proposed course.

For our purpose here, A, B, and C represent concepts from quality control, reliability engineering, and warranty methods. The results are illustrated in Figure 5. The objectives for the course are given in the Appendix. Twenty-four topics were taken from typical conventional courses in the three subject areas. An association analysis was then conducted to identify the relationships among the concepts. These are mapped into the Venn diagram. The following seven concepts lying at the intersection of all three courses are identified as basic topics for developing a QRW course and learning platform.

1. Quality Definitions
2. Data Analysis
3. Statistical Methods
4. Quality Management
7. Failure Time Distributions
11. Reliability Improvement
23. Warranty Methods

Four other topics; six sigma, failure physics, operating characteristics, and design of experiments overlap with conformance and reliability. Reliability and warranties have common overlap for failures and lifetime characteristics, and product reliability. After synthesizing this information the final selection of topics for the new course is listed in the outline in the Appendix.



1. Quality Definitions	7. Failure Time Distributions	13. Quality Improvement	19. Control Charts
2. Data Analysis	8. Design for Reliability	14. Fault Tree Analysis	20. Operating Characteristics
3. Statistical Methods	9. Failures and Lifetime Characteristics	15. Statistical Process Control	21. Types of Warranties
4. Quality Management	10. Systems Reliability	16. Warranty Economic Models	22. Warranty Feedback
5. Six Sigma	11. Reliability Improvement	17. Reliability Testing	23. Design of Experiments
6. Failure Physics	12. Reliability Interference	18. Product Reliability	24. Standby Systems

Figure 5. A Concept Map for developing a QRW learning platform.

5. Concluding Remarks

Product quality depends on how well a product is made, how it performs, and how customers value it. Reliability is a dominating influence and warranties provide feedback from customers on the overall quality. Being multidimensional and complicated by the mixture of subjective elements and objective measures makes it very difficult to get a single measure that incorporates the weighted mixture of the quality elements. The feedback on warranty claims and costs can provide an overall indication of this weighted mixture. Therefore, understanding the relationship among the threesome of quality, reliability, and warranties is important for understanding how to develop high quality products.

Although this paper is focused on product quality, the concepts presented apply equally well to service quality. The quality dimensions for services and service processes are for the most part the same as those for products. The measures used for assessing services will vary with the type of service and likewise for the warranties that are applied.

Industrial engineers lead the way in the integration of resources for producing products and services. Quality has always been an important subject and area of focus within the discipline but the continuing pressures have relegated quality to become more of an area of specialization than an integrated core requirement that is threaded throughout the curriculum. The contention is that this results in entry level professional IE's lacking the solid foundation that they should have for designing and developing integrated systems. The strength of IE is the diversity of the discipline. This also presents the greatest challenge for IE educators to maintain a curricula core for the discipline and profession.

End Notes

The views expressed in this article are those of the author and do not reflect the official position of the Air Force, Department of Defense, or the U.S. Government.

References

1. ALDRICH, J.G., 1912. "The Present State of the Art of Industrial Management," *Trans. of the ASME*, Vol. 34, Paper 1378, pp. 1182-1187

2. BILLINGS, C., J.J. Junguzza, D.F. Poirier, and S. Saeed, 2001. "The Role and Career of the Industrial Engineer in the Modern Organization," Ch. 1.2, *Maynard's Industrial Engineering Handbook*, Ed. K.B. Zandin, Ch. 1.2, pp. 1.21-1.37

3. EMERSON, H.P. and D.C.E. Naehring, 1988 , *Orgins of Industrial Engineering, the Early Years of a Profession*, Industrial Engineering and Management Press, Norcross, GA

4. GARVIN, D.A., 1987, "Competing on the eight dimensions of quality," *Harvard Business Review*, **65**, 6: pp. 107-119

5. KELLEY, C.A., 1995, "Warranty Legislation," *Product Warranty Handbook*, Eds. W.R. Blischke and D.N.P. Murthy, Dekker, New York, Ch. 4, pp. 79-96

6. KUO, W., 2001, "Education Programs for the Industrial Engineer," *Maynard's Industrial Engineering Handbook*, Ed. K.B. Zandin, Ch. 1.3, pp. 1.39-1.53

7. LOOMBA, A.P.S. 1995, "Historical Perspective on Warranty," *Product Warranty Handbook*, Eds. W.R. Blischke and D.N.P. Murthy, Dekker, New York, Ch. 2, pp. 29-45

8. MARTIN-VEGA, L.A., 2001. "The Purpose and Evolution of Industrial Engineering," *Maynard's Industrial Engineering Handbook*, Ed. K.B. Zandin, Ch. 1.1, pp. 1.3-1.20

9. THOMAS, M.U, 2006. *Reliability and Warranties: Methods for Product Development and Quality Improvement*, Taylor & Francis, Boco Raton

10. THOMAS, M.U. and S.S. RAO, 1999. "Warranty economic decisions models: A summary and some suggested directions for future research," Operations Research, **47**, No. 6, pp.807-820

11. TURNS, J., C.J. Atman, and R. Adams, 2000. “Concept Maps for Engineering Education: A Cognitively Motivated Tool Supporting Varied Assessment Functions,” IEEE Trans. On Education, Vol. 43, No. 2, pp. 164-173

APPENDIX

Quality, Reliability and Warranty Methods and Processes

Course Description: The course deals with modern quality concepts and methods for assessing and evaluating product quality, reliability and warranties with a view toward quality improvement. Topics include conformance quality monitoring and QC tracking, product failure and lifetime characteristics, reliability measures, failure analysis, and warranty policies and economic models.

Course Objectives: The purpose of the course is to prepare students with an overall understanding of quality, reliability, and warranty concepts by integrating core and related courses in the curriculum that relate to the design, manufacturing and production, and economics of products and services. Students will develop competencies for dealing with the following issues:

1. Analysis and characteristics of produce failures.
2. Assessing product reliability.
3. Estimating and predicting warranty costs.
4. Developing and evaluating quality improvement strategies.

Background and Prerequisites: Students are expected to have a basic understanding of probability, statistical estimation and inference methods, and fundamentals of stochastic processes with introductory level exposure to Markov chains and Poisson processes.

Course Outline:

1. Product Quality
   Quality Management Philosophies
   Product Quality
   Elements of Quality
   Quality and Reliability
   A QRW Paradigm

2. Conformance Quality
   Quality Control Measures
   Control Charts for Variables and Attributes
   Acceptance Sampling
   Process Capability Analysis

3. Reliability Measures
   Failure Time Distributions
   Reliability and Hazard Functions
   Reliability Interference
   Lifetime Characteristic Curve
   Fitting Distributions

4. Reliability Improvement
   A Product System
   Redundancies
   Load Sharing and Standby Systems
   Failure Modes Analysis and Fault Trees

5. Product Warranties
   Warranty Types and Policies
   Warranty Cost Models
   Economic Warranty Decisions
   Product Improvement through Quality Planning