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The Design of Engineering Education as a Manufacturing System

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Walter T. Towner Jr.
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Christopher A. Brown

Christopher A. Brown, PhD, Committee Chair

RD Sisson Jr

Richard. D. Sisson Jr.
Director of Manufacturing and Materials Engineering

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Abstract

In recent years there has been great concern over what many are calling the “tuition bubble” in American higher education. Baumol and Bowen, in 1966, observed that because personally delivered services, like professors teaching engineering, exhibit low productivity growth there is a continuing and compounded rise in its real cost. Additionally, universities, in competing for students, tend to invest in expensive assets. The resulting cost of the education and the amount of student debt threatens to rise beyond the intrinsic economic value of a US college degree, especially in the face of equivalent substitutes.

While the problem and possible solutions are discussed by politicians, journalists, scholars, and college administrators, their solutions are not always supported by scientific evidence. There is no discipline in which this concern is more critical than engineering. The United Nations Educational, Scientific and Cultural Organization (UNESCO) has found that without technological innovations, there will be no production of new goods, no economic growth and no human development.

The overall objective of this research is not only to analyze but also to design, or re-design some of the essential aspects of engineering education systems using principles from manufacturing and industrial engineering, axiomatic design, computer simulation and financial analysis. The proposed system is able to operate at lower costs while producing high-caliber engineers.

A review of the state of the art revealed examples of value-added functions in higher education used to support public policy decisions in primary and secondary schools, but value-added functions for engineering education were not found. There was no evidence of process charts or value stream maps for engineering education in the literature. Examples of value and financial analysis, manufacturing system design and simulation have been applied in industries other than manufacturing such as healthcare. The literature does not reveal substantial attempts to apply these methods to the higher education industry as a whole or to engineering education in particular.

The approach presented relies on the decomposition of the functional elements of engineering education as well as defining a quantum of learning as an inventory unit.

Methods used include a value-added analysis, process charting and value stream mapping as well as axiomatic design decomposition, computer simulation and financial analysis.

The results show that the net present value (NPV) for the student increases over the interval from [t_{start} to $t_{\text{graduation}}$] as the time to employment post gradation decreases for a given discount rate. This is due to receiving employment income sooner during the cash flow. Engineering schools might benefit economically from reduced costs and higher tuition revenue resulting from greater system capacity.

The synthesis and generalizations show that by decomposing engineering education to a quantum unit of learning, a new system based on manufacturing principles is able to be designed, simulated on a computer and then analyzed for financial results leading to a new engineering education paradigm.

Acknowledgments

More thanks than I can ever give are owed to my beautiful wife and soul mate Carolyn, who is a WPI classmate from the great class of 1983. Carolyn and I (and Dan McCrory) worked on our Major Qualifying Project together and she is still proofing my work after all of these years.

The single most influential person in seeing me through this life accomplishment is most definitely Professor Christopher A. Brown. Chris, your patience, thoughtful prodding, round the clock emails and above all else, the time you devoted to me was above the call of duty for someone like me returning to engineering academic work after graduating from college 30 years ago. I will never be able to thank you enough. This all started when I went to meet Professor Brown for the first time in 1998 and I asked him “what I should do now?” and he said “take my class.” That was the start of it. Fifteen years later, enclosed herein please find the results of that fortuitous meeting.

I owe a debt of gratitude to Professor Sharon Johnson, whose courses I taught in her absence over 15 years. Professor Amy Zeng helped me teach her course in supply chain management, and Professor Chrys Demetry helped me to think about how a manufacturing system, when applied to engineering education, might be received by the academic community. Thanks also to Dean Frank Hall of Worcester State University who is working to bring axiomatic design to STEM teachers.

Laura Hanlan edited this dissertation with the same effort that I put into writing it. Chris Butcher covered the five courses I was teaching while I was finishing the writing. Toby Bergstrom was always asking questions that I could not answer.

I also want to thank Nat and Pete, and my mom and dad Meg and Walter; they all know privately what they did to help me get here.

I have had the great fortune to meet Professor Nam Suh on a few occasions, and I have read and re-read more of his writing than any other person on earth.

Professor J T. Black, Emeritus Professor from Auburn University really started this dissertation off with a few remarks to me about how he was passed over to be a dean when the ideas presented here scared off a search committee. He coined the phrase academic manufacturing system.

And finally, special thanks are owed to both Dean Mark Rice and Dean Richard Sisson for the support they have given to me. Without them none of this would be possible.

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Foreword

Twenty-first century manufacturing is a precision science. Long gone are the days of Charlie Chaplin's portrayal of a factory in *Modern Times* (1936), in which Chaplin is employed as a factory worker on an assembly line. Management's strategy is to increase output by accelerating the pace of assembly line without regard for the workers who cannot keep up. The worker is far removed from any process improvement and non-value-added time is reduced by simply making the line run faster.

Manufacturing and industrial engineering applies hierarchical design methods and advanced scheduling. In 1999 Mike Rother and John Shook published *Learning to See* and advocated mapping the entire production process to know when value is being created for process improvement.

Even hospitals use advanced manufacturing methods to improve the quality of patient care, surgery and financial position. Doctors and nurses now practice in mock operating rooms like pit crews in automobile racing. The goal is to identify and eliminate the non-value-added time from start to finish. Engineering education can be improved using these techniques by designing the system from a student centric point of view. In 1997, J T. Black proposed the idea of an academic manufacturing system. The students are the "raw material" being processing by the system with the professors "operating" their courses. If this analogy holds, then production metrics could be used to describe and improve the system.

Manufacturing's Holy Grail is mass customization. The idea that the customer can have whatever item that he or she wants, in the right amount and quickly, is exemplified by the 'replicator' from the 1960's television series Star Trek. This imaginary processing system delivered any meal or tool or device to the user upon a verbal command. The replicator produced the desired object from an inexhaustible supply of imaginary 'inventory' of some reconfigurable base matter. Work in progress did not accumulate because the replicator made what was required, when it was required and in the right amount. The Star Trek replicator is a model of an ideal manufacturing system and helps us to think about why the academic manufacturing system operates in the way that it does.

This research does not prescribe specific pedagogy or curricular content. In fact, it demonstrates just the opposite, advocating for a high degree of customization, breaking down the currently used batch mode of student processing found in most higher education. This work differentiates value-added and non-value-added time from the student's perspective. The objective is to present a financially viable educational system that will produce high quality engineering graduates with the skills to tackle engineering challenges facing 21st century society. This research shows, through various methodologies, that the application of manufacturing principles in the realm of engineering higher education will deliver quality and value, and resolve some of the financial challenges that currently threaten the stability of higher education systems in the United States and around the globe.

Chapter 1 - Introduction

1.1 Objective

This chapter discusses the rationale for designing engineering education as a manufacturing system, reviews the literature, defines the problem and proposes an approach.

An important premise is that the manufacturing system that would be most applicable to education is *mass customization*, i.e. individualization of processes and products to suit individual needs versus *mass production* i.e., identical products and processes, to educate engineers currently in broad use. Nonetheless, the system makes use of economies of scale where possible.

1.2 Rationale

Applying manufacturing principles to engineering education makes sense because a system that transforms incoming students into graduate engineers is, perhaps surprisingly, remarkably similar to a manufacturing enterprise. A factory expects the arrival of raw materials in a workable form; engineering schools accept students with complex and varying skillsets and needs. In both environments, those who design and operate the production system must make adjustments (in the case of a factory) or accommodations (in the case of higher education) in order to maximize the output, and lower scrap rates or decrease attrition, respectively.

Factories periodically rework raw materials in preparation for the production process. Engineers and managers review customer requirements and administer quality assurance to meet the customers' minimum standard of acceptability. Engineering education has its own standard of quality assurance, accreditation by the Accrediting Board for Engineering and Technology (ABET), a non-governmental organization that assures the quality of schools of higher education that offer degrees in applied sciences, computing, engineering, and engineering technology.

A great deal of what a manufacturer might refer to as *specialized processing* must take place between the time that a student arrives at an institution's door and the time that he or she leaves with a diploma. In engineering school, a great deal of specialized processing takes place. Manufacturing firms have been shown to work best using methods such as lean, six sigma, just-in-time, kanban, visual factory, and others in order to avoid errors and the accumulation of raw material and completed products inventories. Efficient manufacturers work towards adding value and eliminating waste and non-essential services (Rother and Shook 1999).

These simple ideas of matching the amount of work performed on a product with its demand or pace, and not spending time on things customers don't need or want to have to pay for is the foundation of lean manufacturing (Womack and Jones 1996).

In order for lean manufacturing to be applied to students in an engineering school, the work and processing performed on the student "product" should be viewed from the point of view of student needs (Chauhan and Singh 2012). Questions that might be asked include the following: When is the school adding value? What happens during the time in-between these value adding activities? A factory set up for production should know how the final product is being assessed, and in the schools case, the quality assurance standard is ABET.

The main production questions that a school should be asking are:

- How does the school know when it is adding value to the learning process?
- How can learning be quantified?
- How are delays in the learning production system eliminated?
- How will successful completion of the learning requirements be known?
- What constitutes on time delivery, throughput rates, production cost and system flexibility?

These basic questions cover the major concerns of a manufacturing engineer who is designing a production system for either the engineering school or the automobile factory. They are the first steps in designing a better system. The methods of achieving these goals will be different for the school, because factories work on physical objects and schools build knowledge and skills, but the *operational* aspects of the processing are exactly the same.

The first industrial revolution produced the job shop (Black 2013). The second industrial revolution gave the world interchangeable parts on a global scale by using the mass production “cookie cutter” approach in every way from building homes to automobiles (Schnaars 2009). Higher education has, to a large degree followed the mass production and standardization of product approach by processing students in a way academia claims to abhor (Simpson 1979). Student learning activities are currently scheduled en masse independent of an individual student’s learning rate.

Today, the antithesis of the mass production approach employed by higher education is emerging. Students have more options regarding the delivery method of educational material than ever before. Online, blended and formal lectures and massive open online courses (MOOCs) are some of the methods available. Each of these course delivery methods intends to achieve the same goal of student mastery of the course content. Each of these, and other methods, have similar value streams to accomplish this goal. This work suggests that mass customization in higher education is the way of the future and presents a design and analysis of a new engineering education system.

1.2.1 Unmanageable student debt

There are some imperatives at work in higher education today indicating the need to act sooner rather than later. The current system could be economically unsustainable in its current form. Since 1982 the cost of living has increased by 95% while the cost of higher education increased by 375% shown in Figure 1. (Augustine 2007). The average earnings for full-time workers age 25-34 with a bachelor’s degree are down 15% while the average public and private student-loan debt at college graduation is up 24% (Mitchell 2012). There has been much media discussion about a potential student debt bubble which might alter the funding of higher education in general and engineering education in particular because it is generally more expensive (Schumpeter 2011). C. D. Mote, Jr., an engineer and past president of the University of Maryland, sums up the debt situation in this way: “The debt burden has already become unmanageable -- defined as debt payments that exceed more than 8 percent of income -- for nearly 40 percent of the nation's graduates” (Mote 2004). The need for a new system is clear. Student loan borrowing is now the largest form of consumer debt (Schlesinger 2012).

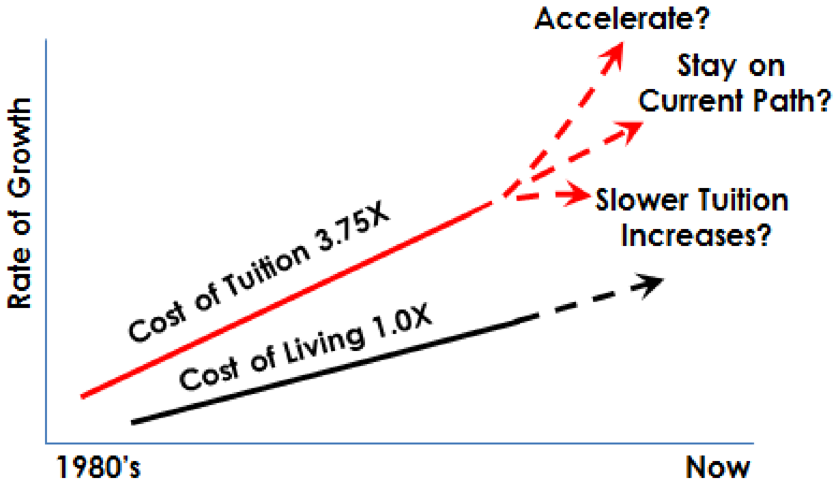


Figure 1 - Tuition is rising much faster than the cost of living

1.2.2 Standard of living created by engineers

The availability and access to engineering education is paramount to a nation's standard of living. Countries need engineers in order to produce value and to be competitive in global markets. Engineering education is a foundation for the development of industrial economies. Without technological innovations, there will be no production of new goods, no economic growth and no human development (UNESCO 2010).

The U.S. economy in particular needs engineers. In 2007 the National Science Foundation found that science based engineering education had become a commodity. In order to remain competitive in the global market, the output and cost of engineering education should be analyzed and improved. U.S. engineering education has long been regarded as the best in the world (Times Higher Education 2011). Many countries are now able to produce engineers with similar skills at lower cost. This shift has allowed global companies to employ engineers elsewhere at 20% of the cost of U.S. engineers (NSF 2009). The National Science Foundation recently funded a study to examine this issue which is now causing concern among engineering faculty (NSF 2009). This dissertation presents a method of reducing waste and increasing the value-added in engineering education. The economic future of a nation's economy could hinge on engineering schools being able to provide technically innovative citizens.

1.2.3 Adapting to the changing landscape of higher education

Arthur Levine speculated in 2000 that five powerful forces would potentially dramatically change higher education. They are the rise of an information economy, changing demographics, new technologies, privatization of higher education, and a convergence of knowledge producing organizations. In the more than ten years since this speculation, much of what Professor Levine envisioned has come true. He anticipated the following trends:

- Higher education will be individualized
- The focus of higher education will shift from teaching to learning
- Degrees will wither in importance

Levine speculated that universities may not respond and change to meet the new reality and that the business community will not wait. The consequences of inaction will be other competitive forces that will reshape the higher education landscape independent of these universities' lack of action (Levine 2000).

Massive open online courses (MOOCs) are changing the way higher education is delivered (Abeles 2011). MOOCs present the learning material in short segments often with questions embedded in their courseware (Martin 2012). The MOOC method of teaching makes educational material scalable to reach a larger audience by reconfiguring it into smaller segments. In some instances it allows students to go at their own pace. One feature of MOOCs that is still being developed is the personalized individual feedback mechanism that most, if not all tuition paying college students expect. In a typical college course, the student is able to get direct feedback to their questions either from the professor or a teaching assistant. The advent of artificial intelligence built into a courseware system is the lynch pin in solving the cost reduction problem of a previously un-scalable service that has been performed personally by the professor or the teaching staff (Koller 2012) (Severance 2012). Some of the most prestigious names in education like Harvard University, Massachusetts Institute of Technology, and University of California, Berkeley, and others, are collaborating on MOOCs (www.edX.com 2013).

1.2.4 Why should it take four years to earn an engineering degree?

Is it possible to deliver high quality engineering education in less than four years? In 1942, the US ARMY created the Army Specialized Training Program (ASTP 2012). ASTP educated over 9000 engineers with the functional equivalent of a four year degree in addition to the physical and military science educational requirements for junior officers (ASTP 2012). This was accomplished by reducing the throughput time from four years to one and a half years.

Currently, it appears that in most cases, engineering students advance through their academic course of study at a pace set by the school. These educational systems make little accommodation for either the exceptional or unexceptional student being transformed.

Engineering schools can be seen as manufacturing systems that further process and refine the incoming raw material of students' knowledge and skills. As in many manufacturing processes, adjustments must be made to accommodate the high degree of variability of the initial state of incoming raw material to be able to meet end user requirements. Some examples of manufacturing processes that have a high degree of variability in the incoming state of the raw materials are the reduction of ore to metal, processing of food or the distillation of oil to a minimum level of acceptable quality to meet customer needs. Similarly, an engineering student is also processed and refined to a higher quality state.

The University of Missouri-Kansas City's School of Medicine developed the "docent system" to complete doctor training in six years instead of eight (Marbury et al. 1991). The docent system is described by *The Academic Plan for the School of Medicine* (UMKC 2009).

> "We have defined a docent as a university scholar whose first responsibility is to the education of the students in his or her area. The Docents provide individualized attention to the needs of students by virtue of their geographic proximity to them and the presentation of a model of the integration of personal commitment and competence into a professional career of delivering health care services. In short, docents serve as guides and coaches in the development of clinical competence. In a real sense, the docent is society's representative and carries the responsibility of escorting the

> uninitiated student through the complicated experiences resulting in a blend of knowledge, judgment, self-motivation, compassion and ethics, qualities which society expects from the physician."

According to Marbury, *all graduates* of this program pass their National Board of Medical Examiners examinations.

One way the Docent system reduces the graduation time for doctors is by the availability of a university scholar to respond to students' questions. The Docent system does not leverage the professor s time, but it does reduce the non-value-added time in the learning value stream through the Docent's physical proximity to the students. Engineering schools might not want to increase the number of professors to achieve this same outcome, but schools could take note of how the reduced response time to the students keeps the students moving through the system with the least delay.

1.2.5 Manufacturing principles applied in non-manufacturing environments

Manufacturing principles have been applied in a number of non-manufacturing environments such as software, farming, newspaper production, commercial property management, financial services, banking services, healthcare and surgery (Collar et al. 2012) (Kollberg et al. 2007) (Delgado et al. 2010) (Zimina and Pasquire 2011) (Wang and Chen 2010) (Walley 2000) (Engum 2009) (Staats et al. 2011). Engineering education could benefit from the application of manufacturing principles.

1.2.6 Re-engineering engineering education

There is little in the way of process or production methods related to increasing the efficiency of engineering education in the literature. What is found are articles and opinion pieces about the need to reform engineering education from an outcomes or skills perspective (Lucena et al. 2008). Other articles about education process improvement, but not about production metrics or evaluation, include the following topics: re-engineering engineering education might call for new types of government or industry partnerships (Masi 1995); moving away from the almost exclusively technical focus (Augustine 2009), more interactive experiences with professors (Wankat 2009); collaboration and responsibility (Heinig 2005); quality and curriculum development in China (Li and Guo 2007); using assessments to re-engineer the process (Felder et al. 2000) and project management (Zu et al. 2012). Analysis and system design applied to the engineering education process using manufacturing principles is not evident.

1.2.7 Application of manufacturing principles to human oriented processes

All of the work presented herein does not prescribe how to teach a course. What is presented is a system that allows production to take place at a faster pace, and at the discretion of the participant, to progress through the process steps at a learner centric pace which can have a variable rate. This variable rate actually takes place in engineering education now as students that need more time to learn a subject have to put in extra student time to meet deadlines. But the opposite case does not appear to happen as learning schedules are not easily accelerated from the student's perspective.

A precedent exists that utilizes manufacturing principles to increase value-added in teaching engineering courses, but these courses were not formally described from a manufacturing perspective at the time. Worcester Polytechnic Institute (WPI), among other schools, has previously made use of a course management system that allowed for student paced learning. The system was called Individually

Prescribed Instruction (IPI) (Sisson 2011). The course material was made available to the students to learn at their own pace and through a series of assessments, along with support from the course teaching assistant (TA). A student could finish the course in a shorter time period if they were able to. The IPI courses were developed from the research of Professor Fred S. Keller (Keller 1968). The author participated in two IPI courses as a freshman at WPI. The demise of the IPI course offerings have been attributed to the issue of learning styles and cost effectiveness and faculty time commitment. Since the time of the original IPI courses, information technological enablers might have addressed some of these concerns (Turgeon 1997).

1.3 Field of review by chapter

This dissertation is organized into seven chapters shown in Figure 2. The first chapter provides the general introduction, which includes the general objective and rationale for this work.

Chapter 2 contains a literature review of themes used in the dissertation to avoid burdening the chapters with too much support material.

Chapter 3 addresses the question of how value is created and accounted for in engineering education. The chapter defines a value-added function for engineering education and shows a process chart and value stream map. The premise that engineering education exhibits a fractal nature is shown. As a result, a quantum of learning is developed through decomposition of the value stream. A main idea considered is the *potential* to improve the value-added proposition and how it is characterized.

A simple student centered discounted cash flow model is presented and drives home the point that in manufacturing, once the customer’s quality needs are able to be met, the system’s lead time to cash is the most important consideration (Ohno 1988). In the case of engineering education this would be the lead time to graduation and subsequent earnings from employment.

Chapter 4 uses Suh’s axiomatic design method to decompose ABET Criterion 3 in order to design a new engineering education system modeled as a manufacturing system. The goal of the design is to maintain the independence of the functional elements and minimize the information content in order to maximize the probability of success. Manufacturing and industrial engineering concepts are used to determine throughput, takt time and other metrics.

Chapter 5 presents a manufacturing system simulation using commercially available industrial engineering process modeling software. The simulation of the new design as a stochastic system is used to observe its behavior and report the results for proof of concept.

Chapter 6 contains a financial estimate of potential operating results for the new system and a proposed lean accounting method offers a way to support process improvement by professors.

Chapter 7 ties together the first six chapters through synthesis and generalizations that include interactions throughout. The main themes of each of the chapters are connected in chapter seven. The first chapter provides the rationale for why it could be necessary to design engineering education as a manufacturing system. Once value creation is able to be measured, a hierarchical decomposition method yields a solution for a new system design. A computer simulation then models the new system. The simulation allows for the adjustment of parameters to suit different schools’ needs and provides a visual representation of the operation of new design. A discussion of how MOOCs as an education system relate to the dissertation is included. And finally, the new design is translated into projected financial results of the new system. Lean accounting is discussed as a method of facilitating process improvement.

Finally, a critical examination of the main tenets of each of the chapters is presented in the discussion. What uncertainties exist in the new design and what are the uncertainties at the seams between the chapters?

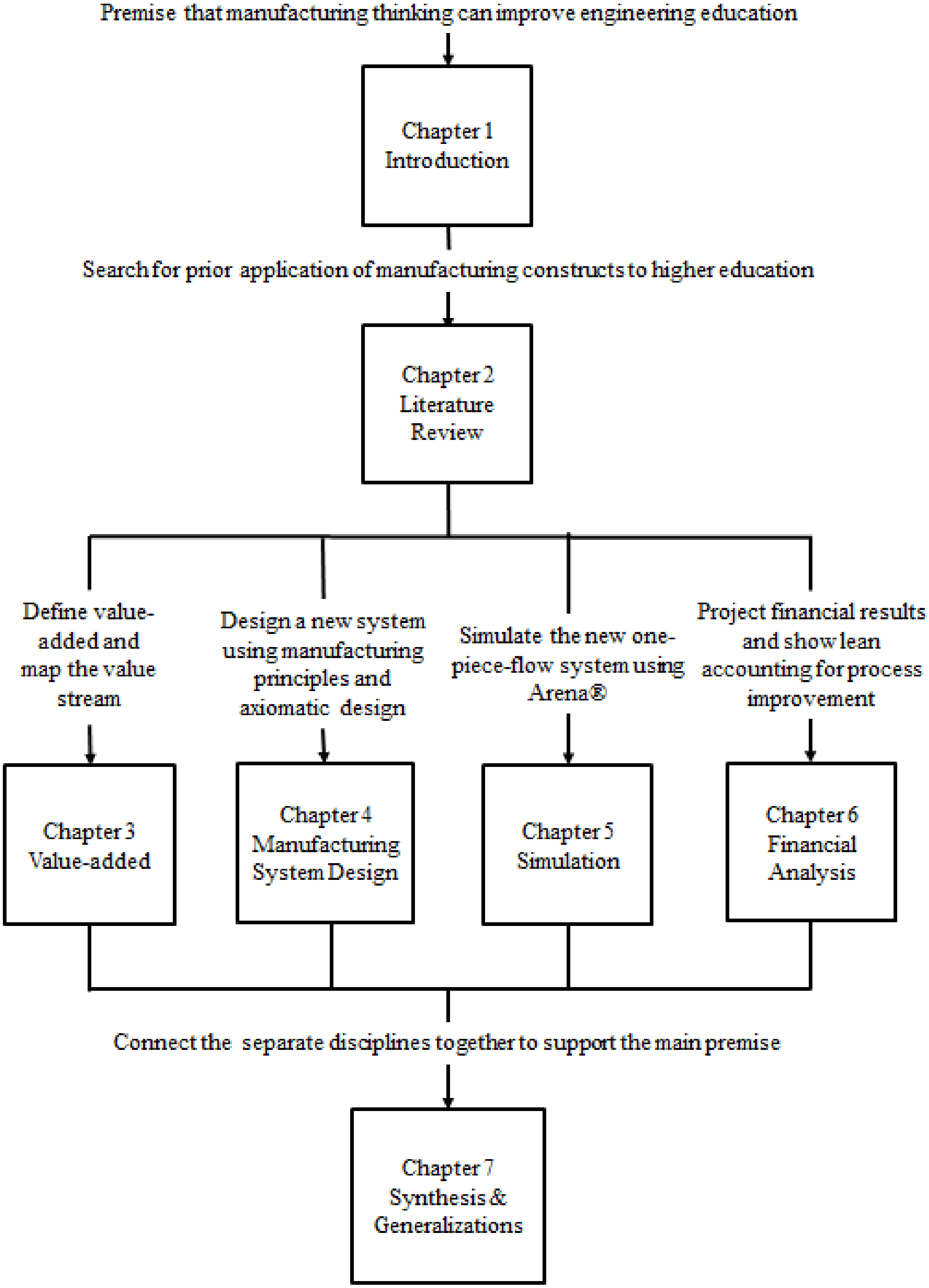


Figure 2 - Flow chart showing dissertation structure

Chapter 2 – Literature Review for the Design of Engineering Education as a Manufacturing System

2.1 Introduction

This literature review focuses on research and published trade and popular news in support of four premises. A multidisciplinary body of research has been examined. There are many aspects that are interesting and worthy of lengthy discussion. This chapter takes up some of this discussion to reduce the burden of reviewing the literature in the later chapters. The premises focus the discussion on the most relevant components of the literature an include:

1. Value-added functions for education can be used to explain the relationship between an engineering student’s tuition and income after graduation.

2. The use of manufacturing principles and methods, like value stream mapping, can be used to design or redesign higher education systems.

3. Industrial engineering simulation models can be used to model higher education systems.

4. Manufacturing process improvement has both strategic and tactical components, each of which is supported by different accounting methods.

The objective of this chapter is to review the literature with regard to designing engineering education as a manufacturing system. The primary objective is to review information about how an education system delivers value to its stakeholders. A secondary objective is to review the use of computer simulation of education systems and financial versus lean accounting methods for process improvement support.

The rationale for the literature review is based on U.S. engineering activity facing increased global economic pressure and the concept that a new, more efficient education system, based on manufacturing principles for achieving engineering education functional requirements can be developed.

Professor J T. Black of Auburn University suggested in a 1997 conference paper that a university could be modeled as an academic manufacturing system (AMS) for process improvement, increased throughput, and better quality (Black 1997). A manufacturing system model of university education and engineering education in particular, does not exist in the published literature.

This dissertation brings together interdisciplinary topics from education, industrial and manufacturing engineering, manufacturing system design, and axiomatic design in order to design an education system. A computer based simulation model is developed and the projected financial results of operating the system are analyzed along with process improvement support from lean accounting.

The literature review is designed to present current thinking from the literature. Publically available search tools such as ERIC, Google, and Google Scholar have been searched in addition to academically licensed research databases, namely Summon, Engineering Village, ScienceDirect, and Web of Science.

A search for "value-added function" and "engineering education" and “value-added function for engineering education” using Web of Science and Google Scholar yielded two results. One concerned engineering education’s economic value to a sovereign state (Arora and Kumar 2000). The other referenced sources on how to use the internet for engineering education (Kinghorn and Slaper 2009). Neither of these references relates to how an education system delivers value to its stakeholders, or, more specifically, how student tuition might relate to income after graduation.

2.2 Literature Review

This section categorizes the literature search results by various combinations of key words such as, but not limited to, “value-added,” “value-added function,” “engineering education,” and “higher education.”

2.2.1 Search results pertaining to “value-added function” and “engineering education”

A search of the literature yielded examples of value-added functions being used in education, but not necessarily in regard to the engineering education value proposition. Much of this prior work is focused on how government funding should be allocated in relation to socio-economic and other parameters of a particular school system (Goe 2008). The literature also contains references to primary and secondary schools in the U.S. concluding that good teachers create substantial economic value and that test score impacts are helpful in identifying such teachers (Chetty et al. 2011).

An example of a value-added function for education at the tertiary level was developed to relate how the earnings of college graduates in Texas correlate to the thirty-three colleges in the Texas higher education system (Cunha and Darwin 2009). Not surprisingly, it shows that the technical schools produce the highest earnings for graduates.

2.2.2 Search results pertaining to “value-added function” and “higher education”

A broader search of the literature for a “value-added function for higher education” produced many results that are not readily applicable to understanding engineering education as a manufacturing system.

A search for "value-added in education" returned eight results. This search returned studies investigating socio-economic factors in grade schools. Examples are research investigating the mathematics skills of pupils entering primary school in Cyprus (Kyriakides and Campbell 1999), and a study of the impact of teachers' engagement in the Emergent Literacy Baseline Assessment (ELBA) project (Kyriakides and Kelly 2003). An additional study reports on national assessment results for core curriculum areas of inner London primary schools (Sammons et al. 1997).

One article focuses on pupil performance in relation to a tool designed to help promote school improvement in England (Sammons and Elliot 2001). Research examining the effect of private school competition on public schools found no impact was evident in Georgia in 1980 (Geller et al. 2006). The key words “value-added analysis” identified differences between primary schools in Wandsworth, England, but causal correlations were not clear enough to initiate change (Strand 1997). One researcher investigated whether American students are getting the value-added in education that they need for work and life just because they have passed and received a diploma (Berg 2006).

A search for "value-added function" and "higher education" returned twenty three results. These demonstrated that research itself has a value-added function (Ghosh et al. 2001), and described how outreach was a value-added function in a university (Skivington 1998). Studies were conducted to investigate how materials are used in teaching (Jamtsho and Bullen 2007). One study showed there was a value-added function related to the gross domestic product of a country (Harrigan 1997); another investigated wage earnings in Pakistan (Kurosaki and Khan 2006).

2.2.3 Search results pertaining to “value-added function” and “education”

First used in 1935, the term “value-added” is defined as “of, relating to, or being a product whose value has been increased especially by special manufacturing, marketing, or processing” (Merriam-Webster 2013). The value-added for education is specific to the inputs and outputs of a particular set of circumstances (Saunders 1999). Value-added models in education likely do not estimate causal effects (Rubin et al. 2004) and can be complex statistical works that are difficult to understand and apply (Amrein-Beardsley 2008) (Rodgers 2005).

Kelly and Downey (2010) comment on the potential difficulty in developing and using such statistics based value-added functions:

> “Value-added measures can be used to allocate funding to schools, to identify those institutions in need of special attention and to underpin government guidance on targets. In England, there has been a tendency to include in these measures an ever-greater number of contextualising variables and to develop evermore complex models that encourage (or ‘impose’) in schools a single uniform method of analysing data, but whose intricacies are not fully understood by practitioners. The competing claims of robustness, usability and accessibility remain unresolved because it is unclear whether the purpose of the measurement is teacher accountability, pupil predictability or school improvement. This paper discusses the provenance and shortcomings of value-added measurement in England (and the Pupil Level Annual Schools Census that informs it) including the fact that although the metrics are essential for School Effectiveness Research, they fail to capture in its entirety the differential effectiveness of schools across the prior attainment range and across sub-groups of students and subjects.”

The literature review confirms the prior work of Saunders (1999) and other researchers that a value-added function might not be truly objective and is influenced by the aims of its developer. A value-added function can be a simple relationship or a statistical model so complex that its usefulness is in doubt (Kelly and Downey 2010). Value-added models in higher education should be simple, but not at the expense of accuracy (Rodgers 2005). More evidence of the dubious nature of sophisticated value-added functions are seen in a well-known method, the Education Value-Added Assessment System (EVAAS): “[…] although EVAAS is probably the most sophisticated value-added model, it has flaws that must be addressed before widespread adoption [….] the model was used to advance unfounded assertions” (Amrein-Beardsley 2008).

The value-added model for engineering education designed as a manufacturing system is concerned with system operational costs and the value of the output for the graduate. For the engineering education process, tuition is the relevant cost, and earnings after graduation are the relevant output value. Searches of the literature yielded results examining value-added in higher education. However, none focused on how the cost of production is related to the learning process and to the subsequent earnings for the student.

Clearly, value-added in education is a widely used term that is not understood or well defined (Saunders 1999).

2.2.4 Search results pertaining to the "calculation of value-added"

A search for methods on how to define the value of products or processes introduces the area of value engineering developed by Lawrence D. Miles. According to the Society of Value Engineers, value is defined as a fair return or equivalent in goods, services, or money for something exchanged (SAVE International 2007).

The value methodology, a systematic and structured approach, improves projects, products, and processes. The value methodology is used to analyze all manner of manufacturing products and processes, design and construction projects, and business and administrative processes. The value methodology helps achieve balance between required functions, performance, quality, safety, and scope with the cost and other resources necessary to accomplish those requirements. The proper balance results in the maximum value for the project. The Society of Value Engineers defines value by the following relationship: value equals function divided by cost (SAVE International 2007).

Similar to the cost-benefit ratio method in engineering economy, value engineering analyzes tables of factors that result in an index value to inform of the relative merits of a project or endeavor (Newnan et al. 2012) (Parker 1998). When an item has a value greater than 1.0, the item is perceived to be a fair or good value. When an item has a value of less than 1.0, the item is perceived to be a poor or lesser value (Parker 1998). The value methodology might be adapted to measuring the performance of an engineering education system, but a discounted cash flow analysis can be easier to calculate and understand.

2.2.5 Search results pertaining to "value-added metrics"

A widely used method known as The Balanced Score Card could be useful as a value-added metric in engineering education. The method ties together both financial and non-financial factors to get a sense of the larger picture of providing customer value metrics (Kaplan and Norton 1992, 1996). This method provides aggregated data about progress towards an organization's strategic goals. It could be configured to show school administrators how the school is performing, by relating the cost of the students' tuition to their wages and income after graduation and how the outcomes are meeting the quality standards set by ABET. The customers of the AMS are industry and government (Black 1996).

Methods similar to The Balanced Score Card are product development based models that weigh and sum various components attributed to customer value (Jacobs and Chase 2011). These methods also define value-added from the customer attribute perspective but not from an operations point of view.

2.2.6 Search results pertaining to "value-added" and "education"

Results of the search phrase containing variations on the terms "value-added" and "education" fell into two broad categories. Some references were of a qualitative nature. An example of this discusses the shortcomings of using graduate attributes as a primary approach in determining the value of an engineer (Palmer , Teffeau and Newt 2001). Another example describes a firm upgrading capacity to increase the value-added of its product and processes (Giuliani et al. 2005). An example in computer science reveals that in the preparation of public examination papers, the administrator becomes a bottleneck in the system, rather than providing a value-added function because the administrator has to needlessly process the electronic scripts (Chadwick et al. 1999). A library was examined according to what value-added functions are being performed (Shaughnessy 1996). Other references examine a service operations management transition from routine back office processing to becoming a value-added research department for a large company (Youngdahl et al. 2010). One source discusses how government purchasing officials offer more value-added than in the past (Callender and Matthews 2000).

Quantitative results from the socio-economic domain discuss various correlations like the value-added from the aging work force in Europe (Cataldi, Kampelmann and Rycx 2011). Another paper discusses which factors are generating higher value-added per worker in various Chinese industries (Xu 2008).

More examples of quantitative value-added research pertain to small firm growth in developing countries affected by the value-added functions of production (Nichter and Goldmark 2009) and small business growth of German, U.K. and Irish companies from the subcontracting of lower value-added function to lower cost areas (Roper 1997). Other studies examine value-added in particular industries, such as the apparel industry in Guatemala and Columbia (Pipkin 2011). An examination of the value-added function for each commodity in a tax system was found (Coady and Harris 2004). Work was done analyzing the data limitations that prevent the specification of a value-added function for students in academic versus vocational high schools (Maxwell and Rubin 2002). Research was found on the value-added by education coursework for teachers (Floden, Wilson and Ferrini-Mundy 2002). Another paper discusses that the value-added of education is high even though the final product is not necessarily great (Brasington 1999).

2.2.7 Literature review for a value stream map for engineering education

A search of the literature for a value stream map for higher education, especially value stream maps of the learning process, produced few viable results. Value stream maps, in general, tend to focus on physical production systems in manufacturing environments because they originated in the manufacturing sector (Cima et al. 2011).

A search for "value stream map" "engineering education" returned three results. The results discuss how to create value stream maps (Whitman et al. 2005) , using value stream maps in healthcare (Bird et al. 2010) and the use of value stream maps of businesses to facilitate student understanding of management (Emiliani 2006). These sources do not describe a value stream map for engineering education. A search for "value stream map of education" did not produce any results.

Value stream maps of higher education processes frequently consider service oriented administrative tasks like the ordering of supplies and managing university enrollment (Bonaccorsi et al. 2006). Examples of value stream mapping in higher education from non-peer reviewed sources include physical plant work orders, key access control distribution, inventory records and other transactional processes (Kusler 2008). Still others consider classroom processes such as syllabus construction, grading and feedback, but not the actual learning process (Emiliani 2004).

More examples of value stream mapping in non-manufacturing environments include the use of value stream maps to influence executive behavior (Emiliani and Stec 2004), or to map a physician’s clinic (Lummus et al. 2006). Value stream mapping of the product development process was found (McManus and Millard 2002) (Millard 2001) but there are no examples of a value stream map linking the knowledge/information domain and the physical domain of the engineering education process (Shuman et al. 2005).

Dahlgaard and Østergaard (2000) stated that a new organizational structure for higher education should be discussed in order to improve student and faculty learning and they offer the following conclusion:

"Violations of the principles of lean thinking and Total Quality Management are widespread in education and the result is too much waste."

They suggested that in order to apply lean education to higher education, the following steps be taken from *Lean Thinking. Banish Waste and Create Wealth in Your Corporation* (Womack and Jones 1996).

1. Specify *value* (the required qualities) by product. In the area of engineering education ABET provides much of this value specification.
2. Identity *value stream* for each product. If the product is the student's knowledge and skills then the value stream of education is of the learning process.
3. Make the *value flow* without interruptions through "the ability to have continuous learning among both students and teachers doing the things that constitute value." A value stream map will elucidate this value flow.
4. Let the customer *pull value* from the producer (faculty) – 'the customer may be defined in two groups, (1) students (the product) and (2) employers (the customer) and graduates who "pull" the (knowledge) value from the teachers (who operator the process). The demand for highly skilled engineers is assumed to be of sufficient nature that over production is not a concern at this point in time.
5. *Pursue perfection* - "the individual customer and staff members may try to pursue some personal perceptions of perfection, which might be significantly out of touch with the general agreed upon definitions of value, value flow, value stream, and so on."

Dahlgaard and Østergaard discuss value, value stream and value flow for a new organizational structure but they do not provide a value stream map.

Lean thinking necessitates viewing the value stream from the learner's perspective (Alagaraja 2010). Lean sustainability in the higher education field has been focused on the operations or administrative side of the enterprise rather than the teaching or research side (Comm and Mathaisel 2005).

Applying lean process improvement to individual courses has been performed in a business school course, but a value stream map was not developed. It has been pointed out that the batch and queue characteristics of many university systems leads away from lean processing (Emiliani 2004). The AMS is a job shop (Black 1996).

While value stream mapping of processes seems to be considered important, a model of the education value stream is not evident. A basic tenet of value stream mapping of a process flow is to differentiate the value-added and non-value-added times (Rother and Shook 1999). Once the non-value-added times are found, they are minimized or eliminated. No research was located that addresses the analysis of the non-value-added time component in learning activities.

The ideas put forward in the literature also do not challenge the academic course year schedule system broadly in place. The underlying assumption is that the in-school processing time remains on the same schedule as the original traditional university calendar. Calculations of throughput time or cycle time of student learning are missing.

Dahlgaard and Østergaard suggest that attempts to view the education process from a production point of view are inappropriate because colleges do not create skills on an assembly line basis (Dahlgaard and Østergaard 2000). A counter argument is that a university *actually is* a production process that has schedules, throughput requirements and quality assurance mechanisms. In the case of engineering education at least, specific knowledge and skills are transferred somewhat sequentially to the student.

One question might be "why would operating the education system at a university as efficiently as possible diminish the quality of the graduates and the degrees they earn?" Another question is "can industrial production methods be employed to avoid education systems operating sub-optimally?"

Schools could seek to improve their systems using two important manufacturing engineering concepts:

1) Production should not experience unnecessary delays that increase throughput (Kimura and Terada 1981)
2) The pace of production should not impact the quality of the final output (Neely et al. 1995) (Yusuf et al. 1999)

In any production system, speedy production resulting in high quality is desirable.

Graduate business courses have been improved and made more lean by various means. These include improving the syllabus and deliverable requirements (Emiliani 2004) (Emiliani 2006). All of these improvements are worthy of implementation. But they still do not address the central question of how to eliminate waste from non-value-added activities to achieve more learning in a shorter time.

Course improvements suggested in the literature say little about how learning during courses progresses or how the students are spending their time relative to a course. No assessment of the *production* aspect of the course is attempted. What are offered are examples of fine tuning the course content without really getting to the heart of the subject matter; how do we eliminate the non-value-added portion of the learning activity?

The time in which a student could expect to earn an engineering degree is usually prescribed by the school's academic calendar and course offering schedule. This system, which has been in effect since the end of the 19th century does not allow students to move through the system at a pace faster than the schedule even if they are able to do so. Individual students periodically might be able to arrange courses so that more is able to be accomplished in a given period of time, but the system precludes fast learners from quickly demonstrating mastery and moving on to the next subject at their own pace. Presumably this reality has been and will remain entrenched because it will take a coordinated effort from faculty and administration to change the system which is also true in industry.

A major outcome based on improving a value-added measure for a school is to acknowledge the impact of non-value-added time spent in the system. The elimination of non-value-added time will allow for a student to graduate in a shorter length of time or for a student to cover additional subject matter in the same major or other through a dual degree while in school. If more students choose to graduate faster as a result of the non-value-added time being reduced, this would allow for greater numbers of students to enter the system as the demand on school resources is reduced thereby increasing revenue for the school. More students, working at a faster pace, should not result in a reduction of quality.

The world's first recognized degree granting university, the University of Bologna was founded in 1088 (University of Bologna 2012). Student centered learning was such that professors could be fined for not completing a course on time. This suggests that the speed at which subject matter is presented has been an issue of concern to degree seeking students for a very long time (Long 1994). The modern form of academic scheduling has presumably been developed more for the benefit of the instruction givers rather than the instruction receivers, leading to inefficiencies for the students. Historically this could potentially have been for cost reasons. As technology shifts cost structures, different models are possible.

2.2.8 Literature review for a process chart for engineering education

An important milestone in the history of process charting can be traced to a meeting at Dartmouth College in 1911 for the first Conference on Scientific Management. Participants included Frederick W. Taylor, Frank B. Gilbreth, Lillian M. Gilbreth, Henry L. Gantt, Harrington Emerson and others. In that year, Taylor published *The Principles of Scientific Management* and Gantt published *Work, Wages and Profits* (Graham 2004).

In 1947 the American Society of Mechanical Engineers formalized much of the work done previously and established the ASME Standard for Operating and Flow Process Charts. Many of the symbols and conventions in this standard are still in use today such as a circle representing an operation or an upside down triangle representing storage or delay (Graham 2004).

A variation of process flow-charting today is value stream mapping, made popular by Rother and Shook in their 1998 book *Learning to See* (Towill 2010). The main concepts in process charting have not changed much since their origination, but the methods of moving from paper to software based tools have made multiple iterations of a process chart much easier to generate.

A search for "process map" and "engineering education" returned fourteen results on topics not specific to a process map of engineering education. References include a student's design performance (Adams et al. 2003), and references to other citations on engineering education contained in a paper (Amin et al. 2006) . Also discussed were the use of process maps for inventing (Golish et al. 2008), and for the path for lifelong learning (Janssen et al. 2011). Methods for assessing knowledge (Walker and King 2003) and cost management (Hollmann 2006) were also identified.

Research performed on process mapping as the key step in understanding a management process was found (Prasad et al. 2012), as well as a description of using process maps in engineering design (Daly et al. 2011). Similarly, searches for "process chart of education," "process chart of engineering education," "process map of education," and "process chart of engineering education" all yielded no relevant results.

2.2.9 Literature review for manufacturing system design and education systems

A literature search attempted to discover prior work in the following areas relative to manufacturing system design. What examples of accelerated engineering education might be found in the literature? Has university education been modeled as a manufacturing system? What effort has been made to characterize value-added and non-value-added time in the university student learning process?

2.2.9.1 ASTP - accelerated engineering education: an example from WWII

The Army Specialized Training Program (Appendix A) was a military training program instituted by the United States Army during World War II at a number of American universities to meet wartime demands for junior officers and soldiers with technical skills. Utilizing major colleges and universities across the country, the Army provided what was supposedly the equivalent technical content of a four-year college education combined with specialized Army technical training, and over a period of one and half years trained over 9000 engineers. Other than the ASTP program, detailed production system designs of education modeled as a manufacturing system were not found.

2.2.9.2 Contemporary view of the industrial model of higher education

Leading higher education researchers resist describing higher education as a business or management process that has customers and yields students as production output (Emiliani 2004). Manufacturing is argued to be in the physical domain of converting raw materials and, therefore, not applicable to the education of students. While this might be true in the literal sense, operationally, schools have many characteristics in common with manufacturing production systems.

Astin wrote in his book *What Matters Most in College?* that colleges cannot stamp out graduates like physical parts on an assembly line (Astin 1993). But accredited engineering schools do have clear metrics regarding the quality of students' achievements as promulgated by ABET in its publication: Criteria for Accrediting Engineering Programs (ABET 2012).

Higher education can be modeled as a manufacturing system (Black 1997). The students' knowledge and skills are processed over time to meet a minimum ABET quality standard. The system has inputs of raw material in the form of students' initial knowledge and skills which are modified and improved over time by processes similar to those in a factory. Some raw materials are initially of a higher quality than others (e.g. advanced placement, SAT scores). The engineer-creating factory, in other words, the university, has process yields, rework, and scrap rates that can be calculated. It may be difficult to measure process yield s and scrap rates for students attending university due to the complex nature of the task. Passing through the system to graduation means the high quality product is fit for use by subsequent entities, referring to Juran's definition of quality output (Juran 1999). This leads to the premise that engineering schools function as manufacturing factories that produce graduate engineers.

2.2.9.3 Manufacturing system design of the engineering education process

J T. Black suggested that activities in the university system can be modeled as manufacturing functions shown in Table 1 (Black 1997).

Academic	Manufacturing
Professors & staff	Manufacturing process/machine tools
Operations (things professors do): Lecture, Research, Grade, Advise	Operations (things machine tools do): Turning, Drilling, Boring, Tapping
Learning Systems: Problem-based, Project based, Internship	Manufacturing Systems: Job Shop, Flow Shop, Continuous Processes, Cellular
Course Delivery Systems: Lecture, Online asynchronous, Online synchronous, Blended, Massive open online courses (MOOCs), Independent study, Directed research	Design/Layout of Manufacturing System: Functional Layout, Product Layout, Process layout
Academic Department: Design, Personnel, Registrar, Accreditation	Production system: Design, Personnel, Accounting, Sales & Marketing, Quality assurance, Maintenance

Table 1 - Similarities between manufacturing and education systems

An analogy can be drawn from this table that the professors are the machine tool operators, the courses are the machine tools and the students are the inventory being processed in an academic manufacturing system (Black 1997).

2.2.9.4 Process metrics for engineering education

One process metric for manufacturing production systems is takt time. Takt time, the target time between units of production, is “the drumbeat” of the production system and is considered the most important metric in mass production (Black and Hunter 2003) (Wilson 2009).

The takt time of the students pursuing educational processing is currently determined by the pace determined by a school, not by the pace the students are able to perform. Different students learn at different rates posing the challenge of accommodating a wide range of students mastering the material at different rates. The time that a student must wait for new academic challenges within and between courses is waste because the timing of the university system generally does not allow for a new processing task to begin until the entire current batch is complete.

2.2.9.5 Technological disruption in current engineering education systems

Competitive advantage stems from the ability to implement innovation as well as the ability to meet customer demand. Christensen, author of the *Innovator’s Dilemma*, in a recent interview remarked about the vulnerability of higher education. He said “[…] the availability of online learning. It will take root in its simplest applications, then just get better and better. You know, Harvard Business School doesn’t teach accounting anymore, because there’s a guy out of BYU whose online accounting course is so good. He is extraordinary, and our accounting faculty, on average, is average” (Christensen et al. 2013).

Christensen and Horn, in an opinion piece in *Wired Magazine* talk about technology driven disruption in higher education and specifically state that the future is about tailoring education to individuals. “We believe they are likely to evolve into a “scale business”: one that relies on the technology and data backbone of the medium to optimize and individualize learning opportunities for millions of students” (Christensen and Horn 2013).

Stated another way, competitive advantage is the ability to envision and create an alternative future that introduces a technological discontinuity or disruption in the marketplace.

Is the analogy of engineering education and a manufacturing system an appropriate one? The answer today is yes, more than ever. The new thinking is that education can be appropriately viewed as a production process.

2.2.9.6 Emergence of the massive open online course (MOOC)

MOOC is an acronym for Massive Open Online Course. The term was first used in 2008 to describe a large online course run by George Siemens and Stephen Downes (Cormier and Siemens 2010).

MOOCs have been in the press in recent years as a new way for higher education to be delivered. One new organization, edX, is a not-for-profit enterprise of its founding partners, the Massachusetts Institute of Technology (MIT) and Harvard University that offers online learning to on-campus students and to millions of people around the world. To do so, edX is building an open-source online learning platform and hosts an online web portal at www.edx.org for online education (www.mit.edu 2011).

EdX currently offers HarvardX, MITx BerkeleyX and other universities’ classes online for free (www.edX.com 2013). These institutions aim to extend their collective reach to build a global community of online students. Along with offering online courses, the three universities undertake research on how students learn and how technology can transform learning both on-campus and online throughout the world (www.edX.com 2013). MOOCs have throughput rates just like on-campus courses do. The difference is that the scale and methods leverage technology differently than traditional courses. If MOOCs are to be accepted for college credit, a method of maintaining high quality and tracking the pass fail rate is necessary as evidenced by currently low passing rates of 5 to 14% (Watters 2012).

2.2.10 Literature review for simulation of education processes

A key finding is made by Donatelli and Harris who state that simulation “adds the fourth dimension, time, to a value stream map” (Donatelli and Harris 2002). They posit that “[…] value stream mapping is an efficient design tool, while simulation is an efficient analysis tool.”

There exists a plethora of articles about using computer simulation as a tool to be used in teaching courses. Phrase search terms for “computer simulation” and "model of education"; computer "simulation of education" and Arena^{TM} (the industrial process simulation software used in this dissertation), "simulation of education" and variants that included college processes and learning, produced no results in the peer reviewed literature or news, including online blogs.

The developer website for the Arena^{TM} software product lists many industries such as logistics and manufacturing, but education or learning was not one of them. Proprietary examples can exist, but published examples of using industrial engineering process modeling software were not found.

2.2.11 Literature review for financial improvement of education system

2.2.11.1 Improving the overall financial results in higher education

A search for efforts to control costs in higher education found that there were at least a few researchers who believe that making professors more productive could result in worse quality (Archibald and Feldman 2010). A 1995 study at the University of Rhode Island attempted to determine the margin contribution of each program and analyze the relevant operational costs and revenue source. It was concluded that the overhead in a university is where the problem lies. Universities need more accountability in their financial statements (Doost 1998). Two other researchers wrote that "Gains from eliminating inefficiencies cannot produce the financial base needed by higher education" and "that higher education cannot gain enough from improving operations and that public funding is the best way to support universities" (Kallison Jr. and Cohen 2010). Improving teaching operations to increase enrollment might be believed to be impossible in academia.

2.2.11.2 Lean accounting used to support course operating results

Lean accounting derives from lean manufacturing. The goal of lean accounting is to eliminate waste by organizing costs by value stream. The value steam includes everything done to create value for a customer that can be reasonably be attributed to a product or process (Emiliani 2007).

Traditional accounting is insufficient to support value stream process improvement (Modarress et al. 2005). Management of the day to day value stream for a professor's course can be assisted by using lean accounting. Some benefits of supporting process improvement from lean accounting include better communication to meet the demand rate of students, reducing the inventory or queuing of students seeking support from the course and the professor, and improved decision making for value stream management (Brosnahan 2008). Lean accounting is the link between the school's strategic initiatives and tactical controls during process improvement (Kennedy and Widener 2008). Lean accounting supports mass customization (Albright and Lam 2006). Mass customization is a goal of the new engineering education system.

2.2 Discussion

The terminology used in manufacturing can seem out of place when describing an education process. Some of the citations above specifically state that manufacturing and education do not or should not be mixed. If dark, dirty, noisy places where workers perform their tasks by rote are what manufacturing is all about, then these authors would be correct in their assertions.

What is missing from the researchers' arguments is the point that what is most important to manufacturing, namely adding value to the output for the least cost while maintaining high quality and on time delivery to the customer is also vital to engineering education. Based on these principles, education and manufacturing systems have a lot in common. Throughput rates are important to schools, as the administration would not be able to plan for the school's operation without knowing how many students are enrolled or graduating, or how many professors are needed. The AMS pays the professors who run the processes (courses) to add value to the students. The customer (industry) pays for the product.

Engineering schools need to have positive cash flow to survive. The aggregated financial statements are important in order to know about changes from year to year, but the connection between a professor's daily activity and how these activities influence the financial health of the school it tenuous at best. A means of supporting process improvement, close to the activity is accomplished by using lean accounting methods, as the literature asserts.

2.3 Conclusions

The first conclusion is that prior work on value-added functions for education focused on determining the underlying causes for socio-economic results that stemmed from previous funding decisions. The closest example found for value-added functions for education to explain the relationship between an engineering student's tuition and graduate income was the higher education system in Texas, but this study did not tie tuition to income, just which school the student had attended (Cunha and Darwin 2009).

Second, regarding the use of manufacturing principles and methods, like value stream mapping, being used to design or redesign higher education systems little evidence was found in the literature that these tools were being used. This seems to be because education researchers' views of manufacturing are from the purely physical processing perspective; no consideration is given to the application of the organizational methods that manufacturing and industrial engineering have to offer. Some examples of value stream maps for the administrative aspects of a school system were found, but not for the learning process itself, although calls for value stream maps of the learning process in higher education have been made (Emiliani 2006).

Third, lack of industrial engineering simulation modeling of higher education systems results from the view that student learning is not a production process that lends itself to industrial process simulation. There were no examples found at software vendors' websites or in the academic literature. Simulation of the value stream map adds the important component of time to the analysis of a value stream map (Donatellli and Harris 2001).

Finally, manufacturing process improvement has both strategic and tactical components, each of which is supported by different accounting methods. Strategic financial projections will not be fulfilled unless the tactical needs of the production operators are supported. The reason for this is top level school administrators develop strategic direction and magnitude in the form of pro-forma financial statements which lack detail on how overall goals will be accomplished. Consequently, the professors who deliver education services need their own tactical reporting information from lean accounting to influence results.

Lean accounting is the link between strategic initiatives and tactical controls during process improvement. Lean accounting supports mass customization by providing actionable financial data to the process operators about the value creating activities under their control (Kennedy and Widener 2008) (Albright and Lam 2006).

One system was identified that showed the elimination of non-value-added time in education to produce large numbers of engineers: the ASTP program, administered by the U.S. Government during WWII (ASTP 2012).

In conclusion, some researchers view manufacturing methods as not being applicable to the operation of higher education systems. These researchers recommended that such principles should not be applied at all because education and manufacturing do not mix (Astin 1993) (Dahlgaard and Østergaard 2000). The opposite argument has also been made that higher education would benefit from manufacturing principles (Black 1997). This dissertation provides evidence to support the latter.

Chapter 3 - An Examination of “Value-Added” in Engineering Education

3.1 Introduction

The premise for this chapter is that the value to a student of a particular school’s engineering degree and the value-added time spent earning the degree can be calculated to facilitate process improvement. The objective of this chapter is to employ three process analysis tools commonly used in manufacturing engineering and apply them to an engineering education system. These tools are a value-added function, a value stream map, and a process chart.

The rationale for defining a value-added function for engineering education is that it can be used to differentiate between the monetary input and market value output relationship when producing an ABET accredited graduate engineer. A value-added function for engineering education could show how one school is performing in relation to another or to its own baseline standards. Production oriented fields of endeavor, like supply chain management and lean manufacturing, use value-added metrics to inform the process operators of how the process is performing (Davis and Novack 2012) (Gopinath and Freiheit 2009). Engineering education has inputs in the form of student tuition. Subsequent processing completes a transformation into the output of income received after graduation. Manufacturing has been described in a simple input/output model (Toussaint and Cheng 2002). Engineering education is an identical construct, allowing it to be modeled as a manufacturing production process.

In order to improve how a process functions, its operational metrics must be known first. According to Lord Kelvin:

> “I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be” (Kelvin 1883).

The rationale for developing a value stream map for any production process stems from the desire to determine when the production process is adding value and when it is not. Knowing this facilitates reconfiguration for process improvement. The reduction of lead time in order to more quickly receive cash should be a major focus of manufacturing process improvement (Wilson 2009). The elimination of non-value-added time is critical to improving process metrics (Rother and Shook 1999). In engineering education the ‘cash’ is the ability to work in the field as an engineer. For the student who desires to start working in the field, sooner is better.

The rationale for developing a process chart is to provide information about the work being performed (Graham 2012). The process chart is important for understanding value creation in a system and will answer some questions about responsibilities and production steps in the engineering education process. (Graham 2004). Graham asks: “What documents, forms, email, reports, databases... are involved in the process. Where is the work being done? Who is doing the work? When and where does most of the process time occur? Where are decisions made? Where are the controls? And where are the "value-added" steps?”

(Graham 2012). These three process analysis tools work together to facilitate improvements in a production system.

3.1.1 State-of-the-Art

Value-added in education is a widely used term that is not understood or well defined (Saunders 1999). For the engineering education process, tuition is the relevant economic cost while earnings after graduation is the incoming economic value.

Manufacturing systems benefit from operational and value-added metrics according to Joseph Juran who wrote that the value-added of a process should be based on its intended use (Juran 1999). In manufacturing, a value-added metric is needed for production system optimization (Cochran and Dobbs 2001) (Neely et al. 1996). Since production metrics can be found for any production system output, the system should compete by increasing the value-added (Chien et al. 2005) (Black 1997).

Examples in the literature analyze administrative processes such as ordering supplies or managing enrollment (Kusler 2008). The value stream maps that are found are not focused on the learning process itself. In his recent book entitled *Lean Higher Education: Increasing the Value and Performance of University Processes*, Balzer examines a school’s business operations and support services but not “the core process of higher education: student learning” (2010). Emiliani says that a value stream map in [higher] education would be useful to improve course design and delivery, but does not provide any published examples (Emiliani 2004, 2006) (Emiliani and Stec 2004).

In manufacturing engineering, value stream maps are used to identify and eliminate or reduce non-value-added activities during the available production time (Rother and Shook 1999). Engineering education generates value-added and non-value-added time that can be quantified. Neither a value stream map nor process chart for engineering education was found in the literature.

3.1.2. Approach

This chapter employs three process analysis tools commonly used in manufacturing engineering and applies them to an engineering education system (Gurumurthy and Kodali 2011). The three tools commonly used in manufacturing engineering are a value-added function (Raisinghani et al. 2005), a value stream map (Rother and Shook 1999), and a process chart (Graham 2004).

The development of a value-added function for engineering education, along with a value stream map and process chart, will advance the state of art by providing an easily calculated metric of the value being created by the education process, a map of the sequence of when value is created and a process chart that shows the responsibilities and interactions of the students and professors.

To start the value stream mapping process, the student’s value-added and non-value-added activities are defined for use in development of a value-added time ratio as well as for use later in the development of the value stream maps.

Satisfying the objective of developing a value-added function is accomplished by calculating the net present value of the stream of payments which includes the student’s tuition paid and wage income earned over a period of years. This stream of payments is related through a discount rate. The result represents the value-added to the student earning an engineering degree.

The objective of creating a value stream map is accomplished by decomposing an engineering degree from a fractal geometry point of view to a natural limit and then defining this amount as a quantum of learning. This quantum of learning amount of value-added time is compared with the total of learning activity time to find the percentage of value-added versus non-value-added time for a degree program. Development of a process chart is completed by examining the duties and responsibilities of the students and professors modeled as a manufacturing cell.

3.2 Methods

The three steps shown in Table 2 were used to examine the concept of value-added in engineering education modeled as a manufacturing system.

	Method Used	Purpose
Step 1	A value-added function and value-added to total time ratio is defined	Measures how well the customer's needs are being satisfied
Step 2	Value stream maps are generated	Relates the quantum of learning to the student's total learning activity time
Step 3	A process chart is produced	Shows responsibilities of system participants

Table 2 - Methods used in modeling engineering education as a manufacturing system

3.2.1 Definitions of student value-added time and the value-added to total time ratio

Value in education might be defined as the mastery of a concept or skill. The first step to define the value-adding and non-value-adding activities in the student learning process is to know when they occur. Table 3 shows a possible sequence of steps that students could go through when being introduced to an idea or concept in class. The value-added steps lead to the eventual recognition that some level of mastery over the subject has been obtained. The instructor quantifies this mastery through distribution of an end-of-course assessment and grade.

Student Value-added Time (VA)	Value-added activity	Student Non-value-added Time (NonVA)
Learning time	Discovery of a concept or idea presented by professor	None
Internalizing time	New idea or concept is thought about in the process of internalizing its meaning	None
Questioning and solving time	Problem solving & questions are generated for understanding	Waiting time for feedback to questions on problems
Problem sets & quizzes time	Deliverables are completed like problem sets, quizzes and labs	Waiting time for feedback on problem sets & quizzes
Inspection examination or presentation time	Quality assurance by exam or project presentation	Waiting time for feedback time on exams & presentations
Ownership of the material where the student has some proficiency	Grade is received, marks the learning time for the subject	Waiting for feedback scores or grades

Table 3 - Comparison of value-adding and non-value adding activities for students

By summing all of the value-added time activity time for a student and comparing this total to the entire learning time, a ratio of value-added to non-value-added time can be calculated.

If all of the value-added time in a process is summed and compared to the total time that the process takes, a ratio can be calculated that illustrates the following: as the non-value-added time approaches zero, the ratio of value-added to total time approaches one, indicating that there is no non-value-added time during the learning activity as shown in Table 4 and Equation 1.

$$Value\ added\ Time\ Ratio = \sum VA \frac{\sum VA}{\sum VA + nonVA}$$

Equation 1 - Value-added time ratio

Student Value-added Time (VA)	Student Non-value-added Time (nonVA)
Defined as: $\Sigma VA = L + I + Q + S + E + O$	Defined as: $\Sigma\ nonVA = QF + SF + EF + OF$
L = Learning Time	= Zero (because the student controls this activity)
I = Internalizing Time	= Zero (because the student controls this activity)
Q = Questioning Time	QF = Questioning Feedback waiting time
S = Solving Problem Sets & Quizzes Time	SF = Solving Feedback for prob. sets & quizzes waiting time
E = Examination or Inspection Time	EF = Examination Feedback waiting time
O = Ownership of the material	OF = Ownership Feedback waiting time for competency

Table 4 - Definition of variables used in the value-added time ratio

3.2.2 Development of the value-added function for engineering education

Since engineering education is a process that generates engineers, a value-added metric that shows the real value of an ABET degree should be defined as relating: 1) a graduate's ability to get a high paying job in a rewarding career with 2) the cost of production, i.e. tuition. A value-added function so described will allow schools to measure and improve (Harris 2011) (Hersh 2004). Knowing the value-added metric for a manufacturing process is central to achieving a manufacturing system's goals and a value-added function creates a link between what is important to the customer and how well it is being achieved (Neely et al. 1996) (Setijono and Dahlgaard 2008).

Equation 2 shows that the value-added function in engineering education is the discounted cash flow of the stream of payments including the tuition paid upon entering the school until earnings commence post-graduation, for some time period, calculated using the net present value (NPV) equation. NPV was originally formalized in *The Rate of Interest* (I. Fischer 1907, 1930, 1974):

$$VA_{Eng\ Ed} = NPV(i) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$

Equation 2 - Value-added in engineering education

Where:

t = time of the cash flow   note: income is inflated annually by the CPI
i = discount rate (opportunity cost of capital)   : tuition is inflated by 'tuition rate of inflation'
R_t = net cash flow (income minus tuition) at time t

Figure 3 shows changes over time how value-added function for engineering education allows the student to calculate, in financial terms, the income value of their engineering degree relative to the length of time it takes to earn it. A key point is that the student has little control over the time to graduate. The school controls all of the elements of this value-added function except for the discount rate.

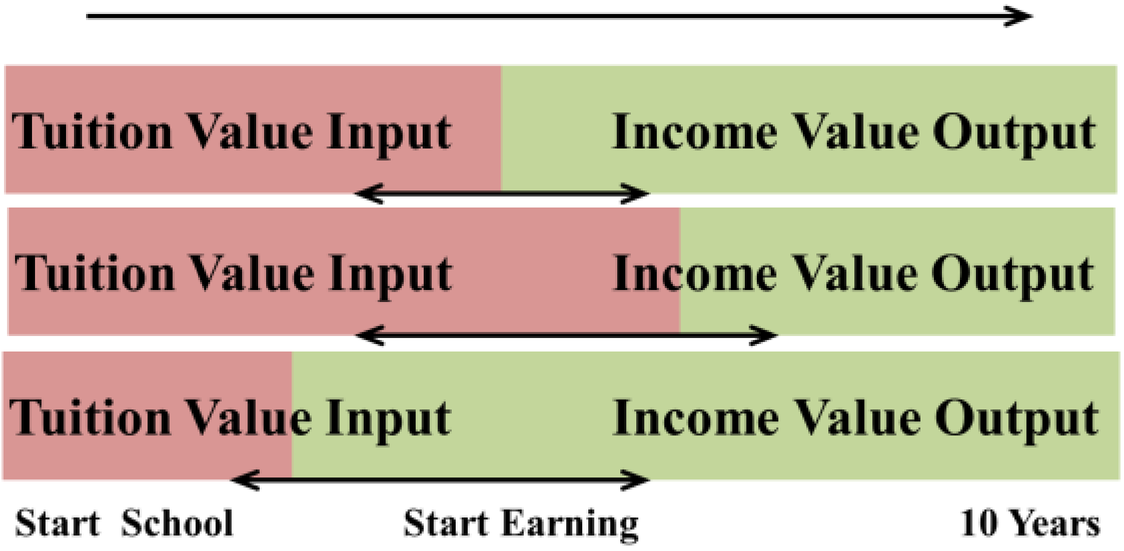


Figure 3 - Value-added Function for Engineering Education

3.2.3 Development of the value stream map for engineering education

A unit of value-added production is derived and defined through the decomposition of the learning process into its smallest reasonable component part. As mentioned above, this will be defined as a quantum of learning. Sequential value stream maps that incorporate the learning process are created terminating at the degree level.

The value stream maps developed here are parametric, meaning that users can define values relative to their courses and school. A unit of learning, and the core structure upon which it is based, can be defined differently for each school according to its needs.

3.2.4 The fractal nature of higher education

The premise that an engineering education value stream map can be developed requires understanding of the nature of the learning process itself. In the engineering education space, students are presented with learning material and over time, this information is assembled and combined to the point where the student, upon graduation, is able to design a fuel cell, an automobile engine or an artificial intelligence system.

The output of the engineering education process is for the students to be able to generalize the underlying topics, formulas and information acquired in order to synthesize solutions to problems. The development of a traditional value stream map for a manufacturing process requires the analysis to begin at the end of the process (Rother and Shook 1999). The finale of the engineering education process is the issuance of the degree upon graduation. The step prior to graduation is finishing final courses and projects. Value stream mapping in a real factory requires “walking” backward into the production process from the output end to make detailed notes of all of the activities that go into the output (Rother and Shook 1999). In a physical environment such as a factory, the “walking” is literal. In the case of engineering education, the walking is done by thinking through the process steps.

In the case of a school producing engineers, the end result of the engineering education process is in the words of Joseph Juran, an engineer that is *fit for further use* (Juran 1999). This education “tree trunk” has main “branches” that are comprised of mathematics, humanities, engineering specific courses and more. Each main branch can be broken down into subject areas, such as calculus and statistics. At finer scales the fractal branches further decompose into topics such as integration and differentiation. At the natural limit of this decomposition are the basic building blocks of the learning process in the form of leaves on the small branches. Further decomposition yields components too small to be of value by themselves. This “fractal” aspect of engineering education is shown in Figure 4.

The mastery of engineering course content cannot be accomplished in one or two class sessions. This implies that the amount of subject matter learned in a specific time period does not cover everything there is to know about the subject at hand. Learning an academic subject one printed letter or number at a time is inefficient and might not result in the material ever being understood and mastered by the student. Therefore, as subject matter is presented, there are upper and lower limits to the amount of content and time required for the student learning activity. Knowing this minimum or *quantum* amount is useful in designing a manufacturing system.

Engineering requires synthesis and generalization based on broad underlying ideas. The gathering and mastery of these ideas over the course of an engineering education leads to the conferral of a degree.

Since the separate underlying ideas form more advanced concepts, engineering education can be modeled as having a fractal nature. An engineering degree can be decomposed in a self-similar manner until a natural limit is reached like fractals found in nature such as trees and ferns. While it might not be possible or even desirable to account for every idea that a student needs to know, the model helps to describe the structure and process that takes place in the learning environment. The decomposition of the fractal nature of education leads to a quantum of learning that could subsequently be used in calculating production metrics. The fractal tree of the Worcester Polytechnic Institute (WPI) Industrial Engineering (IE) degree is shown in Figure 4.

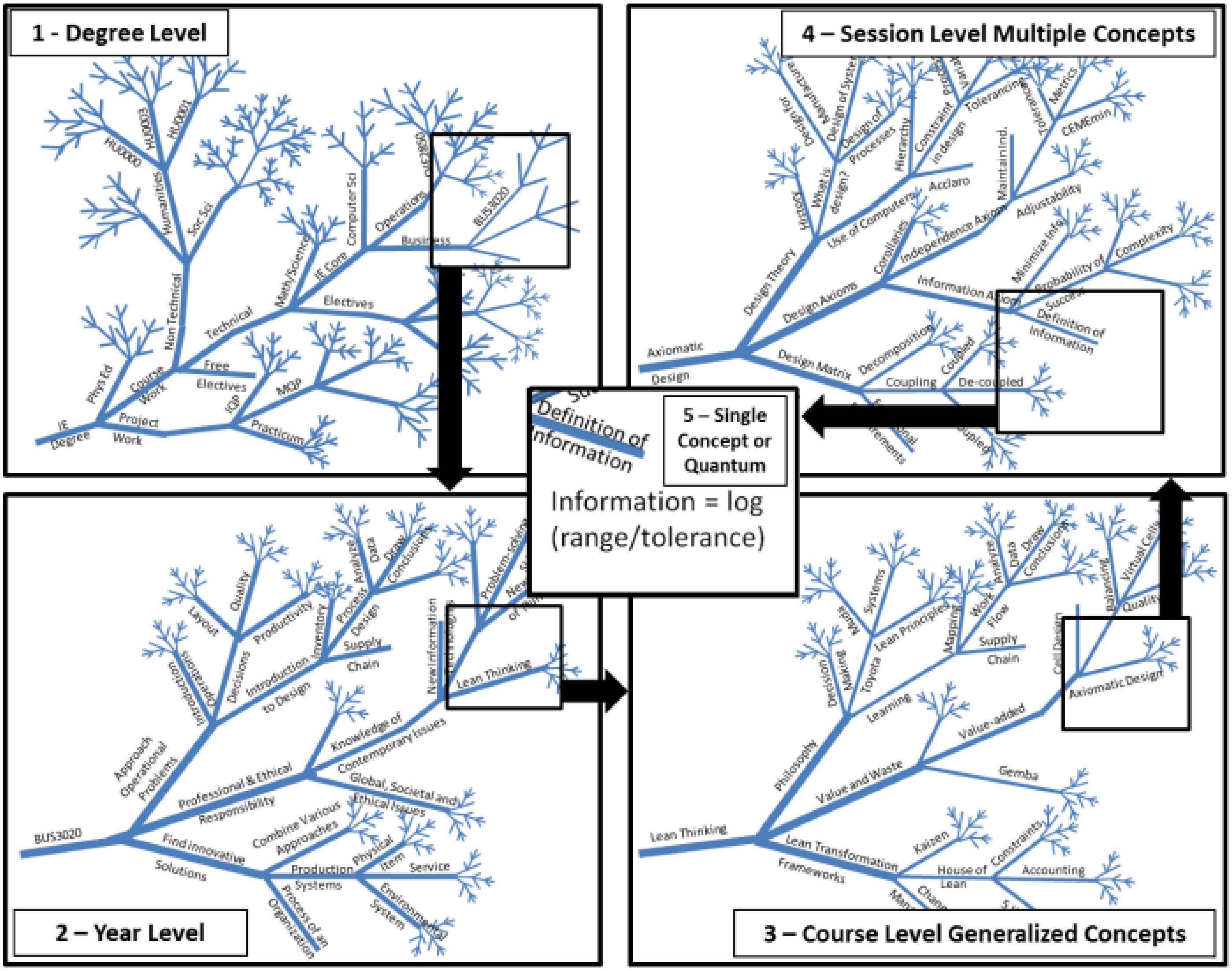


Figure 4 - Fractal nature of engineering education

The decomposition starts at the degree level representing the forty-eight courses students must take in order to earn a degree in IE. The major branches off of the trunk aggregate the student’s main efforts like project and course work. At the second level of the decomposition, individual courses are shown that can be decomposed into the main topics from the course schedule or syllabus. The third level shows generalized course concepts like axiomatic design as a possible sub-topic of lean process improvement. At the fourth level, main ideas with multiple sub-concepts such as the definition of information, which is used in disciplines other than IE, can be seen. Finally, at the fifth level of the decomposition, the sub-component concepts, for example, the definition of information (i.e. Information = log(range/tolerance)) which, when broken down any further, have no meaning. This is the natural limit of a fractal decomposition that can be used to estimate the time is takes for a student to learn about the definition of information. The amount of time consumed when a student recognizes new concept information is defined as the quantum of learning and can be used to construct value stream maps of the engineering education process.

3.2.5 Modeling the education production system based upon the quantum of learning

The goal in a discrete production system is to create one-piece-flow production, processing only what is needed and when it is needed (Sekine 1992). It is possible to extrapolate this concept to a four year engineering degree program. For example, assuming a WPI degree has forty-eight opportunities for learning, defined as courses and projects, each of which might be broken down into fourteen academic material delivery periods, or some other schedule, called class meetings, lectures, or sessions.

Within each of the content delivery sessions there is a minimum of one, concept that should be mastered by the student before advancing to the next session. A premise is that this logical progression through a course of study is limited by a maximum amount of academic content that can be taught and absorbed in one session by a student. The exact number of quantum units that can be taught and absorbed in a session is not known or specified, and neither is it important to do so. What is important is to assign a reasonable number of concepts per session for value stream modeling purposes.

It is assumed for this example that students are taught three concepts over a two-hour time period during a single class session. Using this logic, each new concept in a two-hour class session will take two-thirds of an hour, or about forty minutes. The number of concepts learned during each class session is not critical to the analysis. The length of the class session is determined by the course schedule, and whether the students are shown three, or thirty-three, new ideas in a session, this learning is contained within the time bounds of the allotted class session. Each course has its own value stream map based upon the definition of quantum units for a particular course and any other details that pertain to that course like the average completion time, the number of hours of study expected and other production metrics. The quantum of learning is defined in this manner so that professors are able to examine the pacing of concepts as the course transitions to mass customization and one-piece-flow.

Similarly, the amount of time that a student spends on learning activities can be differentiated from the time that does not contribute to learning, which is known as non-value-added time. The rate at which a student acquires knowledge and skills is now able to be modeled as a classical or linear fractal similar to the pattern found in a linear fractal tree. The trunk of the tree is the embodiment of the knowledge acquired while the main arms, branches, twigs and leaves represent increasing detail within the subject matter. The subject matter tree is self-similar within and among its component parts. The tree might not be able to grow pending demonstration of mastery of each of the subset concepts to be learned.

3.2.6 Construction of the value stream map for engineering education

Construction of a value stream map usually requires documenting the production process starting at the customer output end of the process and working through the sequence of steps, in reverse order, back to the start of the process (Rother and Shook 1999).

Value stream mapping begins with the amount and quality condition of what the customer receives as output of the process. Information is recorded about what is taking place throughout the entire production process. Such items that are found include the time it takes to complete each production task, any change-over time for tooling or employee shift changes. These could be compared to the time students need to walk between classes on a campus.

The number of people involved, the amount of work they do, and how much work time is consumed are recorded. Additionally, the amount of inventory resulting at the end of each process step is accounted for and tallied.

These levels can be described in descending order of aggregation from the macro to the micro levels: from degree level, year level, course level, and session level, ending at the concept level. Since no physical product is involved, and the knowledge and skills produced in the engineering student are not actually able to be directly measured and quantified, the value stream can be built from the bottom up. In this way it serves as the central process of learning, initializing, questioning, solving problem sets, completing exams and finally receiving a score for the course, and is a repeating fractal that takes place at each level of the education process.

Higher education can function similar to a mass production transfer line shown in Figure 5. A transfer line prevents individual advance of one part ahead of another in the sequential production process (Borisovsky et al. 2012). Mass customization requires decoupling of the sub-processes (Sandelands 1994).

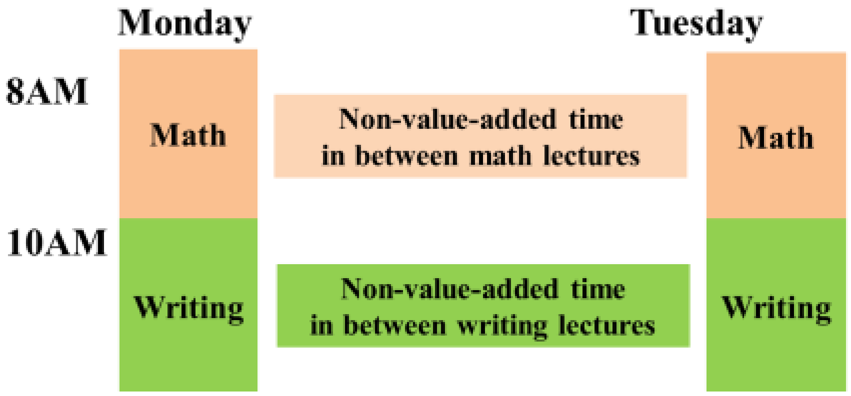
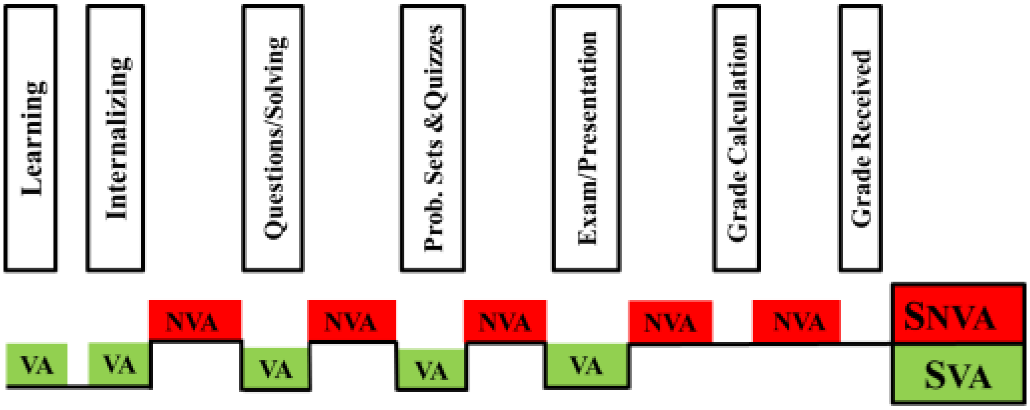


Figure 5 - The Higher Education Mass Production Transfer Line

Figure 6 shows how value-added time is calculated from the value stream map of the learning process (Rother and Shook 1999).



$$\text{Value-added Time Ratio} = \frac{\Sigma VA}{\Sigma VA + \Sigma NVA}$$

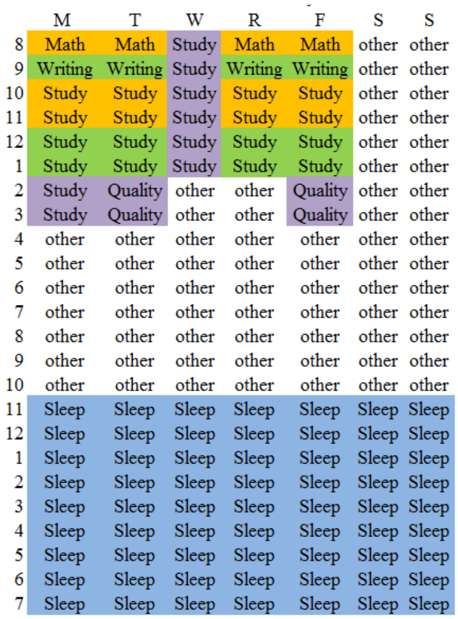
Figure 6 - Value Stream Map Calculation of Value-added Time

3.2.7 How much time is available and how do students spend their time?

As an example from the Associate Dean of the College for Administrative Advising at Colgate University, “There are 168 hours in a seven-day week, plenty of time to do your work and still have an enjoyable college experience. The typical class meets three or four times per week for about an hour per class session. Not counting labs, this means that the typical student has somewhere between twelve and sixteen contact hours per week. Most faculty believe that students need to devote somewhere between two and three hours of preparation outside of class for every hour in class, so for the majority of students, the total workload comes down to around forty hours per week or eight hours per day, five days per week” (Glos 2007).

Engineering students are reported to study on average nineteen hours per week with two in five seniors in engineering studying more than twenty hours per week (NSSE 2011). This amount is less than the generally accepted ratio of class time to study time ratio of two-to-one (Young 2002).

A pictorial representation of a typical WPI undergraduate student showing the two-to-one ratio is shown in Figure 7. The figure shows graphically the ratio of class to study time over a 7 day 24 hour time frame. The following analysis uses a 5 day week for production throughput calculations. If the weekend time is included, the resulting non-value added time will increase.



	M	T	W	R	F	S	S
8	Math	Math	Study	Math	Math	other	other
9	Writing	Writing	Study	Writing	Writing	other	other
10	Study	Study	Study	Study	Study	other	other
11	Study	Study	Study	Study	Study	other	other
12	Study	Study	Study	Study	Study	other	other
1	Study	Study	Study	Study	Study	other	other
2	Study	Quality	other	other	Quality	other	other
3	Study	Quality	other	other	Quality	other	other
4	other	other	other	other	other	other	other
5	other	other	other	other	other	other	other
6	other	other	other	other	other	other	other
7	other	other	other	other	other	other	other
8	other	other	other	other	other	other	other
9	other	other	other	other	other	other	other
10	other	other	other	other	other	other	other
11	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
12	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
1	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
2	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
3	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
4	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
5	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
6	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
7	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep

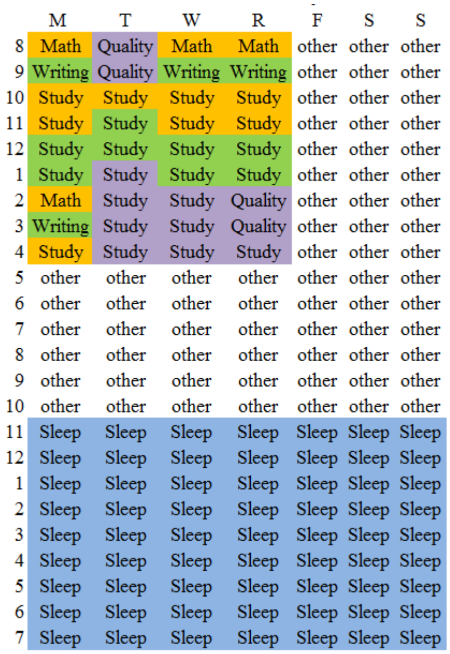
Weekday
12 hours of class time
24 hours of study time (2:1)
39 hours of other time
45 hours of sleep time

Weekend (not counted)
30 hours of other time
18 hours of sleep time

Figure 7 - Model of student time for three WPI courses on a traditional schedule

In a pull production system, the student would be able to draw the learning materials from subsequent classes at a pace that is on the student's personal schedule and not on an arbitrary academic calendar. An example of how time becomes more available as a result of breaking free from the schedule is shown in Figure 8.

Following this logic, a motivated student could learn more in a shorter time by being able to pull in more learning materials and receive faster responses to questions and grading in this system. Figure 9 shows an example of a pull system for a motivated student who is able to add two additional courses to a schedule by eliminating waiting time for learning material and feedback.



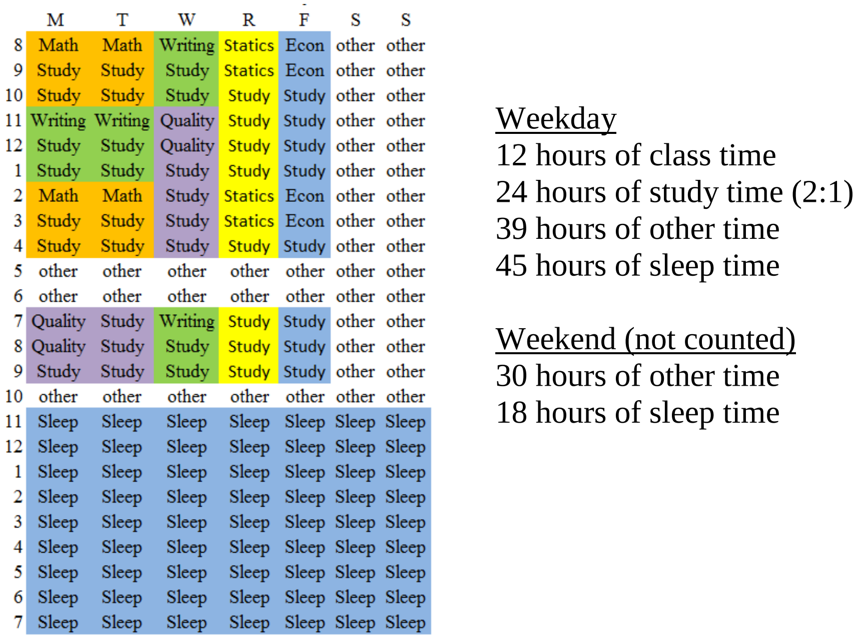
	M	T	W	R	F	S	S
8	Math	Quality	Math	Math	other	other	other
9	Writing	Quality	Writing	Writing	other	other	other
10	Study	Study	Study	Study	other	other	other
11	Study	Study	Study	Study	other	other	other
12	Study	Study	Study	Study	other	other	other
1	Study	Study	Study	Study	other	other	other
2	Math	Study	Study	Quality	other	other	other
3	Writing	Study	Study	Quality	other	other	other
4	Study	Study	Study	Study	other	other	other
5	other	other	other	other	other	other	other
6	other	other	other	other	other	other	other
7	other	other	other	other	other	other	other
8	other	other	other	other	other	other	other
9	other	other	other	other	other	other	other
10	other	other	other	other	other	other	other
11	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
12	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
1	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
2	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
3	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
4	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
5	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
6	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
7	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep

Weekday
12 hours of class time
24 hours of study time (2:1)
39 hours of other time
45 hours of sleep time

Weekend (not counted)
30 hours of other time
18 hours of sleep time

Figure 8 - Model of student time for three WPI courses on a pull schedule

Figure 8 shows that that a day becomes free to use for other activity as a result of the *pull* system. The pull system allows the student to continually access learning material independent of the professor's timetable.



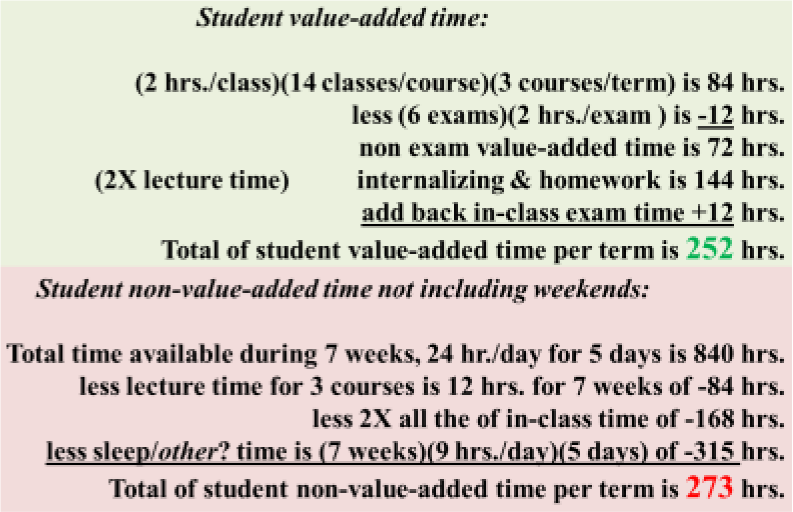
	M	T	W	R	F	S	S
8	Math	Math	Writing	Statics	Econ	other	other
9	Study	Study	Study	Statics	Econ	other	other
10	Study	Study	Study	Study	Study	other	other
11	Writing	Writing	Quality	Study	Study	other	other
12	Study	Study	Quality	Study	Study	other	other
1	Study	Study	Study	Study	Study	other	other
2	Math	Math	Study	Statics	Econ	other	other
3	Study	Study	Study	Statics	Econ	other	other
4	Study	Study	Study	Study	Study	other	other
5	other	other	other	other	other	other	other
6	other	other	other	other	other	other	other
7	Quality	Study	Writing	Study	Study	other	other
8	Quality	Study	Study	Study	Study	other	other
9	Study	Study	Study	Study	Study	other	other
10	other	other	other	other	other	other	other
11	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
12	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
1	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
2	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
3	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
4	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
5	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
6	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep
7	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep	Sleep

Weekday
12 hours of class time
24 hours of study time (2:1)
39 hours of other time
45 hours of sleep time

Weekend (not counted)
30 hours of other time
18 hours of sleep time

Figure 9 - Model of student time for five WPI courses on a pull schedule

More permutations of the student schedule could exist as weekend time and time during term breaks are factored-in. In the two pull system examples above, rearranging the traditional lecture and examination meeting times shows what an example student schedule could look like. It could be argued that students are able to accomplish this by overloading courses in their schedules. While this might be true, the overloaded schedule is still on the traditional academic calendar; interference with course availability and meeting times preclude the student from consistently maintaining a traditional overloaded schedule in order to graduate sooner. A summary of the assumptions for value-added time calculations is shown in Table 5.



Student value-added time:

(2 hrs./class)(14 classes/course)(3 courses/term) is 84 hrs.
less (6 exams)(2 hrs./exam) is -12 hrs.
non exam value-added time is 72 hrs.
(2X lecture time) internalizing & homework is 144 hrs.
add back in-class exam time +12 hrs.
Total of student value-added time per term is 252 hrs.

Student non-value-added time not including weekends:

Total time available during 7 weeks, 24 hr./day for 5 days is 840 hrs.
less lecture time for 3 courses is 12 hrs. for 7 weeks of -84 hrs.
less 2X all the of in-class time of -168 hrs.
less sleep/*other?* time is (7 weeks)(9 hrs./day)(5 days) of -315 hrs.
Total of student non-value-added time per term is 273 hrs.

Table 5 - Assumptions for Value-added Time Calculations per term

3.3 Results

3.3.1 Results from applying the value-added function

For comparison purposes, information for WPI's peer group, the Association of Independent Technological Universities, is shown (AITU 2013). Any reasonable length of time for the calculation of the value-added function can be used with the caveat that longer time frames might provide less accurate information on income. A timeframe of ten years was chosen for the analysis because it allows for graduates to complete their degree in two to six years while still having some earning years in the ten year time frame. The value-added of a process should be based on its fitness for its intended use (Juran 1999). In this case the objective is to relate the stream of tuition and income payments for an ABET engineering degree through appropriate inflation and the discount rates. The values used in the calculation are shown in Table 6.

The average tuition not including fees and room and board for The Association of Independent Technological Universities for 2012 is $38,739 (AITU 2013) (www.collegedata.com 2013). Webb Institute is excluded as students do not pay tuition, and Keck Graduate Institute does not have undergraduate programs.

	Tuition	Room and Board	Cost of Attendance
California Institute of Technology	$39,382	$ 12,084	$ 56,382
Carnegie Mellon University	45,760	11,550	59,710
Case Western Reserve University	40,490	12,436	55,476
Clarkson University	38,610	12,534	55,030
Cooper Union	40,250	na	na
Drexel University	36,090	14,175	56,165
Embry-Riddle Aeronautical University	30,720	10,080	46,314
Franklin W. Olin College of Engineering	40,475	14,500	57,225
Harvey Mudd College	44,442	14,471	61,113
Illinois Institute of Technology	37,914	10,626	52,117
Kettering University	33,946	6,660	48,420
Lawrence Technological University	28,470	8,200	41,932
Massachusetts Institute of Technology	42,050	12,188	57,010
Milwaukee School of Engineering	32,370	8,028	43,598
Polytechnic Institute of New York University	39,564	13,500	57,710
Rensselaer Polytechnic Institute	44,475	12,450	59,470
Rochester Institute of Technology	33,258	10,800	46,133
Rose-Hulman Institute of Technology	41,478	10,935	55,413
Stevens Institute of Technology	43,656	13,400	58,906
Worcester Polytechnic Institute	41,380	12,650	56,030
Avg. Tuition	$38,739		

Table 6 - Average 2012 Tuition of the Association of Independent Technological Universities

The WPI tuition cost of $42,178 for 2013-2014 was found on the WPI Admissions web page (www.wpi.edu 2013). Additional data for median pay for a mechanical engineer, inflation and other values are summarized in Table 7.

Influencing Factor	Value	Source
2013-14 Tuition (WPI)	$42,178	(www.wpi.edu 2013)
2013 starting pay of a mechanical engineer	$65,294	(www.salary.com 2013)
2013 median pay of a mechanical engineer	$83,120	(U.S. Dept. of Labor 2013)
Wage inflation escalator (CPI)	1.9%	(U.S. Dept. of Labor 2013)
10 yr. historical college tuition inflation rate	7% to 8%	(Odland 2012)
2011-12 college tuition inflation rate	4.36%	(www.collegesavingsbank.com 2012)
2012 discount rate for high yield savings	1%	(www.bankrate.com 2012)

Table 7 - Economic factors used in value-added function calculation

The ten year historical college inflation rate is shown for reference only, but it is not used in the net present value calculation. A more recent value of 4.36% was used to reflect a change since the financial downturn in 2008 which has put downward pressure on tuition increases (www.collegesavingsbank.com 2012). The values in Table 7 are conservative in light of the 1% yield on savings used (www.bankrate.com 2012). If investment yields are higher than 1% or tuition inflation higher than the 4.36% used has a measurable impact on the results. The value-added function can be adjusted for any combination of pay, tuition and length of time, inflation modifiers and discount rate for any school desired.

An example of value-added in engineering education based on the data in Table 7 is reiterated in Table 8.

	Amount/Value	Inflation Modifier
Starting Tuition	$42,178	4.36%
Starting Earnings	$65,294	1.90%
Discount Rate	1.0%	
Number of Years	10	

Table 8 - Data used in net present value calculation

A net present value analysis of the stream of payments relating tuition and income through their respective inflation modifiers result in Table 9.

0	$ (42,178)	$ (42,178)	$ (42,178)	$ (42,178)	$ (42,178)
1	$ (44,017)	$ (44,017)	$ (44,017)	$ (44,017)	$ (44,017)
2	$ (91,872)	$ (45,936)	$ (45,936)	$ (45,936)	$ (45,936)
3	$ 65,294	$ (47,939)	$ (47,939)	$ (47,939)	$ (47,939)
4	$ 66,535	$ 65,294	-	-	-
5	$ 67,799	$ 66,535	$ 65,294	-	-
6	$ 69,087	$ 67,799	$ 66,535	$ 65,294	-
7	$ 70,400	$ 69,087	$ 67,799	$ 66,535	$ 65,294
8	$ 71,737	$ 70,400	$ 69,087	$ 67,799	$ 65,294
9	$ 73,100	$ 71,737	$ 70,400	$ 69,087	$ 66,535
10	$ 74,489	$ 73,100	$ 71,737	$ 70,400	$ 67,799
	2 years to income	3 years to income	4 years to income	5 years to income	6 years to income
NPV	$ 280,605	$ 214,782	$ 152,389	$ 92,770	$ 33,002

Discounted to the start of the program time = 0

All 4 years of tuition is paid prior to graduation.

No allowance is made for more than four years of tuition.

Table 9 - NPV over 10 years of ABET degree time to earnings.

The method used to determine the value-added function is the net present value of the stream of the payment of tuition and the subsequent income received after graduation, both of which take place within a ten year time frame. The interest and inflation rates used are shown in Table 8.

Figure 10 illustrates that as the length of time of earning the degree increases due to non-value-added time, the economic value of paid economic value of the engineering degree declines from a breakeven standpoint.

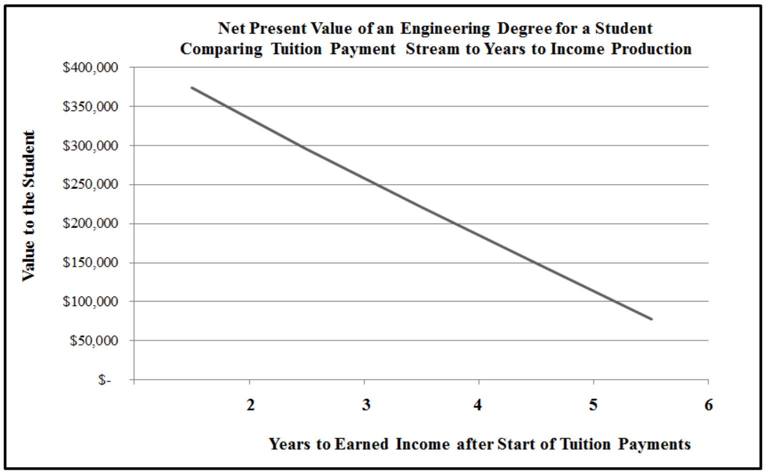


Figure 10 - Graph of NPV over 10 years of tuition paid to earn income

3.3.1.1 Example value-added function calculation comparing two engineering schools

Table 10 compares the tuition at a public university (UMASS) and a private university (WPI) over various time frames. The table shows the economic benefit to the graduate in attaining an ABET accredited engineering degree and the subsequent income from employment based upon the length of time to graduation from the two different schools (www.umass.edu 2012) (www.wpi.edu 2012).

		NPV to income				
	2013-2014					
	Tuition	2 years	3 years	4 years	5 years	6 years
Private	$ 42,178	$368,709	$290,025	$215,338	$143,970	$ 72,426
Public	$ 13,230	$482,994	$404,691	$330,004	$258,636	$187,092
	Difference	$114,285	$114,666	$114,666	$114,666	$114,666

Table 10 - Comparison of the NPV of engineering degrees from a private versus public university

The results in Figure 11 show that the public university degree is more economical than the private degree in that the student will save more than $114,000 in NPV by attending a public university, based upon the less expensive tuition for its ABET accredited engineering degree. The tuitions shown do not include any board expense or financial aid a student might receive. The data presented does not reflect differences in the salary data from specific universities and is based on Department of Labor figures. No adjustment was made for any differences in the quality of the degrees earned by the students.

Financial aid to students is coming under increasing pressure evidenced by President Obama in his January 24, 2012 State of the Union address. The President said “If you can’t stop tuition from going up, then the funding you get from taxpayers each year will go down” (Obama 2012).

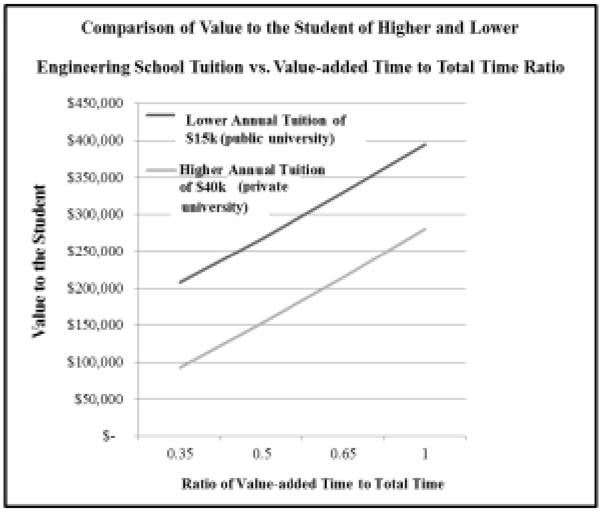


Figure 11 - Comparison of NPV over 10 years for a $40K versus a $15K annual tuition

Figure 11 shows the difference in value to an engineering student who is able to attend a school for $15,000 annual tuition rather than $40,000. If both schools are ABET accredited, it is assumed that there should be a great deal of equivalence between the two school’s engineering degrees.

The relationship between the value-added time ratio and tuition lends itself to a breakeven analysis. As the value-added time ratio approaches unity, the time to breakeven will be shorter. Additionally, Figure 12 shows that as the tuition increases in the absence of an improving value-added ratio, the time to breakeven is extended making the degree much more expensive for the student.

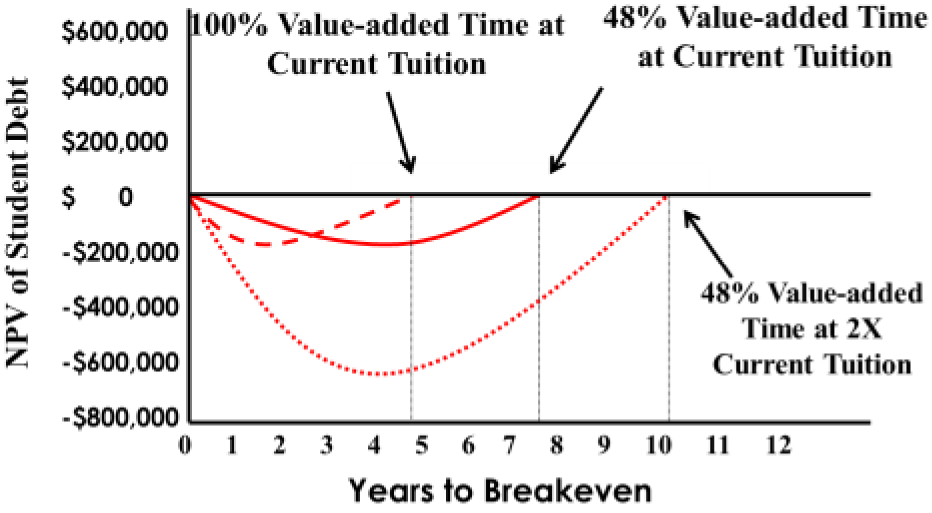


Figure 12 - Graph of tuition paid to income receipt breakeven for three value added ratios

The ideal situation for a student is to have an improving value-added time ratio with stable or decreasing tuition in order to achieve maximum value. Figure 13 shows the relationship between how the value-added time ratio affects the breakeven point of tuition recovery after graduation.

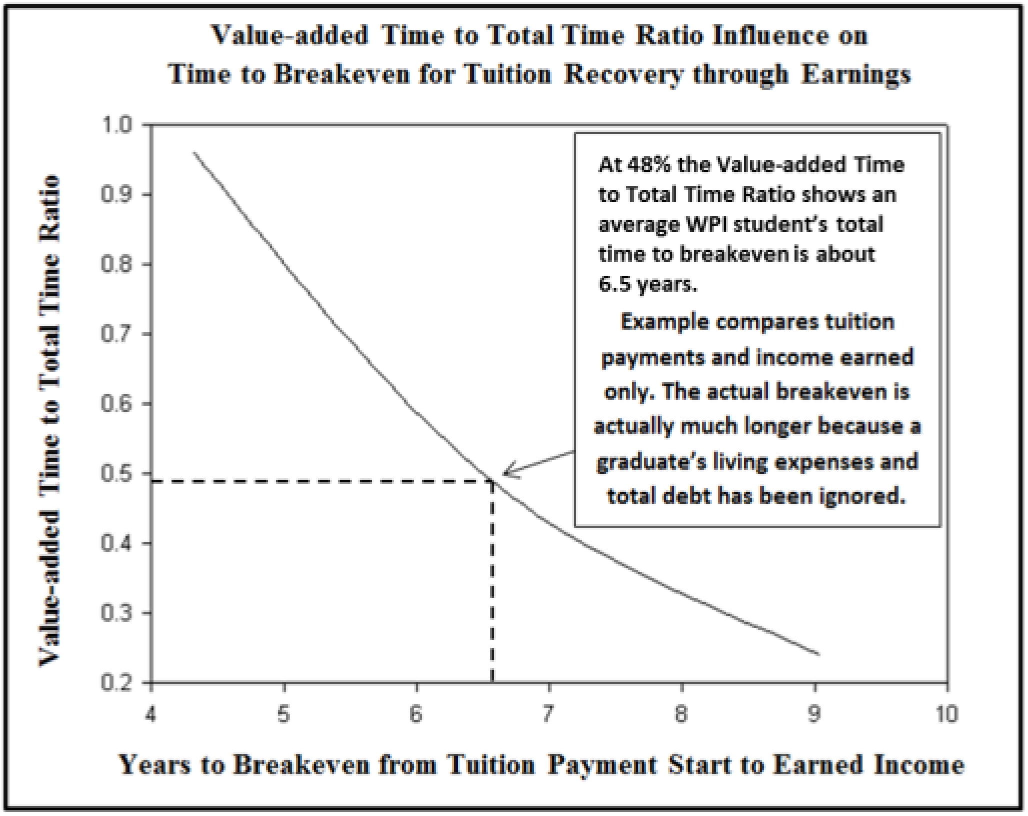


Figure 13 - Graph of the value-added function vs. value-added time ratio

As the value-added time ratio approaches one, the time to reach breakeven decreases which causes the economic value to the student to increase.

3.3.2 Results from the value stream map

3.3.2.1 Quantum of learning as the foundation of the value stream map

Referring to the learning process shown in Figure 14, the heart of the engineering education value stream map is contained in its first two steps. These first two steps are 1) learning and 2) internalizing. The learning steps can take place either in class, viewing an online lecture, observing a demonstration, having a discussion or some other means. The premise in the value stream map is that the student is made aware of an idea or concept by the professor or other instructor. For example, in an online scenario, the lecture might be delivered by someone else. The concept is the starting point because it is not able to be decomposed any further without losing meaning or relevance in the context of a course. The quantum of learning, does not have a fixed length of time associated with it, but estimates of its value can be made.

While attending a lecture, a student should be made aware of at least one concept. Professors do not put forth dozens of new ideas at the same time in order to avoid confusion. The student is being exposed to a number of concepts which are defined by each professor individually to suit the needs of the course. No matter the number of concepts, if a single lecture time is fixed at two hours, for example, and twelve new concepts are presented by the professor, the quantum of learning time value would be two hours divided by twelve concepts, averaging ten minutes for each idea or course concept.

The value stream map developed here uses this same reasoning. It assumes three concepts per two hour lecture as the basis for investigation. The value stream map is fully customizable to account for any number of concepts offered by a professor for any length of time. Continuing with this model, three concepts per two hour lecture offered twice per week will be used throughout this analysis.
A unit of value-added was found earlier by decomposing the learning process to find a basic amount of learning beyond which, further decomposition does not make any sense. Traditional value stream mapping dictates that the mapping starts at the output end of the process (Rother and Shook 1999). Based upon this common practice, the engineering education process was initially laid out in this traditional manner and is shown in Figure 14 below. Engineering education does not produce a physical product. As a result, due to the fractal nature of value stream mapping, and the fact that there is no differentiation between education processing steps due to nature of the activity, this allows for a value stream map to be created based on the single course concept (Venkatadri et al. 1997) (Glenday and Brunt 2007). This single concept is then scaled up through the session, the course, the term, and finally the degree level.

3.3.2.2 Leaf level of the value stream map

Recall Table 3 which shows the presumed education process sequence of learning, internalizing, questioning, solving, inspection and ownership. The value stream map based on this construct is shown in Figure 14.

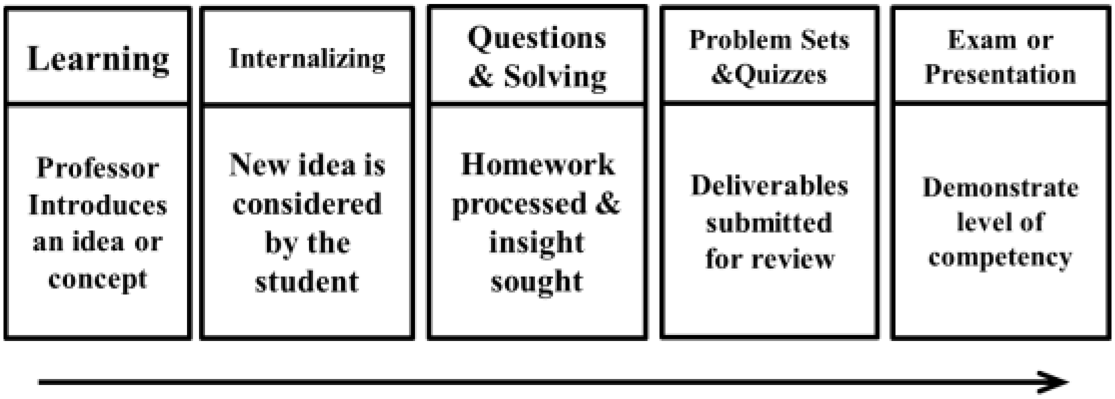


Figure 14 - Leaf level of the fractal value stream map

The model in Figure 14 is the foundation for a spreadsheet that scales up the value stream map from the concept level to the degree level. The framework of courses and degree requirements at WPI is used as an example. Figure 15 shows the non-value added time in-between the learning steps.

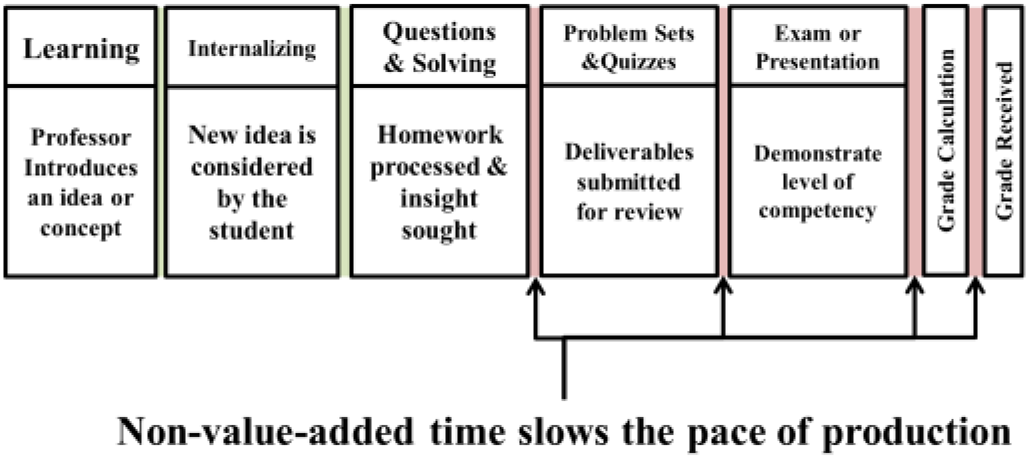


Figure 15 - Value-adding learning process steps for the student

A data input sheet is used to populate the fractal level of the value stream map for up scaling the amount of student activity in subsequently higher levels of fractal value stream maps. The data used is based upon the normal WPI academic schedule of three courses per term, four terms per year and four years in a degree program. The number of concepts and the time allocated of three concepts per two hour course meeting twice per week for seven weeks is able to be modified by the user for different course conditions. The assumptions made throughput this section are summarized in the user data input sheet in Figure 16.

Shaded cells are user input values

Times Are In Hours

	Years	Terms	Courses	Sessions	Concepts Presented	Awareness	Deliverables	Exam Length	Idle Time	Weeks per Term
Concept Level					1	0.667	2	2	N/A	
Session Level				1	3	0.667	2	2	N/A	
Course Level				14	42	0.667	8	4	39	
Term Level			3	42	126	0.667	24	12	273	7
Year Level		4	12	168	504	0.667	288	144	1092	
Degree Level	4	16	48	672	2016	0.667	1152	576	4368	

Figure 16 - Master input table for the value stream maps

The time for questions and solving are assumed to be a multiple of the time spent in class or lecture. The conventional ratio of student class time to study time is two hours spent studying of for every hour spent in class (Reilly 2012) (Young 2002). This allows work to begin on the task of constructing the value stream map based on its smallest recognizable time unit, which is the quantum of learning previously described in the fractal decomposition in section 3.2.4.

3.3.2.3 Term level of the value stream map

The value stream maps described in this section can be found in Appendix B. A value stream map was constructed at the single concept level. This map has at its foundation the notion that the quantum of learning is user definable. The session level value stream map then assumes three quantum units comprise a lecture session.

The lecture sessions are aggregated to show how the fourteen class sessions that make up a course have intermediate stage gates for learning, assessment and grading. If waiting for the next lecture session and feedback queue were eliminated from this value stream then this would hasten the time to master the subject. The course value stream maps are aggregated to that of the current twelve courses in the WPI academic year level. The final iteration of the value stream map for engineering education is at the degree level. A value stream map at the scale of an individual concept, single course session, or whole course is too granular to be useful. However, at the term level, where a WPI student is taking a normal three course load, a sense of the difference between the value-added and non-value-added time begins to emerge. The value stream map shown in Figure 17 is similar to those used in industry. Cycle times and the accumulated waiting time in-between value-added activities are shown.

The time line along the bottom of the value stream map shows value added time below the time line and non-value added time above the time line. The two time lines shown illustrate the difference between the current state and the future state. From this level of value stream map, and on up to the degree level, simple multiplication of the value-added and non-value-added times show how much non-value-added queuing time is accumulated in the current system.

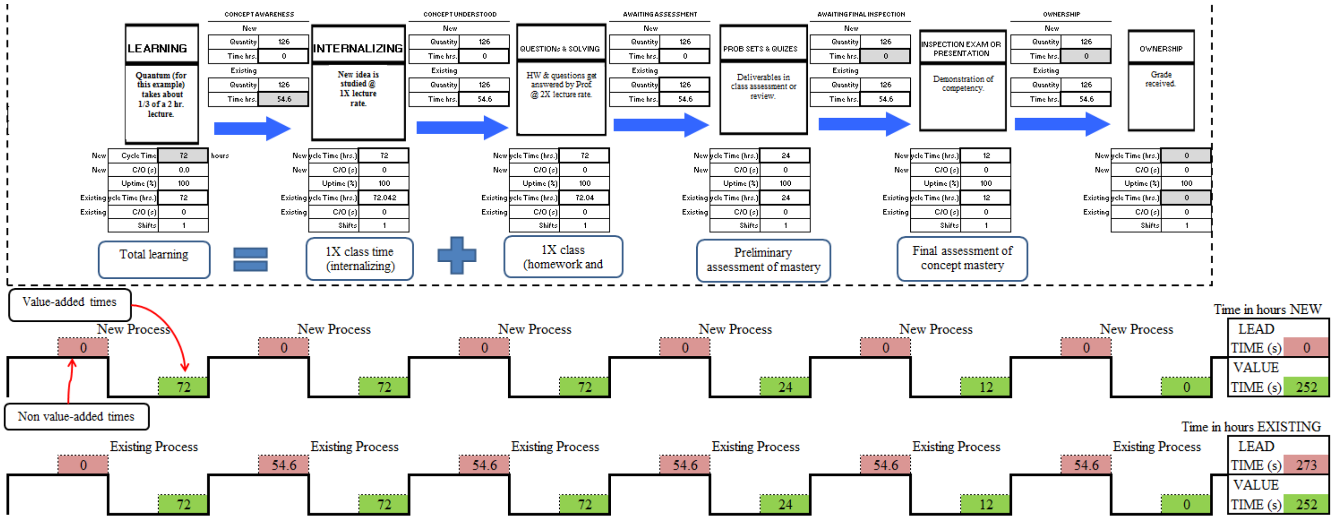
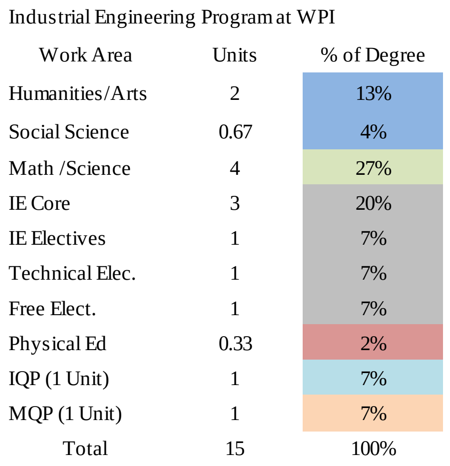


Figure 17 - Term level value stream map

Calculation of time spent in the new system does not include any non-value-added queuing time to show the ideal system capacity.

3.3.2.4 Degree level value stream maps

The top level value stream map incorporates degree requirements specific to the project requirements at WPI. The industrial engineering degree has specific requirements for graduation shown in Table 11. The amount of credit required for each portion of the degree can be tabulated to find the corresponding percentage of the student's learning activity.



Industrial Engineering Program at WPI

Work Area	Units	% of Degree
Humanities/Arts	2	13%
Social Science	0.67	4%
Math /Science	4	27%
IE Core	3	20%
IE Electives	1	7%
Technical Elec.	1	7%
Free Elect.	1	7%
Physical Ed	0.33	2%
IQP (1 Unit)	1	7%
MQP (1 Unit)	1	7%
Total	15	100%

Table 11 - Breakdown of the Industrial Engineering Degree at WPI

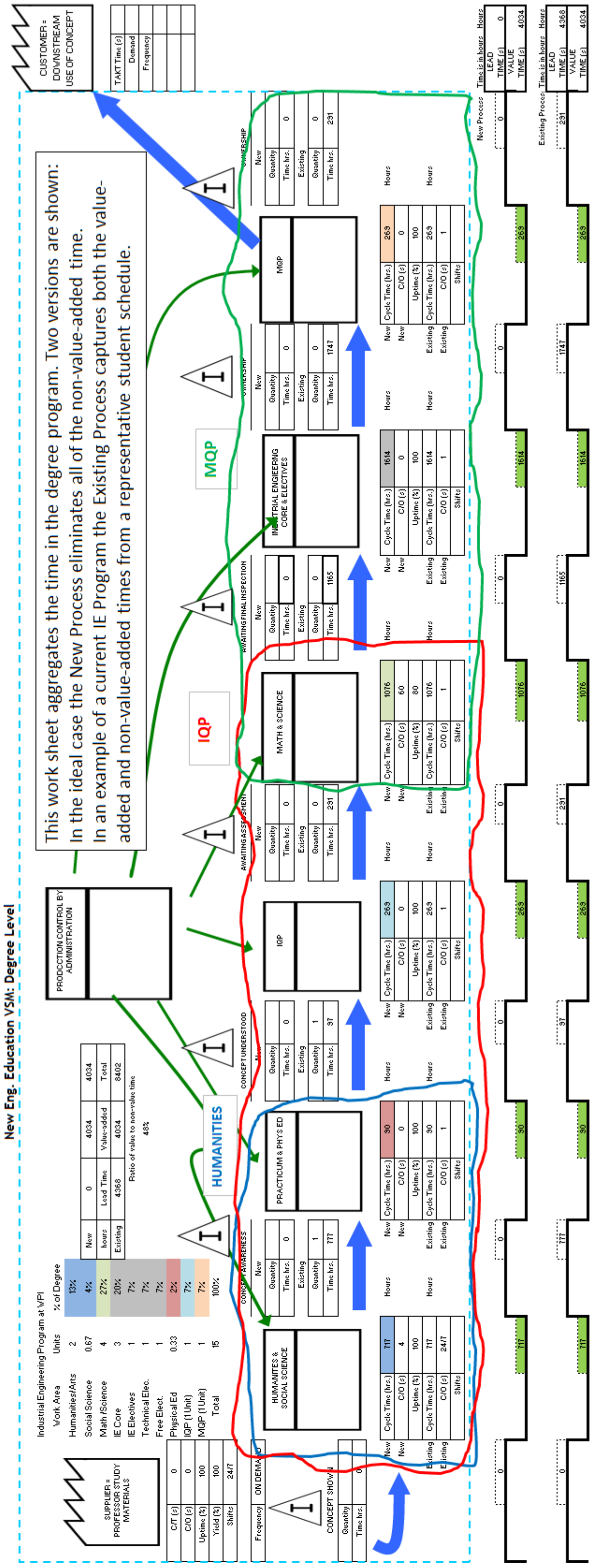
Figure 18 shows the top level value stream map arranged by degree requirements for the IE degree at WPI. The accumulated value-added and non-value-added time is shown in the lower right corner and reproduced in figure Table 12 for convenience.

The value stream map shown includes project based degree requirements. There are three shown in addition to the students regular course work in their discipline. A description of the three projects included in the summary level value stream map follows (www.wpi.edu 2012).

The Humanities & Arts Project allows students to appreciate the values attained through the study of music, history, foreign languages, literature, theatre, art and architecture, rhetoric, philosophy, religion, or their attendant disciplines. Students meet the Humanities & Arts degree requirement by completing a project completed during an Inquiry Seminar or a Practicum in an area of focus. This project provides students opportunities for in-depth encounters with humanistic inquiry or creative expression in an artistic project.

The Interactive Qualifying Project (IQP) is an interdisciplinary requirement involving applied research that connects science or technology with social issues and human needs.

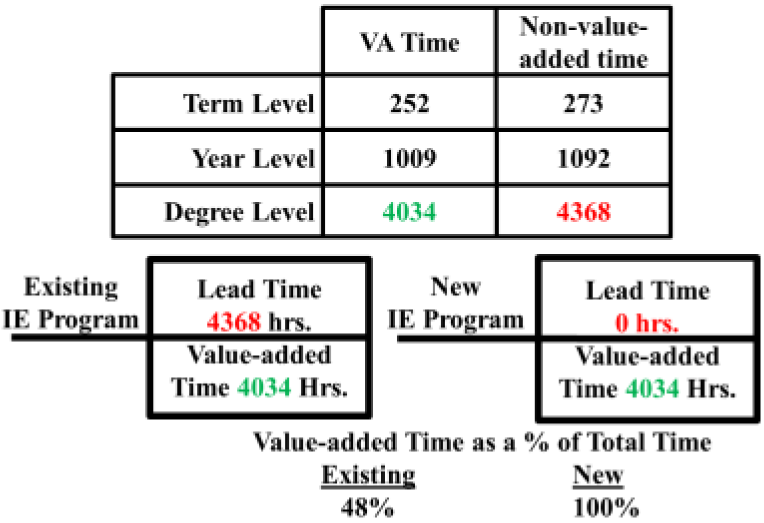
The Major Qualifying Project (MQP) is a high-level design or research project in the student’s major field. Through the MQP every student has the chance to experience the kind of real-world problem solving that will soon characterize their professional careers. The MQP involves problems typical of those found in the student’s professional discipline and often addresses economical, ethical, and safety issues. These qualifying projects are far from trivial; each requires a substantial part of an academic year. Frequently, projects are sponsored by outside agencies to which students must present their oral and written reports.



This work sheet aggregates the time in the degree program. Two versions are shown: In the ideal case the New Process eliminates all of the non-value-added time. In an example of a current IE Program the Existing Process captures both the value-added and non-value-added times from a representative student schedule.

Figure 18 - Top level value stream map arranged by degree requirements for the IE degree at WPI

Each of the percentages found are multiplied by the total credit hours in order to show how each major portion of the degree tree is affected by lead time Table 12 shows about half the time to earning a degree in consumed by activity other than learning. A summary of an entire four year IE Program is shown in Table 13.



	VA Time	Non-value-added time
Term Level	252	273
Year Level	1009	1092
Degree Level	4034	4368

Existing IE Program		New IE Program	
	Lead Time 4368 hrs.		Lead Time 0 hrs.
	Value-added Time 4034 Hrs.		Value-added Time 4034 Hrs.

Value-added Time as a % of Total Time

Existing	New
48%	100%

Table 12 - Non-value-added Time Queues Delay Graduation

Shaded cells are user input values

Times Are In Hours

	Years	Terms	Courses	Sessions	Concepts Presented	Awareness	Deliverables	Exam Length	Idle Time	Weeks per Term
Concept Level					1	0.667	2	2	N/A	
Session Level				1	3	0.667	2	2	N/A	
Course Level				14	42	0.667	8	4	39	
Term Level			3	42	126	0.667	24	12	273	7
Year Level		4	12	168	504	0.667	288	144	1092	
Degree Level	4	16	48	672	2016	0.667	1152	576	4368	

	Existing System			New System			Differences		
	VA Time	non VA Time		VA Time	non VA Time		VA Time	non VA Time	
Concept Level	6	N/A		6	N/A		0		VA to
Session Level	10	N/A		10	N/A		0		non VA
Course Level	96	N/A	Totals	96	N/A	Totals	0	Totals	Ratio
Term Level	252	273	525	252	0	252	0	273	48%
Year Level	1009	1092	2101	1009	0	1009	0	1092	48%
Degree Level	4034	4368	8402	4034	0	4034	0	4368	48%

Table 13 - Calculation of WPI IE Program data sheet and results

Table 13 shows about half of the time WPI students spend in the IE Program is consumed in non-value-added queues, based on astatic analysis (time conflicts are not taken into consideration) and average data.

3.3.3 Results from creating the engineering education process chart

A process chart shows the responsibilities of each participant in the student learning process (ASME 1986) (ANSI 1986). Figure 19 shows the process chart follows the value stream map but separates the responsibilities.

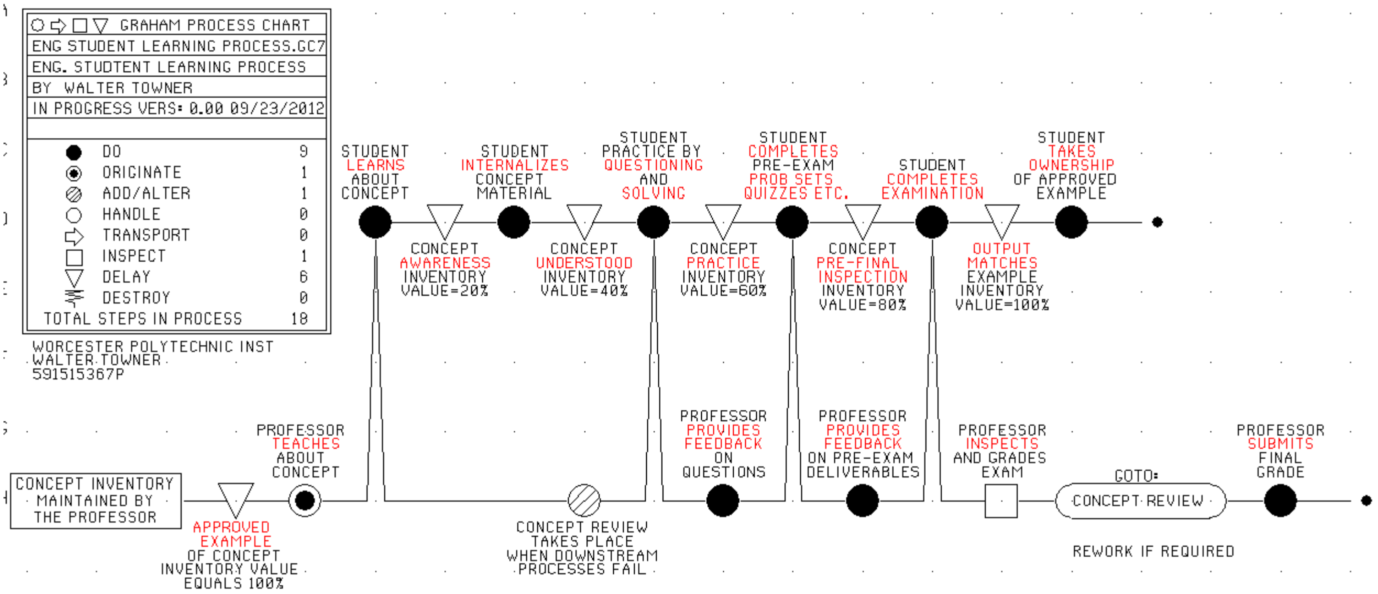


Figure 19 - Process chart showing responsibilities of each participant in the learning process

3.4 Discussion

3.4.1 The value added function

The value added function for engineering education is a simple metric based upon easy to find information. If schools are able to influence the results of the value-added function because of better operating results, it might become useful to students choosing between different schools. The data may also be useful to the school itself for purposes of tracking the internal process improvement efforts.

“Many of the developing and potential uses of value-added have not been studied at all, and there are few plans to rectify this. We need rigorous evaluation, not only of the statistical properties, but also of the use of the measures in schools” (Harris 2011).

As Harris indicates, it is vital to be able to describe how an education system is performing relative to the learning activities and its ultimate value to its graduates. Assessment is crucial for teaching and learning, for institutional improvement, and for public accountability.

Currently there are no common or widely used assessment measures of value-added other than student surveys or the ranking of “input” variables and retention. “We would be best served if we in higher education would assess student outcomes and better yet if we developed a strategy to measure value-added in terms of student learning during and over the entire undergraduate experience” (Hersh 2004). Student outcomes should also be assessed after they have gone to work.

3.4.2 Novelty of the quantum of learning

Value stream maps are used to identify which activities are adding value and by how much as a percentage of the total time. A definition of what is considered value-added time requires a universally understood way to quantify value added activity from the student's perspective so that it can be differentiated from all other time in the system. The quantum of learning quantity is able to be defined by the user to suit the needs of a course or school. The exact values used in this dissertation matter little to the overall analysis, only that it is recognized that some percentage of the time spent in school adds value and some does not.

3.4.3 Origin of the quantum of learning

In 1900 Max Planck discovered that energy existed in individual units which he called *quanta*. Planck found that at certain discrete temperature levels (exact multiples of a basic minimum value); energy from a glowing body will occupy different areas of the color spectrum. The result of this discovery became the basis of quantum theory (Planck 1900). In much the same way, an engineering degree can be decomposed into its component parts resulting in the smallest recognizable quanta, i.e. *a basic concept or idea*. Any decomposition beyond this point results in a largely undefined collection of facts and figures that are not useful by themselves. Similarly, molecules can be broken down into atoms. Atoms are known to have certain behavioral characteristics. If the atoms are broken down further into their sub-component parts, the results might not be useful, thus suggesting that there are limits in decomposing things into their component parts.

Fulfilling the second objective, the value stream map presented used an approach modeled after Planck's quantum theory and utilizes constructs in comparing an engineering degree to a tree. A natural tree exhibits self-similar characteristics in its structure that can be seen at finer scales, but the tree's self-similarity has natural limits. So too does the process of engineering education exhibits natural limits as it is decomposed into its basic elements. An overall view of the engineering degree was presented as a fractal showing the self-similar structure of the degree. A succession of value stream maps was created beginning with the most detailed value stream map consisting of a single concept quantum of learning. Subsequent value stream maps built on the previous levels until an engineering degree is able to be described.

The top level value stream map shows that about half of the time spent to complete the degree requirements is spent doing something other than learning and demonstrating mastery. The value stream maps were based upon a 5 day, 40 hour work week over 7 week terms as is customary at WPI. There are other time schedules which can be adapted to any program to allow for different re-characterizations of how the student's time is being used.

3.4.4 The importance of the value stream map in higher education

If engineers are the product, then their learned knowledge and skills are the results of the production system. This implies that there are two inventory systems supporting the value stream. One is physical in nature in the form of students attending classes, accessing data, and similar activities. The other is the intangible learning, knowledge transfer and skill building.

From a production point of view, non-value-added time in engineering education happens in at least two ways. One way is due to the waiting time in-between the presentations of new educational materials. The second way is the waiting time for responses to inquiries of professors and the return of graded material. Students might not be allowed to formally progress in the course of study around these process buffers.

The value of these buffers is in question because they do not add value to the student's learning and can impede the student's progress. The process of learning could therefore have a definition of value-added time.

3.4.5 Defining the minimum amount of learning for the value stream map

The value stream map presented here is defined in terms of *quantum satis*. *Quantum satis* is, for the purpose of developing a value stream map for higher education, the amount of learning to achieve the result, but not more (Ayto 2000). More specifically, education can be considered to have a fractal aspect with some natural limits. The smallest usable *quantum* proposed is that of an idea, formula, method or concept that is learned and subsequently combined with other concepts for solving and understanding more complex problems.

A goal of value stream mapping is to identify and quantify the value-adding and non-value-adding steps in a process. In higher education some ways that waste is created are through the idle time between learning activities. Examples of how waste is created in higher education include:

1. Inefficient use of course tools such as syllabi, quizzes and projects.
2. Waiting time for evaluative feedback.
3. Waiting time between class sessions.
4. Waiting time between courses being offered.

In order to achieve customer needs, a production system should be informed by how value is created and measured (Cochran and Dobbs 2001).

Operating the education system at a university as a producing factory for graduate engineers should not be a cause for diminishing the quality of the final product. A university education is more than the sum of the factual data. Some students will choose to process the learning material at a faster pace due to financial pressure. Others might choose to play on a sports team. The decision should be up to the individual student. The primary issue is that in order to reduce inefficiencies and to improve the value-added, metrics on how the system operates are needed in order to do any type of process improvement (Kelvin 1883). This study does not attempt to address the value of activities external to credit-bearing courses.

3.4.6 Manufacturing engineering principles applied to process improvement

The engineering education system could improve by using two important manufacturing engineering concepts (Koren and Shpitalni 2010) (Mylnek, et al. 2005) (Yoshimura 2007):

1) Production should not experience unnecessary delays thereby increasing throughput
2) The pace of production should not impact the quality of the final output

The time that a student should expect to earn an engineering degree is usually prescribed by the school's academic calendar and course offering schedule. This system, which has been in effect since the end of the 19th century does not allow students to move through the system at a faster pace even if they are able to do so. The traditional system specifically precludes fast learners from quickly demonstrating mastery and moving on to the next subject at their own pace due to course and academic scheduling.

Further exploration of this idea begs the question, is the goal of a school to maximize tuition received from a student? Or should it be to provide the highest value-added for the tuition received that the school can provide for the student? Both of these goals are able to be satisfied in concert if school administrators take a longer term view of the education process. As the current system stands, more efficient schools that offer an ABET accredited degree can attract students seeking a higher value-added experience. This might result in two classes of engineering schools.

One type of school might seek primarily to maximize the short term benefits of operating the school from the administrator's point of view. The other type of school focuses on the longer term by maximizing the value-added to the students, even if tuition revenue is forgone. This forgone short term revenue will be replaced by increasing overall tuition revenue from a growing number of highly competitive students (and their families) seeking to maximize their return on tuition expenditures in the face of potential cuts in financial aid (Obama 2012). This is the strategy that Toyota used to become the world's number one automobile producer (OICA 2012). Administrators and their accountants could be driven by short term revenue enhancement, but alternative education suppliers, especially less expensive foreign sources, might offer a better value-added proposition than the current system. The proposed system can enable faculty and administrators to change the traditional revenue model.

3.4.7 Development of a process chart showing the interaction of the stakeholders

Knowing how and when value is created in a process is important; it is also important to know the areas of responsibility and how interactions take place in education as well as in manufacturing. A process chart is created showing various paths through the system. A proposed process chart is presented illustrating a new method in engineering education process as a manufacturing system.

3.5 Conclusions

The objective to develop a value-added function, a value stream map, and a process chart was achieved.

It can be further be concluded that the development of a value-added function for engineering education is important because it relates two of the largest streams of payments in a student's life up to and including the early years of work life after graduation. Its value for students making financial comparisons among schools is clear. For the engineering school, it is a way to balance the school's desire to increase top line revenue and minimize internal cost of operation by connecting the value of the degrees they produce with the marketplace.

Value stream maps have been used by corporations to improve competitive position and lower costs since their rapid popularization in the 1990s. A university can build its own value stream map of the learning process similar to the one presented earlier in this chapter. The base model of learning can then be used to develop value stream maps for each course in order to understand the magnitude of the non-value-added time in the system. Professors can make their value stream maps in order to evaluate each course to facilitate decreasing the non-value-added time for students. Support for process improvement based on the value stream maps is clear.

Quality is also an outcome which might be captured in income after graduation. The length of time of the value-added function could have a short term and longer time component to reflect a quality metric.

Chapter 4 - Manufacturing System Design of New Engineering Education Process

4.1 Introduction

The premise of this chapter is that improvements can be made to the engineering education process based on manufacturing principles and using Suh's axiomatic design method.

The objective is to design an engineering education system using axiomatic design (Suh 1990). The following themes will be used in the decompositions:

- *Criteria for Accrediting Engineering Programs*, Criterion 3 (ABET 2012)
- Waste reduction in manufacturing processes (Ohno 1988)

Redesign of engineering education in the US is important because the current system is unsustainable due to the cost to operate the system and the inability of students to fund tuition (Wood 2011).

4.1.1 State-of-the-Art

4.1.1.1 Engineering education system design

The literature about engineering education systems focuses on the methods of delivering course content, such as online, blended and traditional lecture and other formats. The key idea is that traditional instructional methods will probably not be adequate to equip engineering graduates with the knowledge, skills, and attitudes they will need (Rugarcia, et al. 2000). There is also a great deal written about course subject matter itself and how it should tie to other disciplines. Key findings include the establishment of a Center for Converging Technologies and the call for more integrative core courses that are multicurricula based (Klein and Balmer 2007) (Plaza 2004).

Searches for lean in higher education found papers, blogs and articles extolling the use of energy saving methods, reduction of paper usage, automated administrative tasks and other energy or time saving concepts from an operational cost point of view. Key findings include, a stated reduction of expenses by $14,000, improvement of process flow, and not relying on tuition hikes, personnel cuts, or program eliminations (Kusler 2008) (Balzer 2010).

Examples of how axiomatic design has been used in education related fields include a re-design of complex sociopolitical-economic systems like the National Science Foundation in 1985 (Suh 2005). The design of the top level functional requirements of higher education for a country was found and the key findings were a list of functional requirements for a country to provide opportunities to learn for all those who want to learn, create future leaders for all sectors of a nation, advance fundamental knowledge and technology, and create professionals in all fields (Suh 2005). Another source discussed the re-design of the mechanical engineering department at MIT in 1991 in order to 1) transform the discipline of mechanical engineering from one that is based on physics to one that is based on physics, information and biology; and 2) to make an impact through research on the knowledge base and technology innovation-the two ends of the research spectrum-rather than being in the middle of the research spectrum; and to provide the best teaching to the students (Suh 2005).

4.1.1.2 Axiomatic design of manufacturing systems

A review of the literature of how axiomatic design has been applied to manufacturing system design yields examples too numerous to list. Some of these examples focus on sub-components of the manufacturing system like the design of cellular manufacturing systems. The results show that the proposed methodology is sound, and easy to follow and implement (Kulak et al. 2005). Other research discusses the design of large scale production systems such as rationalizing the design of the Toyota Production System.

The key finding from axiomatic design was that a decomposition approach can be used to explain, understand, replicate and deploy manufacturing systems. It develops a general framework of requirements for successful manufacturing system design and might someday point the way to the design and development of innovative and effective manufacturing systems that transcend current benchmark companies (Won et al. 2001).

4.1.1.3 Axiomatic design of non-manufacturing systems

Thompson has applied axiomatic design to education by focusing on the educator as the designer of the education process. Graduation can occur only for students who fall within the design range by demonstrating mastery of the concepts and skills concluding that axiomatic design appears to be well-suited to the design of educational curricula (2009). A hierarchical manufacturing system design for engineering education does not exist to the knowledge of the author. A search of the literature reveals no work that applies axiomatic design methods to model engineering education as a manufacturing system.

4.1.1.4 Principles of manufacturing

Two top level functional requirements have been proposed for application to all manufacturing processes and systems. They are shown in Table 14. The proposition is that these could also be axioms to be used as a foundation for manufacturing science (Brown 2011b).

Functional Requirement
(1) Maximize the value-added to the product
(2) Minimize the cost in the production process

Table 14 - The manufacturing principles

Examples of designing an education system based on the manufacturing principles of maximizing value-added and minimizing production cost were not found in the literature.

4.1.2 Approach

The approach to designing engineering education as a manufacturing system uses the axiomatic design method (Suh 1990). The design decomposition starts with the proposal that the top level functional requirement of an engineering school modeled as a manufacturing system is to create engineers. The next two sub-level functional requirements are to 1) maximize the value added to the student, and 2) minimize the cost of production (Brown 2011b). Each of these top level functional requirements are decomposed according to ABET Criterion 3, which can be found in Appendix C (ABET 2012), and wastes in manufacturing (Ohno 1988). The work of Deming is relied upon for the continuous improvement of the system (Deming 2000). Key metrics on the functional requirements are defined. System information is calculated based on assumed system ranges and corresponding design ranges as well as to determine the probability of successfully fulfilling the functional requirements.

All good designs are consistent with two axioms proposed by Suh. The Independence Axiom requires the maximization of the independence of the functional requirements which allows the design to be adjustable and controllable. The Information Axiom requires minimization of the information content in the design in order to maximize the probability of success (Brown 2011a).

Two axiomatic design decompositions are presented. The first iteration of the design decomposition is based on the ABET Criterion 3 student outcomes (a) - (k), but does not apply Axiom One to the design hierarchy. This is to illustrate the redundancy in the criteria. The second iteration of the design decomposition applies Axiom One.

4.2 Methods

4.2.1 First iteration of modeling engineering education as a manufacturing system

The nature of modeling engineering education as a manufacturing system is straight forward. Raw materials, in the form of newly matriculated high school students, are converted into degree-holding engineers.

This raw material takes on two distinct aspects of inventory. The first is the obvious physical presence of people who must be accommodated in a physical way when buildings are occupied. Buildings have physical limits and constraints. The other aspect of inventory being processed is the skill set that is produced during the transformation process. The incoming raw material also comes with different skill sets. Standards are available that define what the final product should be, chief among them being the accreditation outcomes.

The time students spend in the university system is one of the most easily recognizable ‘costs’ associated with the conversion process. Minimizing the throughput time spent in the system by eliminating the parts of the conversion (i. e. education) process that do not add value, is a goal of the manufacturing engineer. Allowing waste to remain in the system creates an opportunity cost for not only the student but for the university as well. This opportunity cost can be capitalized on by competitors whose systems eliminate these costs as a competitive advantage.

The task at hand is to design a manufacturing system that produces engineers whose specifications meet or exceed the accreditation standard and minimize cost. Production techniques for the conversion of physical items in manufacturing are used as a model to accomplish this task.

4.2.1.1 Manufacturing system design and industrial engineering analysis

In addition to the axiomatic design method, other techniques from manufacturing and industrial engineering that describe queuing, cellular manufacturing, scheduling, throughput and constraint management, augment the basic design process to produce a method of manufacturing for any type of production process including the manufacture of engineers.

4.2.1.2 Quality assurance and self-inspection

Quality assurance methods can be adapted to the engineering education system in the form of self-configuring parts, or poke-yoke. In order to maintain high quality in course work, one method of in-process inspection could be to have the students grade each other's work. This might help to prevent a less than fully qualified 'part' to move on in the production process.

Peer grading causes at least two things to happen. The students must first assess what was supposed to be learned and thereby making critical judgments on their own work, and second, the process distributes the assessment work load away from the professor to the students (Sadler and Good 2006).

Educators have used proprietary online tools for confidential self and peer evaluations to produce "formative learning oriented feedback to complete the learning cycle that significantly improved students' learning outcomes." Artificial intelligence programs offer help during homework (Kelly et al. 2013). Providing formative feedback multiple times during the course provides an opportunity for students to reflect and modify their own behavior (Willey and Gardner 2008).

4.2.1.3 Deming's continuous improvement cycle

Process improvement must be incorporated into any manufacturing system so that it can react to changes in the functional requirements (FRs) and the design parameters (DPs) that fulfill them. Deming's Plan-Do-Check-Act (Adjust) cycle of continuous improvement is incorporated into the design hierarchy for engineering education as a manufacturing system (Deming 2000).

4.2.2 Decomposition of engineering education as a manufacturing system using Suh's Axiomatic Design Method

A function refers to what something does and a goal is why a function should be accomplished (Thompson 2012). In the process of designing engineering education as a manufacturing system, functional requirements are used to show how the goals of the system are achieved. A goal of efficiently operating a business process is not the same as the functional components that allow it to operate. An example might be a financial report that shows how the system has changed over time versus the reason the system is desired to change over time. In this work, the term functional requirement or FR is used to be consistent with the axiomatic design lexicon, but the FRs can be considered translations of the goals of the system.

The following material provides the logic and sequence to complete the design decomposition Additional information on axiomatic design can be found in a primer on axiomatic design located in Appendix D.

4.2.2.1 Statement of the highest level functional requirement - FR_0

If the goal of engineering education designed as a manufacturing system is to ‘manufacture’ engineers according to manufacturing principles, then the highest level functional requirement in the design decomposition, known as ‘FR_0‘ can be stated as: FR_0 = 'manufacture' engineers.

FR_0 is the most important functional requirement. If FR_0 is not properly defined, the design decomposition will lead to a solution of a problem that was not originally intended to be solved.

The design of engineering education as a manufacturing system begins with the goal of the desired output being accredited graduate engineers. The highest level FRs in the system are defined using principles from manufacturing and industrial engineering and are stated in Table 15.

Functional requirements
FR0: ‘Manufacture’ engineers (using ABET/MFE/IE principles, efficiently)

Table 15 - The top level functional requirement for the academic manufacturing system - FR_0

The decomposition continues with the specification of the top level functional requirements that are thematically derived from manufacturing principles.

4.2.2.2 Additional upper level functional requirements - FR_1 & FR_2

The next level down in the design hierarchy begins with a theme. The thematic decomposition is developed from manufacturing principles. FR_1 and FR_2 set the theme for the initial design decomposition as shown in Table 16.

FR1: Maximize value added to engineering student's skills and knowledge
FR2: Minimize cost of creating engineering student's skills and knowledge

Table 16 - Design hierarchy decomposition theme

If the goal of FR_1 is defined as maximizing the value-added to the student (product), then engineering education’s productive output is the skill set of the graduate engineer.

If the goal of FR_2 is defined as minimizing the cost of creating the knowledge and skill set of the graduate engineer, then an engineering school’s operating goal is to efficiently manufacture engineers for the least cost. The problem statements above comprise the top level functional requirements for designing engineering education as a manufacturing system.

Table 17 shows FR_0, FR_1 and FR_2 stated at the top of the design decomposition. The underlying principles for this analysis based are based on the work of Deming and Ohno (Deming 2000) (Ohno 1988).

Functional Requirements
FR0: 'Manufacture' engineers (using ABET/MFE/IE principles, efficiently)
FR1: Maximize value added to engineering student's competence (Deming - PDCA Cycle)
FR2: Minimize cost of creating engineering student's competence (Ohno - 7 Wastes & Toyota Production System)

Table 17 - FR_0, FR_1 and FR_2 are the top level of the design decomposition

Continuing the decomposition, the second hierarchical level of FRs, the children of FR_1 are found in Student Outcomes (a) – (k).

4.2.2.3 Functional requirements definition for FR_1

Under FR_1 the customer needs for engineering education are assumed to be aligned with Criterion 3 (ABET 2012) which states, “The program must have documented student outcomes that prepare graduate to attain the program educational objectives.” This objective is common throughout the world where ABET accreditation is the standard. Continuing, “student outcomes (*a*) through (*k*) plus any additional outcomes that may be articulated by the program” are shown in Table 18.

(a) an ability to apply knowledge of mathematics, science, and engineering
(b) an ability to design and conduct experiments, as well as to analyze and interpret data
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
(d) an ability to function on multidisciplinary teams
(e) an ability to identify, formulate, and solve engineering problems
(f) an understanding of professional and ethical responsibility
(g) an ability to communicate effectively
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
(i) a recognition of the need for, and an ability to engage in life-long learning
(j) a knowledge of contemporary issues
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Table 18 - ABET Criterion 3. Student Outcomes (a) – (k)

4.2.2.4 FRs should be collectively exhaustive, mutually exclusive, and minimized

Axiomatic design decomposition demands that the list of FRs satisfying the customer be collectively exhaustive, mutually exclusive and stated in a minimum form. This is to prevent the unnecessary duplication or overlapping of design requirements leading to redundancy in the design. The functional requirements are the foundation for the resulting design effort. As stated by Rasial in his book *The McKinsey Way*, McKinsey’s problem solving process has three major attributes: “the solution will be 1) rigidly structured; 2) hypothesis driven; and 3) facts are friendly." The list of facts will be *mutually exclusive* and *collectively exhaustive* (1999). Additionally, the design axioms are also subject to additional theorems and corollaries that are described by Suh to further support an analysis (Suh 1990). A convenient acronym for "collectively exhaustive, mutually exclusive, minimum list" used by practitioners of axiomatic design is CEMEmin (Brown 2006).

4.2.2.4 First iteration of the design decomposition of ABET Criterion 3, sans Axiom One

The first iteration of the design decomposition maintains fidelity to Criterion 3, and is shown in Table 19. It is a design decomposition of the top level FR for a system that maximizes the value added to the engineering students' knowledge and skills, but the list shown is not CEMEmin because it contains redundancies. Each FR in the decomposition is a statement of the plan to fulfill the school's obligations to the customer of the academic manufacturing system, who is ultimately the employer of the students upon graduation (Black 1996).

Functional Requirements

- FR0: 'Manufacture' engineers (using ABET/MFE/IE principles, efficiently)
  - FR1: Maximize value added to engineering student's competence (Deming - PDCA Cycle)
    - FR1.1: Create an ability to apply knowledge of MATHEMATICS, SCIENCE & ENGINEERING ABET(a) (plan)
    - FR1.2: Create an ability to DESIGN/CONDUCT Experiments, ANALYZE/ INTERPRET DATA ABET(b) (plan)
    - FR1.3: Create an ability to DESIGN a system, component, process w/ realistic constraints ABET(c) (plan)
    - FR1.4: Create an ability to function on Multidisciplinary TEAMS ABET (d) (plan)
    - FR1.5: Create an ability to identify, formulate & SOLVE ENGINEERING PROBLEMS ABET(e) (plan)
    - FR1.6: Create an understanding of professional & ETHICAL RESPONSIBILITY ABET(f) (plan)
    - FR1.7: Create an ability to COMMUNICATE EFFECTIVELY ABET(g) (plan)
    - FR1.8: Create an understanding of eng. on GLOBAL IMPACT, economic, environ'l, soc'l context ABET(h) (plan)
    - FR1.9: Create a recognition of the need for & an ability to engage in LIFE-LONG LEARNING ABET(i) (plan)
    - FR1.10: Create a knowledge of CONTEMPORARY TEAMS ABET(j) (plan)
    - FR1.11: Create an ability to use the techniques, skills, & eng. tools for ENGINEERING PRACTICE ABET(k) (plan)

Table 19 - The third level - FR$_{1.1}$ through FR$_{1.11}$ for maximizing value-added

The protocol for axiomatic design calls for the designer to cycle between one domain to another and then down to the next lowest level to work throughout the decomposition. This process is called *zigzagging*. Table 20 shows the design DPs that fulfill the FRs in the functional domain. Measurements are also included so the system operator is able to compare results over time and understand the designer's original intent. Each FR above has a corresponding DP that describes the method or system that will full an FR.

Functional Requirements

- FR0: 'Manufacture' engineers (using ABET/MFE/IE principles, efficiently)
  - FR1: Maximize value added to engineering student's competence (Deming - PDCA Cycle)
    - FR1.1: Create an ability to apply knowledge of MATHEMATICS, SCIENCE & ENGINEERING ABET(a) (plan)
    - FR1.2: Create an ability to DESIGN/CONDUCT Experiments, ANALYZE/ INTERPRET DATA ABET(b) (plan)
    - FR1.3: Create an ability to DESIGN a system, component, process w/ realistic constraints ABET(c) (plan)
    - FR1.4: Create an ability to function on Multidisciplinary TEAMS ABET (d) (plan)
    - FR1.5: Create an ability to identify, formulate & SOLVE ENGINEERING PROBLEMS ABET(e) (plan)
    - FR1.6: Create an understanding of professional & ETHICAL RESPONSIBILITY ABET(f) (plan)
    - FR1.7: Create an ability to COMMUNICATE EFFECTIVELY ABET(g) (plan)
    - FR1.8: Create an understanding of eng. on GLOBAL IMPACT, economic, environ'l, soc'l context ABET(h) (plan)
    - FR1.9: Create a recognition of the need for & an ability to engage in LIFE-LONG LEARNING ABET(i) (plan)
    - FR1.10: Create a knowledge of CONTEMPORARY TEAMS ABET(j) (plan)
    - FR1.11: Create an ability to use the techniques, skills, & eng. tools for ENGINEERING PRACTICE ABET(k)

Design Parameters

- DP0: System for 'manufacturing' ABET engineers (engineering school)
  - DP1: Function that maximizes value added to engineering student's competence (Time Value of Money
    - DP1.1: System for creating knowledge of math, science & eng (learning activity mngt syst)
    - DP1.2: System for creating how to design/conduct experiments (learning activity mngt syst)
    - DP1.3: System for creating the ability to design w/ constraints (learning activity mngt syst))
    - DP1.4: System for creating the ability to function on multi-teams (learning activity mngt syst)
    - DP1.5: System for creating the ability to identify, formulate, solve eng probs (learning activity mngt syst)
    - DP1.6: System for creating the understanding professional/ethical responsibility (learning activity mngt syst)
    - DP1.7: System for creating the ability to communicate effectively (learning activity mngt syst)
    - DP1.8: System for creating an understanding of impact eng global context (learning activity mngt syst)
    - DP1.9: System for creating recognition of need & ability life-long learning (learning activity mngt syst)
    - DP1.10: System for creating knowledge of contemporary teams (learning activity mngt syst)
    - DP1.11: System for creating the ability to use techniques for eng practice (learning activity mngt syst)

Table 20 - DPs for $FR_{1.1}$ through $FR_{1.11}$

4.2.2.5 List of the second level of functional requirements for FR_2

Decomposing FR_2 relies on waste found in manufacturing shown in Table 21 (Ohno 1988).

Seven Wastes in Manufacturing			
1	Transportation	5	Over-processing
2	Inventory	6	Over-production
3	Motion	7	Defects
4	Waiting		

Table 21 - The seven wastes in manufacturing

Two additional wastes have been included as wastes of precious resources in a school. They are the waste of not leveraging the professor's time, and the waste of not leveraging the school's physical and information technology assets shown in Table 22.

Functional Requirements
FR0: 'Manufacture' engineers (using ABET/MFE/IE principles, efficiently)
  FR1: Maximize value added to engineering student's competence (Deming - PDCA Cycle)
  FR2: Minimize cost of creating engineering student's competence (Ohno - 7 Wastes & Toyota Production System)
    FR2.1: Reduce WAITING waste caused by non-value-added queues (plan)
    FR2.2: Reduce UNNECESSARY INVENTORY waste due to batch processing (plan)
    FR2.3: Reduce UN-LEVERAGED TIME waste of the professor's schedule (plan)
    FR2.4: Reduce DEFECTS waste due to premature advancement of incomplete students (plan)
    FR2.5: Reduce TRANSPORTATION waste caused by co-location of professors and students (plan)
    FR2.6: Reduce UNNECESSARY MOTION waste from incomplete course information (plan)
    FR2.7: Reduce NON-VALUE-ADDED PROCESSING waste from learning unnecessary material (plan)
    FR2.8: Reduce OVERPRODUCTION waste due to teaching redundant material (plan)
    FR2.9: Reduce UN-LEVERAGED ASSETS waste of the school (plan)

Table 22 - The third level - $FR_{2.1}$ through $FR_{2.9}$ for minimizing cost

Following the zigzagging procedure described above, the DPs for FR_2 are shown in Table 23.

Functional Requirements
FR0: 'Manufacture' engineers (using ABET/MFE/IE principles, efficiently)
  FR1: Maximize value added to engineering student's competence (Deming - PDCA Cycle)
  FR2: Minimize cost of creating engineering student's competence (Ohno - 7 Wastes & Toyota Prod. Syst.)
    FR2.1: Reduce WAITING waste caused by non-value-added queues (plan)
    FR2.2: Reduce UNNECESSARY INVENTORY waste due to batch processing (plan)
    FR2.3: Reduce UN-LEVERAGED TIME waste of the professor's schedule (plan)
    FR2.4: Reduce DEFECTS waste due to premature advancement of incomplete students (plan)
    FR2.5: Reduce TRANSPORTATION waste caused by co-location of professors and students (plan)
    FR2.6: Reduce UNNECESSARY MOTION waste from incomplete course information (plan)
    FR2.7: Reduce NON-VALUE-ADDED PROCESSING waste from learning unnecessary material (plan)
    FR2.8: Reduce OVERPRODUCTION waste due to teaching redundant material (plan)
    FR2.9: Reduce UN-LEVERAGED ASSETS waste of the school (plan)

Design Parameters
DP0: System for 'manufacturing' ABET engineers (engineering school)
  DP1: Function that maximizes value added to engineering student's competence (Time Value of Money Function)
  DP2: Function that minimizes cost of creating engineering student's competence (Total Cost Equation)
    DP2.1: System for reducing waiting waste due to non-value-added queues (student paced learning system)
    DP2.2: System for reducing unnecessary inventory waste due to batch processing (production management system)
    DP2.3: System to reduce un-leveraged time waste of the professors schedule (time buffers)
    DP2.4: System for reducing defects waste due to premature advancement of students (frequent gated assessments)
    DP2.5: System for reducing transportation waste due to co-location of professors and students (virtual content
    DP2.6: System for reducing unnecessary motion waste from incomplete course information (course content mgnt.
    DP2.7: System for reducing non-value-added waste of due to learning unnecessary material (course content mgnt.
    DP2.8: System for reducing overproduction waste due to teaching redundant material (course content coordination
    DP2.9: System for reducing un-leveraged assets waste of the school (asset inventory coordination)

Table 23 - DPs for $FR_{2.1}$ through $FR_{2.9}$

4.2.2.6 Continuous improvement using the Deming Cycle for each FR

Ideal manufacturing systems should undergo continuous improvement. Deming's work in quality and production system improvement produced the Deming Cycle of Plan-Do-Check-Act (or Adjust) (Deming 2000) (Moen and Norman 2010). Figure 20 illustrates the Deming Cycle.

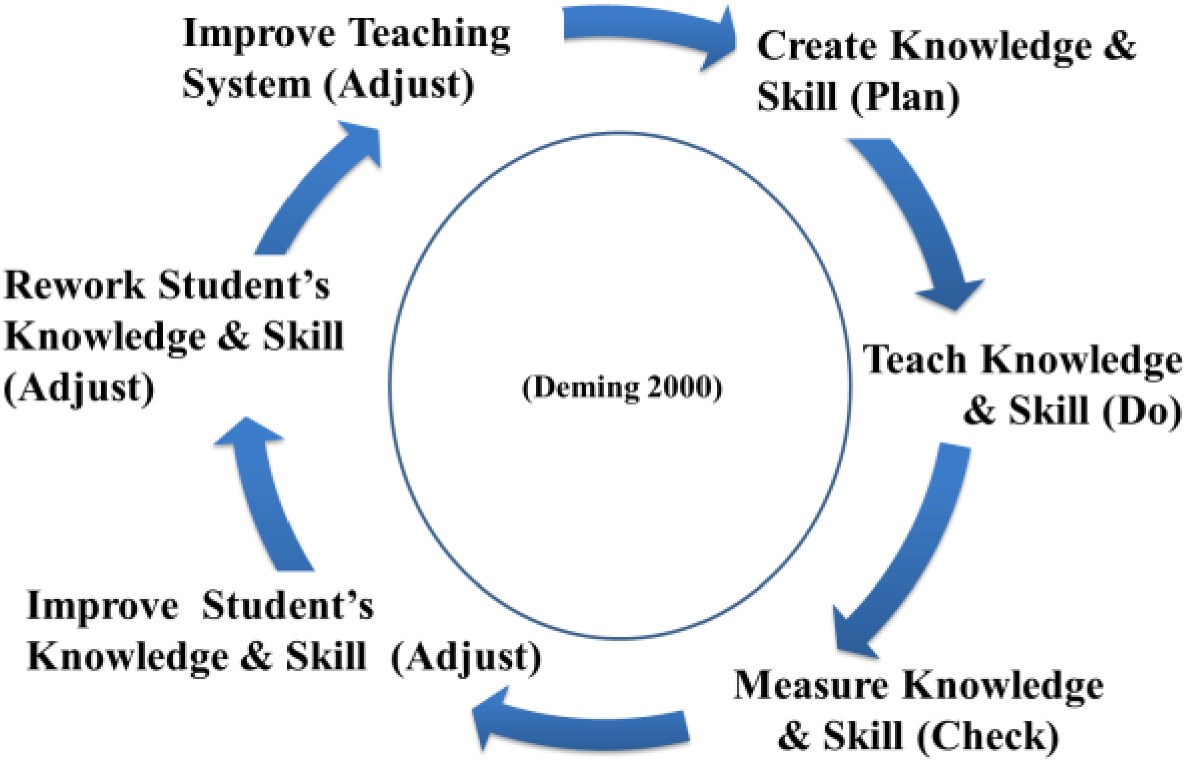


Figure 20 - Deming's Plan-Do-Check-Act Continuous Improvement Cycle

All of the third level FRs (FRs$_{1.1-1.11}$ and FRs$_{2.1-2.9}$) have corresponding Deming cycles for continuous improvement. For example, the Deming cycle for FR$_{1.1}$ Criterion 3: (c) "an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability" is shown in Table 24. The children of FR$_{1.1}$ are summed together to satisfy in FR$_{1.1}$ as shown in Equation 3.

$$FR_{1.1} = FR_{1.1.1} + FR_{1.1.2} + FR_{1.1.3}$$

Equation 3 - FR$_{1.1}$ equals the summation of its children, FR$_{1.1.1}$, FR$_{1.1.2}$, & FR$_{1.1.3}$

Functional Requirements

- FR0: 'Manufacture' engineers (using ABET/MFE/IE principles, efficiently)
  - FR1: Maximize value added to engineering student's competence (Deming - PDCA Cycle)
    - FR1.7: Create an ability to COMMUNICATE EFFECTIVELY ABET(g) (plan)
      - FR1.7.1: Teach how to communicate effectively (do)
      - FR1.7.2: Verify the ability to communicate effectively (check)
      - FR1.7.3: Improve the teaching system for communicating effectively (adjust)
        - FR1.7.3.1: Improve a student's ability to communicate effectively (adjust)
        - FR1.7.3.2: Improve the teaching system for communicating effectively (adjust)

Table 24 - Deming's PDCA Cycle for Criterion 3: (g) communicate effectively

Following this logic, Equation 4 shows how the children of $FR_{1.7.3}$ are also added together to show how they satisfy the parents function.

$$FR_{1.7.3} = FR_{1.7.31} + FR_{1.7.3.2}$$

Equation 4 - $FR_{1.7.3} = \Sigma$ children

All of the children of the FRs in the design decomposition are added together to satisfy the function required of their corresponding parent FR (Suh 1990). The summation of the parent FRs concludes with fulfilling FR_0, which describes the overall design problem to be solved. A partial system of FRs is shown in Table 26 with a fully expanded version of the initial design decomposition is contained in Appendix E.

4.2.3 Metrics for the functional requirements

Each FR should be able to be independently and objectively evaluated in any design. Some of the FRs in the design of engineering education as a manufacturing system have easily quantifiable metrics like instruction and research cost or tuition revenue. This is because they can be read directly from the school's financial statements. Some FRs need derivative values from multi-criteria decision methods such as scoring models, analytic hierarchy process (AHP), analytic network process (ANP) or a utility model applied to qualitative metrics (Nelson 1986) (Kahraman et al. 2004) (Suh 1995). A short description of the proposed metrics for each FR follows.

Functional requirements that can be described quantitatively will have measurement functions to accomplish this objective and are included in the design hierarchy. There are twenty-two FRs that have metrics associated with them. Each of the Deming continuous improvement cycles need metrics as well, but they are not included in this work.

4.2.3.1 Metric for FR_0: system that 'manufactures' engineers

The overall metric of operating a production system that produces graduate engineers is to measure how the overall efficiency of the system is changing over time in Equation 5. Items found on most colleges' financial statements can be used for continuity over accounting periods.

$$\text{Efficiency Ratio for the 'manufacture' of engineers}\ \% = \frac{\text{Income from Tuition \& Fees}}{\text{Instruction \& Research Expense}}$$

Equation 5 - FR_0 Metric: efficiency ratio for the production of engineers

This metric is a financial ratio calculated from aggregate level financial statements, not a managerial accounting metric, thereby negating its usefulness to those close to the teaching process.

4.2.3.2 Metric for FR_1: value-added in engineering education

The value-added to the student as a result of earning an engineering degree was derived in the previous chapter on value-added in education. This metric compares the timing of the tuition payments to the income value of a graduate engineer over a period of time as shown in Equation 6. The net present value of the degree is related through a discount rate described in Chapter 3.

$$VA_{Eng\ Ed} = NPV(i) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$

Equation 6 - FR_1 Metric: value-added in engineering education

Where:

t = *time of the cash flow*
i = *discount rate (opportunity cost of capital)*
R_t = *net cash flow (income minus tuition) at time t*
note:
income is inflated annually by the consumer price index (CPI)
tuition is inflated annually by 'tuition rate of inflation'

The value-added function for engineering education is able to be modified for any series of tuition payments and income received for any degree for which a wage schedule is known.

4.2.3.3 Metric for $FR_{1.1}$ to $FR_{1.11}$: Criterion C: (a) – (k) assurance of learning

The assurance of learning outcomes can be specific to a department and need only be consistent from time period to time period. This can be expressed as a percentage of students that met a minimum standard as the result of an assessment.

4.2.3.4 Metric for FR_2: cost of creating an engineering student's competence

The cost of creating an engineering student's competence is a direct cost of the teaching and research activity of the faculty and can be found on the financial statements for a school shown in Equation 7.

$$Cost\ of\ creating\ engineering\ student's\ competence = \sum Instruction + Research\ Cost$$

Equation 7 - FR_2 Metric: cost of creating engineering student's competence

Full absorption accounting includes the cost of buildings, depreciation, administrative expenses and other overhead categories and they are captured in the school's financial statements.

4.2.3.5 Metric for $FR_{2.1}$: waste of unnecessary inventory

Little's Law states that average inventory or work-in-process (WIP) equals throughput time (TPT) multiplied by production rate (PR) as shown in Equation 8 (Little 1961) (Little 1992) (Little and Graves 2008) (Anupindi, et al. 2012). Little's law reflects the average waiting time and average number of items waiting for service in the system.

$$L = \lambda W$$

Equation 8 - FR_0 Metric: Little's Law

Where:
L = average number of items in a queuing system (WIP)
λ = average number of items appearing per unit time (PR)
W = average throughput time (TPT)

As discussed in Chapter Two, in order to accomplish the goal of minimizing W, which is the student's non-value-added time, a method of reducing the time students spend in queues is necessary. This can be accomplished in at least two ways. The first way is to allow the students to proceed at their own pace in a one-piece-flow system versus the current batch processing system. This can be accomplished in part by on demand learning materials. A second way is to reduce the amount of time students wait for support in the form of answers to questions and scoring of the course deliverables. This can be accomplished by leveraging the professor's time so that more can be done in that same amount of time.

As an example, assume that 1500 students are enrolled in a course. If the professor is able to disseminate the learning material in the form of a live or recorded lecture students can access it asynchronously assuming that the technological infrastructure exists. The number of students enrolled is irrelevant because the professor's time is leveraged over the entire group. This is similar to a journalist writing in a newspaper where the story can be read by millions of people also asynchronously.

The ability of the professor to respond to interrogatories and requests for support becomes limited once the number of students seeking help reaches a threshold where the number of students in the queue multiplied by the average response time required to support them exceeds the time available that the professor has to be able to respond. This is one reason that student to faculty ratios are kept low so that the individual students quality of education can be high. The professor’s time is a limited resource therefore every effort should be made to ensure that this time is not wasted.

A similar situation applies to doctors and hospitals. If the patient’s needs are simple, physician’s assistants, nurses, and doctors in training can provide service as a filter for the most experienced doctors whose work time is expensive and limited to only seeing cases that cannot be attended to by less knowledgeable staff.

In this manner of providing service it is expected that each patient will receive the type of care they require, when they require it, and with the least expensive resources being consumed. Professors have recently been able to manage their work load in a similar manner. Professors do not need to perform their support function in a synchronous manner with the student like doctors do. Patients arriving at the hospital should be seen as soon as possible to prevent a worsening condition. The hospital triage system is used to determine who can perform the needed service in a real time synchronous manner.

Professors, on the other hand, are able to introduce a service filter and respond in an asynchronous manner because the students seeking support can wait without their condition worsening. Forcing the student to wait could actually improve the student’s ability to learn as he or she seeks self-support, and consulting the course materials, classmates and TAs. If these sources have been exhausted, the student will then receive personal attention from the professor.

Professors who do not have a well-designed and up-to-date support system for the students are condemned to be continually re-creating the support solutions requested by students. By re-creating support solutions the professor’s time is wasted, as a previously delivered support solution will need to be created a second or third time. The solution to this problem is to capture all of the support given to students previously in a knowledge management system or wiki. The system will have written and video captures that can be cross referenced, available on demand and allow for continual review by students seeking learning support.

The system reduces the workload on the professor so that larger numbers of students can be processed through the course without degrading the quality of the learning experience. In order for the system to work effectively a systematic way of capturing and storing the professors support efforts must be in place.

Continuing with the example of a course that has 1500 students enrolled and rearranging Little’s Law yields insight into managing the production problem.

$$\text{TPT (average throughput time)} = \frac{\text{WIP (average number of items in a queuing system)}}{\text{PR (average number of items appearing/unit time)}}$$

$$\text{TPT} = \frac{\text{(1500 students) (10 minutes average support time) (10\% of students need support)}}{\text{(2 students/hour)}}$$

$$\text{TPT} = 12.5 \text{ hours} = \text{the average throughput time that a student experiences}$$

The above calculation assumes that with a ten minute help session, professors are using all of their available time to respond to student needs at the expense of everything else, which is clearly unacceptable. The introduction of a self-help support filter can reduce the waiting time that students experience. If an additional 10% of the 10% of students needing support actually need to have direct contact with the professor the queuing time is reduced to 1.25 hours because the inventory in the queue has been reduced.

$$\text{TPT} = \frac{\text{(1500 students) (10 minutes average support time) (10\%) (10\% of students need support)}}{\text{(2 students/hour)}}$$

TPT =1.25 hours = the average throughput time that a student experiences

Manufacturing systems are forced to respond to increases in demand by managing the output rate (Little and Graves 2008). The manufacturing or industrial engineer is called upon to waive the “industrial engineering magic wand” to transform an existing production system into a new state that responds to new demands on the manufacturing system. This magic wand in this case is the capturing and organizing of the support information anticipated to be required by students for reuse. A primary goal of the new system is to eventually be handling only exceptions to normal student support requests or to update the support system as new learning material is introduced to the system. A following chapter presents a computer simulation model of the proposed new one-piece-flow engineering education system with a large number of students enrolled in a course using the filtering method described above.

4.2.3.6 Metric for $FR_{2.2}$: the waste of waiting

The waste of waiting is calculated by how much time students spend in non-value added queues during the learning process. It might be found on a value stream map or calculated as a running total of actual time for a group of students. Equation 9 was derived in Chapter 2 on value-added in education.

$$Value\ added\ Time\ Ratio = \sum VA \frac{\sum VA}{\sum VA + nonVA}$$

Equation 9 - $FR_{2.2}$ Metric: value-added time ratio

Value-added time (VA) is defined as:

$$VA = L + I + Q + S + E + O$$

Where:

L=*learning time*
I=*internalizing time*
Q=*questioning time*
S=*solving time*
E=*exam time*
O=*ownership time*

non-Value-added time (nonVA) is defined as:

$$nonVA = QF + SF + EF + OF$$

Where:

QF=*questioning feedback waiting time*
SF=*solving feedback waiting time*
EF=*exam feedback waiting time*
OF=*ownership feedback waiting time*

4.2.3.7 Metric for $FR_{2.3}$: defect ratio

In order to reduce defects being passed up the production line, manufacturers use various types of in process inspection. Production processes that are able to be defect free through the design of the parts themselves or through the design of the process are highly desirable. In the case of students not assimilating the course content, many short, focused, low-risk, formative assessments could be built into the course. This is similar to trying to alter the trajectory of a rocket as it nears its destination. The earlier in flight corrections are able to be made to the flight path, the easier it is to land at the intended destination. Such is the case with students mastering engineering material. Both the professor and student will want to know quickly if the progress being made is faulty. This can be accomplished with tactical formative assessments that help both student and professor know where difficulty lies and thereby make adjustments. The defect ratio is shown in Equation 10.

$$Defect\ Ratio\ \% = \frac{Number\ of\ Students\ First\ Time\ Pass}{Total\ Number\ of\ Students\ Assessed}$$

Equation 10 - $FR_{2.3}$ Metric: defect ratio

4.2.3.8 Metric for $FR_{2.4}$: waste of transportation ratio

Analogous to the waste of transportation in a factory is that of co-locating students and their professor in the same physical space. This is shown in Equation 11. This is not to say that students and professors meeting in the same place should not happen, but like many blended course offerings and internet web conferences, a high quality learning experience can take place even if the meeting is not face to face.

$$Co-location\ Waste\ Ratio\ \% = \frac{Number\ of\ Students\ Attending\ Virtually}{Total\ Number\ of\ Students\ Attending}$$

Equation 11 - $FR_{2.4}$ Metric: co-location waste ratio

4.2.3.9 Metric for $FR_{2.5}$: waste of overproduction

The waste of overproduction results from teaching redundant academic material. Periodically, students will take courses in which minor or major portions of the course work have appeared in previous courses. This issue can be avoided by use of concept inventory and coordination within a department, as shown in Equation 12.

$$Overproduction\ Waste\ Ratio\ \% = \frac{Number\ of\ redundant\ concepts}{Total\ Number\ of\ concepts\ to\ be\ learned}$$

Equation 12 - $FR_{2.5}$ Metric: overproduction waste ratio

4.2.3.10 Metric for $FR_{2.6}$: waste of non-value-added production

Similar to the waste of overproduction ratio, the non-value-added processing waste ratio resulting from teaching unnecessary academic material is shown in Equation 13. This issue can be avoided by use of a concept inventory and coordination within a department.

$$Non-Value-Added\ Proc.Waste\ Ratio\ \% = \frac{Number\ of\ unnecesary\ concepts}{Total\ Number\ of\ concepts\ to\ be\ learned}$$

Equation 13 - $FR_{2.6}$ Metric: non-value-added processing waste ratio

4.2.3.11 Metric for $FR_{2.7}$: waste of unnecessary motion

Similar to the waste of overproduction ratio, the unnecessary motion waste ratio results from incomplete teaching material. This issue can be avoided by use of syllabus and schedule reviews for course organization documents, as shown in Equation 14.

$$Unnecassry\ Motion\ Waste\ Ratio\ \% = \frac{Amount\ of\ Incomplete\ Course\ Data}{Total\ Amount\ of\ Course\ Data}$$

Equation 14 - $FR_{2.7}$ Metric: unnecessary motion waste ratio

4.2.3.12 Metric for $FR_{2.8}$: waste of unleveraged professor time

Professors' time is a precious resource for a school. Their services are personally delivered and difficult to leverage. Baumol and Bowen, in 1966, observed that personally delivered services, such as customized lessons and class plans, exhibit low productivity growth, this leads to a continuing and compounded rise in real cost (Baumol and Bowen 1966). Methods must be developed to improve the use of faculty time through the use of teaching assistants, student self-management, and technology. Equation 15 compares the professor's total available work time to the value-added activity time.

$$Un - leveraged\ Professor's\ Time\ Waste\ Ratio\ \% = \frac{Amount\ of\ Value - added\ Professor\ Time}{Total\ Amount\ of\ Professor\ Time\ Allocated}$$

Equation 15 - $FR_{2.8}$ Metric: un-leveraged professor time ratio

4.3.7.13 Metric for $FR_{2.9}$: waste of unleveraged assets

A school's physical and virtual assets are a precious and expensive resource. Asset utilization, alone should not be the driving force behind increasing revenue to the school. Asset use needs to be coupled with ways to leverage capacity without adding to the asset base unless it has been substantiated through analysis. Existing classrooms and labs should be in use as much as possible, as they are a fixed asset of the school that is not easily created or reduced. But they can be leveraged to many times beyond their nominal capacity through the use of technology. A metric that represents this utilization is presented in Equation 16.

$$Un - leveraged\ Asset(capacity)\ Waste\ Ratio\ \% = \frac{Amount\ of\ Asset\ (capcity)\ used}{Total\ Amount\ of\ Asset\ (capacity)\ Available}$$

Equation 16 - $FR_{2.9}$ Metric: un-leveraged asset (capacity) waste ratio

4.2.4 The Information Axiom and the probability of achieving the FRs

For designs that satisfy Axiom One, the design with the least amount of information is the best (Suh 2005). For a given system, the likelihood of successfully fulfilling the FRs is determined by how well the design range overlaps with the system range as shown in Figure 21 (Suh 2005).

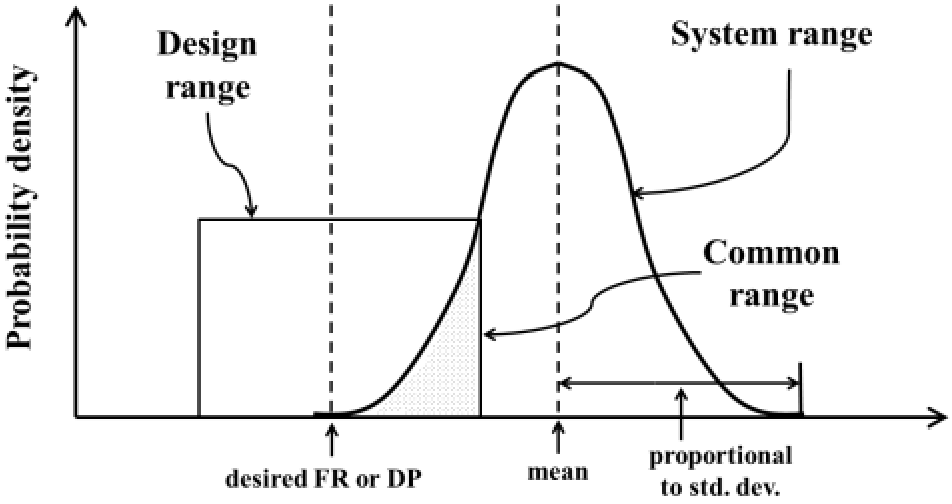


Figure 21 - Probability density function, system range and design range

The design range represents what is intended to take place for a successful design outcome; the system range is what the system is capable of providing in terms of operating results. Where the two systems overlap there is a common range that allows for the information content to be calculated.

4.2.4.1 Definition of Information

Information in a design is defined in terms of the information content *I* that is related to the probability of fulfilling a set of FRs shown in Equation 17 (Suh 1990)(Kahraman et al. 2004).

$$I = log\left(\frac{system\ range}{common\ range}\right)$$

Equation 17 - Definition of information in a design

The information content I_i for an FR is shown in Equation 18:

$$Ii = \log_2 \frac{1}{P_i} = -\log_2 P_i$$

Equation 18 - Information content for a given FR

P_i is defined as the probability of successfully fulfilling the FR_i and the logarithm in base 2 with the information unit in bits as defined by Shannon in 1948 (Kahraman et al. 2004). There are a total of twenty-three first, second and third level FRs in the proposed system.

For the general case of m FRs, the information content for an entire system is shown in Equation 19, where $P(m)$ is the joint probability that all of m FRs are satisfied (Suh 2005).

$$I_{sys} = -\log_2 P_{(m)}$$

Equation 19 - Information content for a system

4.2.4.2 Conditional probability when the FRs are statistically coupled

The FRs in the proposed design are not statistically independent, as seen in Figure 22 later in this chapter. The figure shows many DPs interacting with multiple FRs. This indicates that conditional probabilities must be used to calculate the information in the design. I_{sys} is calculated by Equation 20 below, where $P_{i|\{j\}}$ is the conditional probability of satisfying FR_i given that all other correlated FRs, $\{FR_j\}_{j=1,\ldots,i-1}$,are also satisfied (Suh 2005).

$$I_{sys}=-\sum_{i=1}^{m} \log_2 P_{i|\{j\}} \qquad \text{for } \{j\} = \{1,\ldots,i-1\}$$

Equation 20 - Total system information with conditional probabilities

4.2.4.3 System and common range data

Since the proposed design has more than one measure of performance to be evaluated it can be termed multi-attributed. One way of evaluating multi-attributed criteria is to use a fuzzy information axiom (Kahraman et al. 2004).

Just like investing in advanced manufacturing processes and systems, the decision process will involve multiple and conflicting objectives as in the case of engineering education. These conflicts can include minimizing costs, maximizing flexibility, or maximizing efficiency all of which, and more, are present in designing an education system.

4.2.5 Second iteration of modeling engineering education as a manufacturing system

Another possible decomposition that applies Axiom One is accomplished decomposing Criterion 3 into two additional themes. The first theme is what engineers need to *know*, and the second theme is what engineers need to be able to *do*. The upper level FRs for the second decomposition are shown in Table 25.

Functional Requirements

FR0: 'Manufacture' engineers (using ABET/MFE/IE principles, efficiently)
    FR1: Maximize value added to engineering student's competence (Deming - PDCA Cycle)
        FR1.1: Create knowledge for performing about MATHEMATICS, SCIENCE & ENGINEERING (a) CONTEMPORARY ISSUES (j)
        FR1.2: Create knowledge of consequences from performing ETHICAL RESPONSIBILITY (f) GLOBAL IMPACT (h) (plan)
        FR1.3: Create skill to perform as individual to CONDUCT & INTERPRET (b) DESIGN syst (c) SOLVE probs (e) LIFELEARN (i) ENG PRACTICE (k)
        FR1.4: Create skill to perform as group member for TEAMWORK (d) COMMUNICATE (g)

Table 25 - Second iteration design decomposition showing compliance with Axiom One

4.6. Results

4.6.1 Results of the first iteration of the design decomposition

The FRs and measurements resulting from the first design iteration are presented in Table 26. Appendix E contains additional detailed views including the DPs and the bottom portion of the decomposition.

Functional Requirements	FR Measurement
FR0: 'Manufacture' engineers (using ABET/MFE/IE principles, efficiently)	max %=Tuition Inc./Instruction
FR1: Maximize value added to engineering student's competence (Deming - PDCA Cycle)	max VA=NPV Sum Rt/(1+i)^t
FR1.1: Create an ability to apply knowledge of MATHEMATICS, SCIENCE & ENGINEERING ABET(a) (plan)	Assurance of Learning Results
FR1.1.1: Teach knowledge of mathematics, science, and engineering (do)	Assurance of Learning Results
FR1.1.2: Measure the ability to apply knowledge of math, science, & eng (check)	Assurance of Learning Results
FR1.1.3: Improve the ability to apply knowledge of math, science & eng (adjust)	Feedback Analysis Results
FR1.1.3.1: Improve a student's ability to apply knowledge of math, science & eng (adjust)	Rework Analysis Results
FR1.1.3.2: Improve the teaching system for knowledge of math, science & eng (adjust)	Kaizen Event Results
FR1.2: Create an ability to DESIGN/CONDUCT Experiments, ANALYZE/ INTERPRET DATA ABET(b) (plan)	Assurance of Learning Results
FR1.2.1: Teach how to design/conduct experiments, analyze/interpret data (do)	Assurance of Learning Results
FR1.2.2: Quality Assurance of the ability to design/conduct experiments, analyze/interpret data (check)	Assurance of Learning Results
FR1.2.3: Improve the ability to design/conduct experiments, analyze/interpret data (adjust)	Feedback Analysis Results
FR1.2.3.1: Improve a student's ability to design/conduct experiments, analyze/interpret data	Rework Analysis Results
FR1.2.3.2: Improve the teaching of design/conduct experiments, analyze/interpret data	Kaizen Event Results
FR1.3: Create an ability to DESIGN a system, component, process w/ realistic constraints ABET(c) (plan)	Assurance of Learning Results
FR1.3.1: Teach how to design a system, component, or process w/ realistic constraints (do)	Assurance of Learning Results
FR1.3.2: Quality Assurance of the ability to design a system, component, or process w/ constraints (check)	Assurance of Learning Results
FR1.3.3: Improve an ability to design a system, component, or process w/ realistic constraints ABET(adjust)	Feedback Analysis Results
FR1.3.3.1: Improve a student's ability to design a system, component, or process w/ constraints (adjust)	Rework Analysis Results
FR1.3.3.2: Improve the teaching system for design a system, component, or process w/ constraints (adjust)	Kaizen Event Results
FR1.4: Create an ability to function on Multidisciplinary TEAMS ABET (d) (plan)	Assurance of Learning Results
FR1.4.1: Teach how to function on multidisciplinary teams (do)	Assurance of Learning Results
FR1.4.2: Verify how to function on multidisciplinary teams (check)	Assurance of Learning Results
FR1.4.3: Improve the ability to function on multidisciplinary teams (adjust)	Feedback Analysis Results
FR1.4.3.1: Improve a student's ability to function on multidisciplinary teams	Rework Analysis Results
FR1.4.3.2: Improve the teaching system for functioning on multidisciplinary teams	Kaizen Event Results
FR1.5: Create an ability to identify, formulate & SOLVE ENGINEERING PROBLEMS ABET(e) (plan)	Assurance of Learning Results
FR1.5.1: Teach the ability to identify, formulate, and solve engineering problems (do)	Assurance of Learning Results
FR1.5.2: Quality Assurance of the ability to identify, formulate & solve eng problems (check)	Assurance of Learning Results
FR1.5.3: Improve the ability to identify, formulate & solve engineering problems (adjust)	Feedback Analysis Results
FR1.5.3.1: Improve an ability to identify, formulate & solve engineering problems (adjust)	Rework Analysis Results
FR1.5.3.2: Improve the teaching system to identify, formulate & solve eng problems (adjust)	Kaizen Event Results
FR1.6: Create an understanding of professional & ETHICAL RESPONSIBILITY ABET(f) (plan)	Assurance of Learning Results
FR1.6.1: Teach an understanding of professional and ethical responsibility (do)	Assurance of Learning Results
FR1.6.2: Verify the understanding of professional and ethical responsibility (check)	Assurance of Learning Results
FR1.6.3: Improve the teaching system for understanding of professional and ethical responsibility (adjust)	Feedback Analysis Results
FR1.6.3.1: Improve a student's understanding of professional and ethical responsibility	Rework Analysis Results
FR1.6.3.2: Improve the teaching system for understanding of professional and ethical responsibility	Kaizen Event Results
FR1.7: Create an ability to COMMUNICATE EFFECTIVELY ABET(g) (plan)	Assurance of Learning Results
FR1.7.1: Teach how to communicate effectively (do)	Assurance of Learning Results
FR1.7.2: Verify the ability to communicate effectively (check)	Assurance of Learning Results
FR1.7.3: Improve the teaching system for communicating effectively (adjust)	Feedback Analysis Results
FR1.7.3.1: Improve a student's ability to communicate effectively (adjust)	Rework Analysis Results
FR1.7.3.2: Improve the teaching system for communicating effectively (adjust)	Kaizen Event Results
FR1.8: Create an understanding of eng. on GLOBAL IMPACT, economic, environ'l, soc'l context ABET(h) (plan)	Assurance of Learning Results
FR1.8.1: Teach an understanding of the impact of engineering solutions (do)	Assurance of Learning Results
FR1.8.2: Verify an understanding of the impact of engineering solutions (check)	Assurance of Learning Results
FR1.8.3: Improve an understanding of the impact of engineering solutions (adjust)	Feedback Analysis Results
FR1.8.3.1: Improve a student's understanding of the impact of engineering solutions (adjust)	Rework Analysis Results
FR1.8.3.2: Improve the teaching system for understanding of the impact of engineering solutions (adjust)	Kaizen Event Results
FR1.9: Create a recognition of the need for & an ability to engage in LIFE-LONG LEARNING ABET(i) (plan)	Assurance of Learning Results
FR1.9.1: Teach the recognition and ability to engage in life-long learning (do)	Assurance of Learning Results
FR1.9.2: Quality Assurance of the recognition and an ability to engage in life-long learning (check)	Assurance of Learning Results
FR1.9.3: Improve the teaching system for the recognition of life-long learning (adjust)	Feedback Analysis Results
FR1.9.3.1: Improve a student's recognition of an ability to engage in life-long learning (do)	Rework Analysis Results
FR1.9.3.2: Improve the teaching system for the ability for in life-long learning (do)	Kaizen Event Results
FR1.10: Create a knowledge of CONTEMPORARY TEAMS ABET(j) (plan)	Assurance of Learning Results
FR1.10.1: Teach about contemporary teams ABET(do)	Assurance of Learning Results
FR1.10.2: Quality Assurance of the knowledge of contemporary teams ABET(check)	Assurance of Learning Results
FR1.10.3: Improve the knowledge of contemporary teams (adjust)	Feedback Analysis Results
FR1.10.3.1: Improve a student's knowledge of contemporary teams(adjust)	Rework Analysis Results
FR1.10.3.2: Improve the teaching system for contemporary teams (adjust)	Kaizen Event Results
FR1.11: Create an ability to use the techniques, skills, & eng. tools for ENGINEERING PRACTICE ABET(k) (plan)	Assurance of Learning Results
FR1.11.1: Teach the techniques, skills, and modern engineering tools necessary for engineering practice (do)	Assurance of Learning Results
FR1.11.2: Verify the ability to use techniques, skills, and modern engineering tools necessary for engineering practice (check)	Assurance of Learning Results
FR1.11.3: Improve the ability to use techniques, skills, and modern engineering tools necessary for engineering practice (adjust)	Feedback Analysis Results
FR1.11.3.1: Improve a student's ability to use techniques for engineering practice (adjust)	Rework Analysis Results
FR1.11.3.2: Improve the teaching system for using techniques for engineering practice (adjust)	Kaizen Event Results

Table 26 - Completed design hierarchy Showing $FR_{1.1}$ through $FR_{1.11}$

The design decomposition is complete based upon manufacturing engineering principles, capturing the proper FRs and corresponding DPs. The FRs have metrics for evaluation on whether they are improving or not. The entire design system is transparent by retaining the design intent and it is able to be modified with new FRs, as necessary.

4.6.2 Interactions between the DPs and the FRs.

The influence of a DP on an FR is known as an *interaction* between the DP and the FR. One DP might interact with more than one FR causing coupling of the FRs. This undesirable condition in the science of design results in designs that are difficult to control or adjust because they violate the independence axiom. Coupled designs can be improved with the introduction of new DPs that allow compliance with Axiom One.

Upon examination of the first iteration of the design of engineering education as a manufacturing system based on Criterion 3 without any modifications of the DPs, it is clear that coupling exists in the design. A DP is said to influence an FR if, by its actions or operation, it will cause the functional requirement to go out of tolerance (Brown 2013). Some DPs have a small influence on one or more FRs, and while this condition may be noted, it can safely be ignored. DPs that have influence to the point that they can cause the FR to go out of tolerance result in inefficient designs that could prove to be problematic during operation.

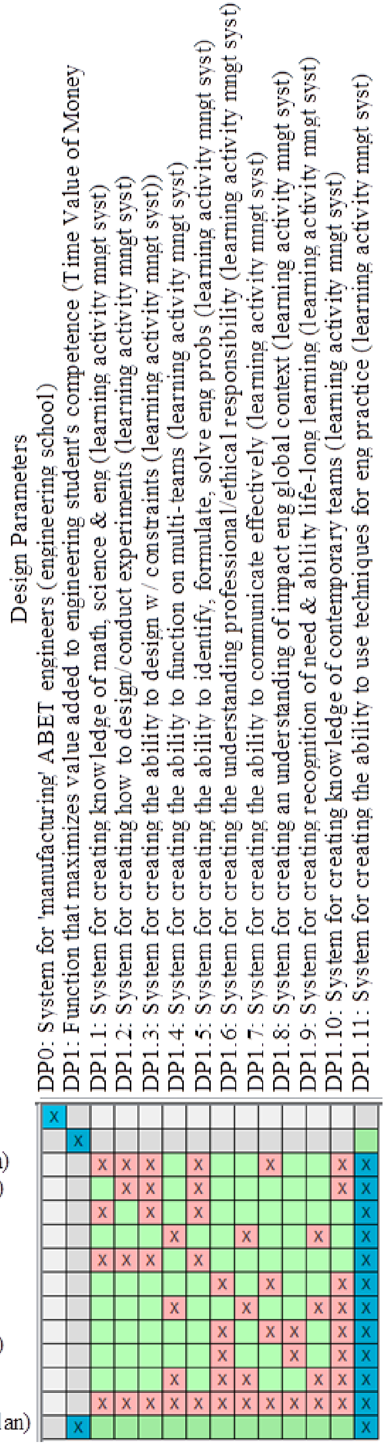
Acclaro® software is used to show the FR-DP interactions present in the design (Axiomatic Design Solutions, Inc. 2012).

4.6.2.1 Coupling caused by the influence of DP_1 on both FR_1 and FR_2.

The design process is used to choose the right set of DPs to satisfy the given FRs. A design matrix showing the relationship between each of the FRs and DPs is shown in Figure 22. The left-hand side of the matrix represents what is desired to be achieved through the FRs and the right-hand side of the design equation is represented on the top of the matrix which shows how they are planned to be achieved by the DPs.

A design can be reconfigured to form a diagonal or triangular matrix in the lower left corner to determine the order of adjustment of the DPs to satisfy the FRS. Figure 17 shows the DPs affecting more than FR in the current design indicates overlapping FRs and prevents the system being independently controllable in its present form. A second iteration of the design of engineering education as a manufacturing system is shown later in the chapter.

This figure shows the design matrix prior to being rearranged in an effort to get the matrix into a triangular form. Clearly, ABET Criterion 3 has many overlapping FRs which can be seen in the design matrix. Details of the interactions between the DP’s and the FRs are described later.



Design Parameters
DP0: System for 'manufacturing' ABET engineers (engineering school)
DP1: Function that maximizes value added to engineering student's competence (Time Value of Money
DP1.1: System for creating knowledge of math, science & eng (learning activity mngt syst)
DP1.2: System for creating how to design/conduct experiments (learning activity mngt syst)
DP1.3: System for creating the ability to design w/ constraints (learning activity mngt syst))
DP1.4: System for creating the ability to function on multi-teams (learning activity mngt syst)
DP1.5: System for creating the ability to identify, formulate, solve eng probs (learning activity mngt syst)
DP1.6: System for creating the understanding professional/ethical responsibility (learning activity mngt syst)
DP1.7: System for creating the ability to communicate effectively (learning activity mngt syst)
DP1.8: System for creating an understanding of impact eng global context (learning activity mngt syst)
DP1.9: System for creating recognition of need & ability life-long learning (learning activity mngt syst)
DP1.10: System for creating knowledge of contemporary teams (learning activity mngt syst)
DP1.11: System for creating the ability to use techniques for eng practice (learning activity mngt syst)

Functional Requirements
FR0: 'Manufacture' engineers (using ABET/MFE/IE principles, efficiently)
FR1: Maximize value added to engineering student's competence (Deming - PDCA Cycle)
FR1.1: Create an ability to apply knowledge of MATHEMATICS, SCIENCE & ENGINEERING ABET(a) (plan)
FR1.2: Create an ability to DESIGN/CONDUCT Experiments, ANALYZE/ INTERPRET DATA ABET(b) (plan)
FR1.3: Create an ability to DESIGN a system, component, process w/ realistic constraints ABET(c) (plan)
FR1.4: Create an ability to function on Multidisciplinary TEAMS ABET (d) (plan)
FR1.5: Create an ability to identify, formulate & SOLVE ENGINEERING PROBLEMS ABET(e) (plan)
FR1.6: Create an understanding of professional & ETHICAL RESPONSIBILITY ABET(f) (plan)
FR1.7: Create an ability to COMMUNICATE EFFECTIVELY ABET(g) (plan)
FR1.8: Create an understanding of eng. on GLOBAL IMPACT, economic, environ'l, soc'l context ABET(h) (plan)
FR1.9: Create a recognition of the need for & an ability to engage in LIFE-LONG LEARNING ABET(i) (plan)
FR1.10: Create a knowledge of CONTEMPORARY TEAMS ABET(j) (plan)
FR1.11: Create an ability to use the techniques, skills, & eng. tools for ENGINEERING PRACTICE ABET(k) (plan)

X													
	X												
		X	X	X		X			X			X	X
			X	X		X						X	X
		X		X		X							X
					X			X			X		X
		X	X	X		X							X
							X		X			X	X
					X			X			X	X	X
							X		X	X		X	X
							X			X		X	X
					X		X	X			X	X	X
		X	X	X	X	X	X	X	X	X	X	X	X
	X												X

Figure 22 - High level coupling in the design matrix

4.6.2.2 Interactions between the second level FR$_1$ and its corresponding DPs

As one might expect, there is lot of coupling between the FRs and DPs that satisfy Criterion 3, seen in Table 27. This means that the FRs are satisfied in many ways through a student's academic work (Brown 2006). Not all coupling is negative in nature (Brown 2013). It would not be feasible to prioritize the order of fulfilling the FRs with so much coupling at this level.

ABET Criterion 3 element	FR	Matrix Symbol X or (none)	DP1.1 System for creating an ability to apply knowledge of mathematics, science, and engineering	Description
(a) an ability to apply knowledge of mathematics, science, and engineering	FR1.1	X	Intended	DP1.1 Required for FR1.1
(b) an ability to design and conduct experiments, as well as to analyze and interpret data	FR1.2	X	Sequential	Students need DP1.1 for FR1.2
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	FR1.3	X	Sequential	Students need DP1.1 for FR1.3
(d) an ability to function on multidisciplinary teams	FR1.4	(none)		
(e) an ability to identify, formulate, and solve engineering problems	FR1.5	X	Sequential	Students need DP1.1 for FR1.5
(f) an understanding of professional and ethical responsibility	FR1.6	(none)		
(g) an ability to communicate effectively	FR1.7	(none)		
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	FR1.8	X	Sequential	Students need DP1.1 for FR1.8
(i) a recognition of the need for, and an ability to engage in life-long learning	FR1.9	(none)		
(j) a knowledge of contemporary issues	FR1.10	(none)		
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	FR1.11	X	FR-FR	Students need DP1.1 for FR1.11

Table 27 - Interactions resulting from DP$_{1.1}$ on FR$_{1.1}$ – FR$_{1.11}$

Table 28 shows that an engineer needs to first learn factual information about engineering before being able to practice in the field. This causes sequential coupling to take place in the system because DP$_{1.1}$ influences FR$_{1.1}$, FR$_{1.2}$, FR$_{1.3}$, FR$_{1.5}$, and FR1.8. FR$_{1.11}$ is coupled to all DPs because it requires fulfilling all of the FRs. Table 28 shows that DP$_{1.2}$ causes intended coupling in FR$_{1.2}$ and sequential coupling in FR$_{1.3}$, FR$_{1.5}$. FR$_{1.11}$ is coupled to all DPs.

ABET Criterion 3 element	FR	Matrix Symbol X or (none)	DP1.2 System for creating an ability to design and conduct experiments, as well as to analyze and interpret data	Description
(a) an ability to apply knowledge of mathematics, science, and engineering	FR1.1	(none)		
(b) an ability to design and conduct experiments, as well as to analyze and interpret data	FR1.2	X	Intended	DP1.1 Required for FR1.2
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	FR1.3	X	Sequential	Students need DP1.2 for FR1.3
(d) an ability to function on multidisciplinary teams	FR1.4	(none)		
(e) an ability to identify, formulate, and solve engineering problems	FR1.5	X	Sequential	Students need DP1.2 for FR1.5
(f) an understanding of professional and ethical responsibility	FR1.6	(none)		
(g) an ability to communicate effectively	FR1.7	(none)		
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	FR1.8	(none)		
(i) a recognition of the need for, and an ability to engage in life-long learning	FR1.9	(none)		
(j) a knowledge of contemporary issues	FR1.10	(none)		
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	FR1.11	X	FR-FR	Students need DP1.2 for FR1.11

Table 28 - Interactions resulting from DP$_{1.2}$ on FR$_{1.1}$ – FR$_{1.11}$

Table 29 shows that $DP_{1.3}$ causes intended coupling in $FR_{1.3}$ and sequential coupling in $FR_{1.1}$, $FR_{1.5}$. $FR_{1.11}$ is coupled to all DPs.

ABET Criterion 3 element	FR	Matrix Symbol X or (none)	DP1.3 System for creating an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	Description
(a) an ability to apply knowledge of mathematics, science, and engineering	FR1.1	X	Sequential	Students need DP1.3 for FR1.1
(b) an ability to design and conduct experiments, as well as to analyze and interpret data	FR1.2	(none)		
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	FR1.3	X	Intended	DP1.3 Required for FR1.3
(d) an ability to function on multidisciplinary teams	FR1.4	(none)		
(e) an ability to identify, formulate, and solve engineering problems	FR1.5	X	Sequential	DP1.3 Required for FR1.5
(f) an understanding of professional and ethical responsibility	FR1.6	(none)		
(g) an ability to communicate effectively	FR1.7	(none)		
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	FR1.8	(none)		
(i) a recognition of the need for, and an ability to engage in life-long learning	FR1.9	(none)		
(j) a knowledge of contemporary issues	FR1.10	(none)		
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	FR1.11	X	FR-FR	Students need DP1.3 for FR1.11

Table 29 - Interactions resulting from $DP_{1.3}$ on $FR_{1.1} – FR_{1.11}$

Table 30 shows that $DP_{1.4}$ causes intended coupling in $FR_{1.4}$ and sequential coupling in $FR_{1.7}$ and $FR_{1.10}$. $FR_{1.11}$ is coupled to all DPs.

ABET Criterion 3 element	FR	Matrix Symbol X or (none)	DP1.4 System for creating an ability to function on multidisciplinary teams	Description
(a) an ability to apply knowledge of mathematics, science, and engineering	FR1.1	(none)		
(b) an ability to design and conduct experiments, as well as to analyze and interpret data	FR1.2	(none)		
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	FR1.3	(none)		
(d) an ability to function on multidisciplinary teams	FR1.4	X	Intended	DP1.4 Required for FR1.4
(e) an ability to identify, formulate, and solve engineering problems	FR1.5	(none)		
(f) an understanding of professional and ethical responsibility	FR1.6	(none)		
(g) an ability to communicate effectively	FR1.7	X	Sequential	DP1.4 Required for FR1.7
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	FR1.8	(none)		
(i) a recognition of the need for, and an ability to engage in life-long learning	FR1.9	(none)		
(j) a knowledge of contemporary issues	FR1.10	X	Sequential	DP1.4 Required for FR1.10
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	FR1.11	X	FR-FR	Students need DP1.4 for FR1.11

Table 30 - Interactions resulting from $DP_{1.3}$ on $FR_{1.1} – FR_{1.11}$

Table 31 shows that $DP_{1.5}$ causes intended coupling in $FR_{1.5}$ and sequential coupling in $FR_{1.1}$, $FR_{1.2}$ and $FR_{1.3}$. $FR_{1.11}$ is coupled to all DPs.

ABET Criterion 3 element	FR	Matrix Symbol X or (none)	DP1.5 System for creating an ability to identify, formulate, and solve engineering problems	Description
(a) an ability to apply knowledge of mathematics, science, and engineering	FR1.1	X	Sequential	Students need DP1.5 for FR1.1
(b) an ability to design and conduct experiments, as well as to analyze and interpret data	FR1.2	X	Sequential	Students need DP1.5 for FR1.2
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	FR1.3	X	Sequential	Students need DP1.5 for FR1.3
(d) an ability to function on multidisciplinary teams	FR1.4	(none)		
(e) an ability to identify, formulate, and solve engineering problems	FR1.5	X	Intended	DP1.5 Required for FR1.5
(f) an understanding of professional and ethical responsibility	FR1.6	(none)		
(g) an ability to communicate effectively	FR1.7	(none)		
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	FR1.8	(none)		
(i) a recognition of the need for, and an ability to engage in life-long learning	FR1.9	(none)		
(j) a knowledge of contemporary issues	FR1.10	(none)		
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	FR1.11	X	FR-FR	Students need DP1.5 for FR1.11

Table 31 - Interactions resulting from $DP_{1.5}$ on $FR_{1.1} – FR_{1.11}$

Table 32 shows that $DP_{1.6}$ causes intended coupling in $FR_{1.6}$ and sequential coupling in $FR_{1.8}$. $FR_{1.11}$ is coupled to all DPs.

ABET Criterion 3 element	FR	Matrix Symbol X or (none)	DP1.6 System for creating an ability to identify, formulate, and solve engineering problems	Description
(a) an ability to apply knowledge of mathematics, science, and engineering	FR1.1	(none)		
(b) an ability to design and conduct experiments, as well as to analyze and interpret data	FR1.2	(none)		
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	FR1.3	(none)		
(d) an ability to function on multidisciplinary teams	FR1.4	(none)		
(e) an ability to identify, formulate, and solve engineering problems	FR1.5	(none)		
(f) an understanding of professional and ethical responsibility	FR1.6	X	Intended	DP1.6 Required for FR1.6
(g) an ability to communicate effectively	FR1.7	(none)		
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	FR1.8	X	Sequential	Students need DP1.6 for FR1.8
(i) a recognition of the need for, and an ability to engage in life-long learning	FR1.9	(none)		
(j) a knowledge of contemporary issues	FR1.10	(none)		
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	FR1.11	X	FR-FR	Students need DP1.6 for FR1.11

Table 32 - Interactions resulting from $DP_{1.6}$ on $FR_{1.1} – FR_{1.11}$

Table 33 shows that $DP_{1.7}$ causes intended coupling in $FR_{1.7}$ and sequential coupling in $FR_{1.4}$. $FR_{1.11}$ is coupled to all DPs.

ABET Criterion 3 element	FR	Matrix Symbol X or (none)	DP1.7 System for creating an ability to identify, formulate, and solve engineering problems	Description
(a) an ability to apply knowledge of mathematics, science, and engineering	FR1.1	(none)		
(b) an ability to design and conduct experiments, as well as to analyze and interpret data	FR1.2	(none)		
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	FR1.3	(none)		
(d) an ability to function on multidisciplinary teams	FR1.4	X	Sequential	Students need DP1.7 for FR1.4
(e) an ability to identify, formulate, and solve engineering problems	FR1.5	(none)		
(f) an understanding of professional and ethical responsibility	FR1.6	(none)		
(g) an ability to communicate effectively	FR1.7	X	Intended	DP1.7 Required for FR1.7
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	FR1.8	(none)		
(i) a recognition of the need for, and an ability to engage in life-long learning	FR1.9	(none)		
(j) a knowledge of contemporary issues	FR1.10	(none)		
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	FR1.11	X	FR-FR	Students need DP1.7 for FR1.11

Table 33 - Interactions resulting from $DP_{1.7}$ on $FR_{1.1} – FR_{1.11}$

Table 34 shows that $DP_{1.8}$ causes intended coupling in $FR_{1.8}$ and sequential coupling in $FR_{1.6}$. $FR_{1.11}$ is coupled to all DPs.

ABET Criterion 3 element	FR	Matrix Symbol X or (none)	DP1.8 System for creating an ability to identify, formulate, and solve engineering problems	Description
(a) an ability to apply knowledge of mathematics, science, and engineering	FR1.1	(none)		
(b) an ability to design and conduct experiments, as well as to analyze and interpret data	FR1.2	(none)		
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	FR1.3	(none)		
(d) an ability to function on multidisciplinary teams	FR1.4	(none)		
(e) an ability to identify, formulate, and solve engineering problems	FR1.5	(none)		
(f) an understanding of professional and ethical responsibility	FR1.6	X	Sequential	Students need DP1.8 for FR1.6
(g) an ability to communicate effectively	FR1.7	(none)		
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	FR1.8	X	Intended	DP1.8 Required for FR1.8
(i) a recognition of the need for, and an ability to engage in life-long learning	FR1.9	(none)		
(j) a knowledge of contemporary issues	FR1.10	(none)		
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	FR1.11	X	FR-FR	Students need DP1.8 for FR1.11

Table 34 - Interactions resulting from $DP_{1.8}$ on $FR_{1.1} – FR_{1.11}$

Table 35 shows that $DP_{1.9}$ causes intended coupling in $FR_{1.9}$ and sequential coupling in $FR_{1.6}$. $FR_{1.11}$ is coupled to all DPs.

ABET Criterion 3 element	FR	Matrix Symbol X or (none)	DP1.9 System for creating an ability to identify, formulate, and solve engineering problems	Description
(a) an ability to apply knowledge of mathematics, science, and engineering	FR1.1	(none)		
(b) an ability to design and conduct experiments, as well as to analyze and interpret data	FR1.2	(none)		
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	FR1.3	(none)		
(d) an ability to function on multidisciplinary teams	FR1.4	(none)		
(e) an ability to identify, formulate, and solve engineering problems	FR1.5	(none)		
(f) an understanding of professional and ethical responsibility	FR1.6	X	Sequential	Students need DP1.9 for FR1.6
(g) an ability to communicate effectively	FR1.7	(none)		
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	FR1.8	(none)		
(i) a recognition of the need for, and an ability to engage in life-long learning	FR1.9	X	Intended	DP1.9 Required for FR1.9
(j) a knowledge of contemporary issues	FR1.10	(none)		
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	FR1.11	X	FR-FR	Students need DP1.9 for FR1.11

Table 35 - Interactions resulting from $DP_{1.9}$ on $FR_{1.1} – FR_{1.11}$

Table 36 shows that $DP_{1.10}$ causes intended coupling in $FR_{1.10}$ and sequential coupling in $FR_{1.4}$, $FR_{1.6}$ and $FR_{1.7}$. $FR_{1.11}$ is coupled to all DPs.

ABET Criteron 3 element	FR	Matrix Symbol X or (none)	DP1.10 System for creating an ability to identify, formulate, and solve engineering problems	Description
(a) an ability to apply knowledge of mathematics, science, and engineering	FR1.1	(none)		
(b) an ability to design and conduct experiments, as well as to analyze and interpret data	FR1.2	(none)		
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	FR1.3	(none)		
(d) an ability to function on multidisciplinary teams	FR1.4	X	FR-FR	Students need DP1.10 for FR1.4
(e) an ability to identify, formulate, and solve engineering problems	FR1.5	(none)		
(f) an understanding of professional and ethical responsibility	FR1.6	X	FR-FR	Students need DP1.10 for FR1.6
(g) an ability to communicate effectively	FR1.7	X	FR-FR	Students need DP1.10 for FR1.7
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	FR1.8	(none)		
(i) a recognition of the need for, and an ability to engage in life-long learning	FR1.9	(none)		
(j) a knowledge of contemporary issues	FR1.10	X	Intended	DP1.10 Required for FR1.10
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	FR1.11	X	FR-FR	Students need DP1.10 for FR1.11

Table 36 - Interactions resulting from $DP_{1.10}$ on $FR_{1.1} – FR_{1.11}$

Table 37 shows that DP$_{1.10}$ causes intended coupling in FR$_{1.10}$. and FR$_{1.11}$ is coupled to all DPs because all of the FRs are necessary to practice as a professional engineer.

ABET Criteron 3 element	FR	Matrix Symbol X or (none)	DP1.11 System for creating an ability to identify, formulate, and solve engineering problems	Description
(a) an ability to apply knowledge of mathematics, science, and engineering	FR1.1	X	FR-FR	DP1.11 Required for FR1.1
(b) an ability to design and conduct experiments, as well as to analyze and interpret data	FR1.2	X	FR-FR	DP1.11 Required for FR1.2
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	FR1.3	X	FR-FR	DP1.11 Required for FR1.3
(d) an ability to function on multidisciplinary teams	FR1.4	X	FR-FR	DP1.11 Required for FR1.4
(e) an ability to identify, formulate, and solve engineering problems	FR1.5	X	FR-FR	DP1.11 Required for FR1.5
(f) an understanding of professional and ethical responsibility	FR1.6	X	FR-FR	DP1.11 Required for FR1.6
(g) an ability to communicate effectively	FR1.7	X	FR-FR	DP1.11 Required for FR1.7
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	FR1.8	X	FR-FR	DP1.11 Required for FR1.8
(i) a recognition of the need for, and an ability to engage in life-long learning	FR1.9	X	FR-FR	DP1.11 Required for FR1.9
(j) a knowledge of contemporary issues	FR1.10	X	FR-FR	DP1.11 Required for FR1.10
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	FR1.11	X	Intended	DP1.11 Required for FR1.11

Table 37 - Interactions resulting from DP$_{1.11}$ on FR$_{1.1}$ – FR$_{1.11}$

4.6.2.3 Satisfying the FRs by rearranging the DPs to achieve a diagonal or triangular matrix

Axiomatic design is a mapping process that establishes relationships between the FRs and the DPs. The FRs are independent allowing them to be described as vectors. The DPs are also vectors. The design process is used to choose the right set of DPs to satisfy the given FRs. A design matrix showing the relationship between each of the FRs and DPs is shown in Figure 23. The left-hand side of the equation represents what is desired to be achieved through the FRs and the right-hand side shows how they are planned to be achieved.

A design can be reconfigured to form a diagonal or triangular matrix in the lower left corner to determine the order of adjustment of the DPs to satisfy the FRS. Figure 23 shows that the DPs affecting more than one FR in the current design indicates overlapping stuff prevents the system being independently controllable in its present form. A second iteration of the design of engineering education as a manufacturing system is shown later in the chapter.

$$\left\{\begin{matrix} FR_{1} \\ FR_{1.1} \\ FR_{1.2} \\ FR_{1.3} \\ FR_{1.4} \\ FR_{1.5} \\ FR_{1.6} \\ FR_{1.7} \\ FR_{1.8} \\ FR_{1.9} \\ FR_{1.10} \\ FR_{1.11} \\ FR_{2} \\ FR_{2.1} \\ FR_{2.2} \\ FR_{2.3} \\ FR_{2.4} \\ FR_{2.5} \\ FR_{2.6} \\ FR_{2.7} \\ FR_{2.8} \\ FR_{2.9} \end{matrix}\right\} = \begin{bmatrix}
X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & X & X & X & 0 & X & 0 & 0 & X & 0 & 0 & X & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & X & X & 0 & X & 0 & 0 & 0 & 0 & 0 & X & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & X & 0 & X & 0 & X & 0 & 0 & 0 & 0 & 0 & X & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & X & 0 & 0 & X & 0 & 0 & X & X & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & X & X & X & 0 & X & 0 & 0 & 0 & 0 & 0 & X & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & X & 0 & X & 0 & 0 & X & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & X & 0 & 0 & X & 0 & 0 & X & X & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & X & 0 & 0 & X & 0 & X & X & 0 & X & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & X & 0 & X & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & X & 0 & X & X & 0 & 0 & X & X & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & X & X & X & X & X & X & X & X & X & X & X & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X
\end{bmatrix} \left\{\begin{matrix} DP_{1} \\ DP_{1.1} \\ DP_{1.2} \\ DP_{1.3} \\ DP_{1.4} \\ DP_{1.5} \\ DP_{1.6} \\ DP_{1.7} \\ DP_{1.8} \\ DP_{1.9} \\ DP_{1.10} \\ DP_{1.11} \\ DP_{2} \\ DP_{2.1} \\ DP_{2.2} \\ DP_{2.3} \\ DP_{2.4} \\ DP_{2.5} \\ DP_{2.6} \\ DP_{2.7} \\ DP_{2.8} \\ DP_{2.9} \end{matrix}\right\}$$

Figure 23 - Design equation for engineering education system (sans Axiom One)

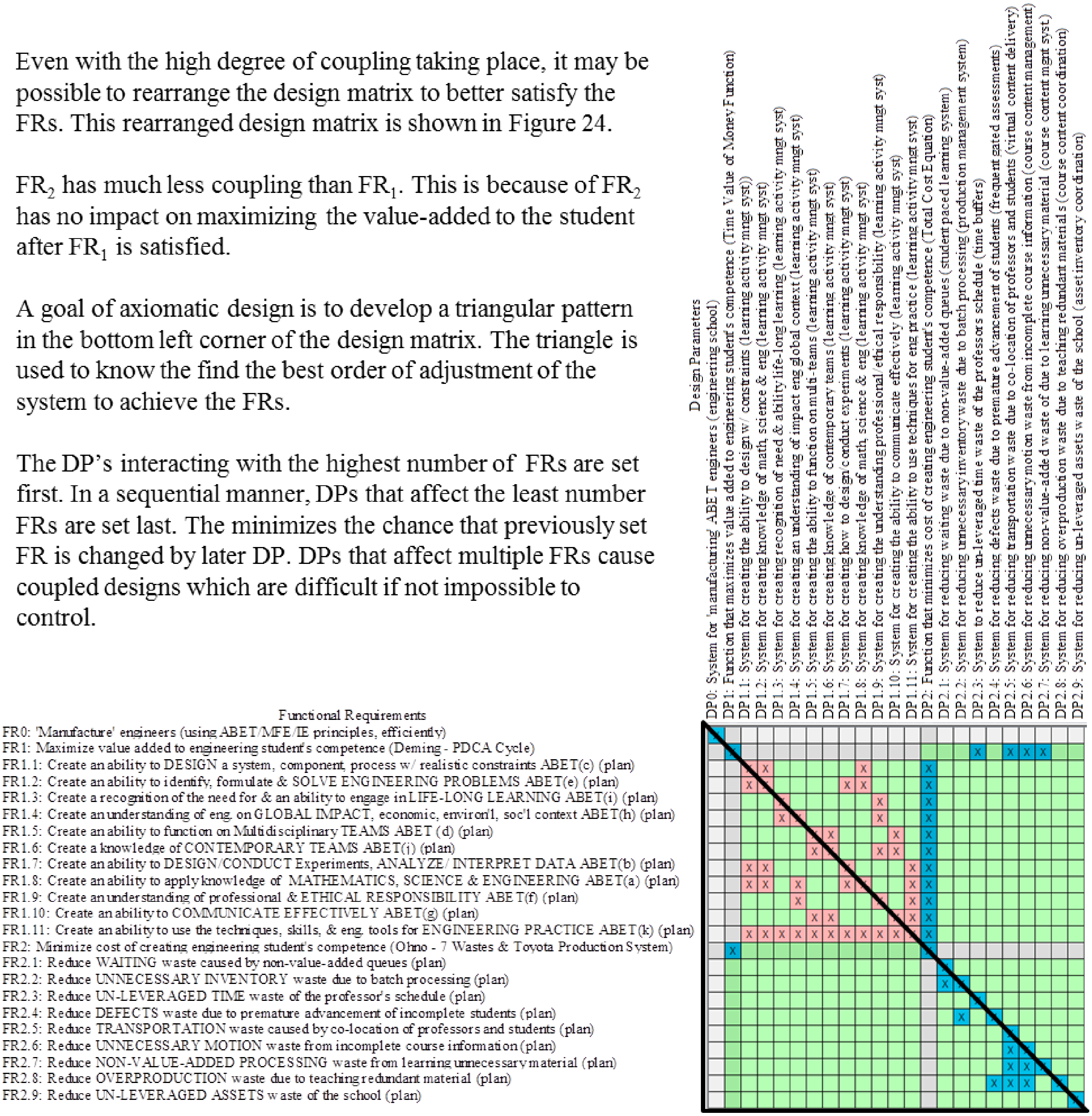
4.6.2.4 Interactions between the second level FR_1 & FR_2 and the corresponding DPs

Even with the high degree of coupling taking place, it may be possible to rearrange the design matrix to better satisfy the FRs. This rearranged design matrix is shown in Figure 24.

FR_2 has much less coupling than FR_1. This is because of FR_2 has no impact on maximizing the value-added to the student after FR_1 is satisfied.

A goal of axiomatic design is to develop a triangular pattern in the bottom left corner of the design matrix. The triangle is used to know the find the best order of adjustment of the system to achieve the FRs.

The DP's interacting with the highest number of FRs are set first. In a sequential manner, DPs that affect the least number FRs are set last. The minimizes the chance that previously set FR is changed by later DP. DPs that affect multiple FRs cause coupled designs which are difficult if not impossible to control.



Design Parameters

Functional Requirements

	DP0: System for 'manufacturing' ABET engineers (engineering school)	DP1: Function that maximizes value added to engineering student's competence (Time Value of Money Function)	DP1.1: System for creating the ability to design w/ constraints (learning activity mngt syst))	DP1.2: System for creating knowledge of math, science & eng (learning activity mngt syst)	DP1.3: System for creating recognition of need & ability life-long learning (learning activity mngt syst)	DP1.4: System for creating an understanding of impact eng global context (learning activity mngt syst)	DP1.5: System for creating the ability to function on multi-teams (learning activity mngt syst)	DP1.6: System for creating knowledge of contemporary teams (learning activity mngt syst)	DP1.7: System for creating how to design/conduct experiments (learning activity mngt syst)	DP1.8: System for creating knowledge of math, science & eng (learning activity mngt syst)	DP1.9: System for creating the understanding professional/ethical responsibility (learning activity mngt syst)	DP1.10: System for creating the ability to communicate effectively (learning activity mngt syst)	DP1.11: System for creating the ability to use techniques for eng practice (learning activity mngt syst)	DP2: Function that minimizes cost of creating engineering student's competence (Total Cost Equation)	DP2.1: System for reducing waiting waste due to non-value-added queues (student paced learning system)	DP2.2: System for reducing unnecessary inventory waste due to batch processing (production management system)	DP2.3: System to reduce un-leveraged time waste of the professors schedule (time buffers)	DP2.4: System for reducing defects waste due to premature advancement of students (frequent gated assessments)	DP2.5: System for reducing transportation waste due to co-location of professors and students (virtual content delivery)	DP2.6: System for reducing unnecessary motion waste from incomplete course information (course content management)	DP2.7: System for reducing non-value-added waste of due to learning unnecessary material (course content mgnt syst)	DP2.8: System for reducing overproduction waste due to teaching redundant materials (course content coordination)	DP2.9: System for reducing un-leveraged assets waste of the school (asset inventory coordination)
FR0: 'Manufacture' engineers (using ABET/MFE/IE principles, efficiently)	X																						
FR1: Maximize value added to engineering student's competence (Deming - PDCA Cycle)		X															X		X	X	X		
FR1.1: Create an ability to DESIGN a system, component, process w/ realistic constraints ABET(c) (plan)			X	X						X				X									
FR1.2: Create an ability to identify, formulate & SOLVE ENGINEERING PROBLEMS ABET(e) (plan)			X	X					X	X				X									
FR1.3: Create a recognition of the need for & an ability to engage in LIFE-LONG LEARNING ABET(i) (plan)					X						X			X									
FR1.4: Create an understanding of eng. on GLOBAL IMPACT, economic, environ'l, soc'l context ABET(h) (plan)					X	X					X			X									
FR1.5: Create an ability to function on Multidisciplinary TEAMS ABET (d) (plan)							X	X				X		X									
FR1.6: Create a knowledge of CONTEMPORARY TEAMS ABET(j) (plan)							X	X			X	X		X									
FR1.7: Create an ability to DESIGN/CONDUCT Experiments, ANALYZE/ INTERPRET DATA ABET(b) (plan)			X	X					X				X	X									
FR1.8: Create an ability to apply knowledge of MATHEMATICS, SCIENCE & ENGINEERING ABET(a) (plan)			X	X		X			X	X			X	X									
FR1.9: Create an understanding of professional & ETHICAL RESPONSIBILITY ABET(f) (plan)						X					X		X	X									
FR1.10: Create an ability to COMMUNICATE EFFECTIVELY ABET(g) (plan)							X	X				X	X	X									
FR1.11: Create an ability to use the techniques, skills, & eng. tools for ENGINEERING PRACTICE ABET(k) (plan)			X	X	X	X	X	X	X	X	X	X	X	X									
FR2: Minimize cost of creating engineering student's competence (Ohno - 7 Wastes & Toyota Production System)		X												X									
FR2.1: Reduce WAITING waste caused by non-value-added queues (plan)															X								
FR2.2: Reduce UNNECESSARY INVENTORY waste due to batch processing (plan)															X	X							
FR2.3: Reduce UN-LEVERAGED TIME waste of the professor's schedule (plan)																	X						
FR2.4: Reduce DEFECTS waste due to premature advancement of incomplete students (plan)																X		X					
FR2.5: Reduce TRANSPORTATION waste caused by co-location of professors and students (plan)																			X				
FR2.6: Reduce UNNECESSARY MOTION waste from incomplete course information (plan)																			X	X			
FR2.7: Reduce NON-VALUE-ADDED PROCESSING waste from learning unnecessary material (plan)																			X	X	X		
FR2.8: Reduce OVERPRODUCTION waste due to teaching redundant material (plan)																		X	X	X		X	
FR2.9: Reduce UN-LEVERAGED ASSETS waste of the school (plan)																							X

Figure 24 – FR-DP interactions for the second level of the design after rearranging the matrix

4.6.3 Analysis of the Independence Axiom for the top level FRs

The result of the axiomatic design process yielded a design matrix that shows the interactions between the DPs and the FRs. The axioms require that independence of the FRs be maintained and that information is minimized. Compliance with the Independence Axiom is observed by one DP fulfilling one FR (Suh 1990). This is an ideal condition. The design matrix for the education system exhibits coupling at the highest level and throughout the third level of the design that was shown in Figure 24.

4.6.4 Calculation of information content in the design

Table 38 shows each FR and potential values of the metrics that might be needed to know if the FR has been achieved. In the case of each FR, a system range has been estimated from the financial statements of a school, calculations of the effects of the time value of money, and other quantities.

FR	**Description**	**FR Measurement**	**System Range**	**Design Range**	**Success = Common Range / System Range**	**I = Log2 (system/ common)**
FR0	"Manufacture" engineers efficiently	$\% = \frac{\text{Income from Tuition \& Fees}}{\text{Instruction \& Research Expense}}$	0% to 275%	0% to 300%	91.7%	0.13
FR1	Maximize value added to engineering student's competence	$VA_{Eng\ Ed} = NPV(i) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$	$80K to 375K/student	$200K to 400K/student	59.3%	0.75
FR1-1	(a) an ability to apply knowledge of mathematics, science, and engineering	Assurance of Learning Results	0% to 100%	95% to 100%	5.0%	4.32
FR1-2	(b) an ability to design and conduct experiments, as well as to analyze and interpret data	Assurance of Learning Results	0% to 100%	90% to 100%	10.0%	3.32
FR1-3	(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	Assurance of Learning Results	0% to 100%	90% to 100%	10.0%	3.32
FR1-4	(d) an ability to function on multidisciplinary teams	Assurance of Learning Results	0% to 100%	90% to 100%	10.0%	3.32
FR1-5	(e) an ability to identify, formulate, and solve engineering problems	Assurance of Learning Results	0% to 100%	90% to 100%	10.0%	3.32
FR1-6	(f) an understanding of professional and ethical responsibility	Assurance of Learning Results	0% to 100%	90% to 100%	10.0%	3.32
FR1-7	(g) an ability to communicate effectively	Assurance of Learning Results	0% to 100%	90% to 100%	10.0%	3.32
FR1-8	(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	Assurance of Learning Results	0% to 100%	90% to 100%	10.0%	3.32
FR1-9	(i) a recognition of the need for, and an ability to engage in life-long learning	Assurance of Learning Results	0% to 100%	90% to 100%	10.0%	3.32
FR1-10	(j) a knowledge of contemporary issues	Assurance of Learning Results	0% to 100%	90% to 100%	10.0%	3.32
FR1-11	(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	Assurance of Learning Results	0% to 100%	90% to 100%	10.0%	3.32
FR2	Minimize cost of creating engineer's competence	$-\sum \text{Instruction} + \text{Research Cost}$	$0K to 15K/student	$0K to 9K/student	60.0%	0.74
FR2-1	reduce unnecessary inventory waste due to batch processing	$\text{Average Flow Time} = \frac{\text{Average Inventory}}{\text{Throughput Rate}} (\text{Little's Law; } I = R \times T)$	0-25 students/week	0-200 students/week	12.5%	3.00
FR2-2	reduce waiting waste caused by non-value-added queues	$\text{Time Ratio} = \sum VA \frac{\sum VA}{\sum VA + nonVA}$	48%	5%	10.4%	3.26
FR2-3	reduce defects waste due to premature advancement of incomplete students	$\% = \frac{\text{Number of Students First Time Pass}}{\text{Total Number of Students Assessed}}$	10%	1%	10.0%	3.32
FR2-4	reduce transportation waste caused by colocation of professor and students	$\% = \frac{\text{Number of Students Attending Virtually}}{\text{Total Number of Students Attending}}$	80%	50%	62.5%	0.68
FR2-5	reduce overproduction waste caused by teaching redundant material	$\% - \frac{\text{Number of redundant concepts}}{\text{Total Number of concepts to be learned}}$	1%	0.1%	10.0%	3.32
FR2-6	reduce non-value-added processing waste from learning unnecessary materiel	$\% - \frac{\text{Number of unnecesary concepts}}{\text{Total Number of concepts to be learned}}$	1%	0.1%	10.0%	3.32
FR2-7	reduce unnecessary motion caused for incomplete course information	$\% = \frac{\text{Amount of Incomplete Course Data}}{\text{Total Amount of Course Data}}$	1%	0.1%	10.0%	3.32
FR2-8	reduce un-leveraged time waste of the professors schedule	$\% = \frac{\text{Amount of Value-added Professor Time}}{\text{Total Amount of Professor Time Allocated}}$	30%	5%	16.7%	2.58
FR2-9	reduce un-leveraged assets waste of the school	$\% = \frac{\text{Amount of Asset (capcity) used}}{\text{Total Amount of Asset (capacity) Available}}$	30%	5%	16.7%	2.58
					Total Information Content	64.56

Table 38 - Theoretical values used to find the system information content

The table is used to compare these values with alternative values for a system operating at a school or to compare values from one school to another.

4.6.5 Calculation of the probability of success

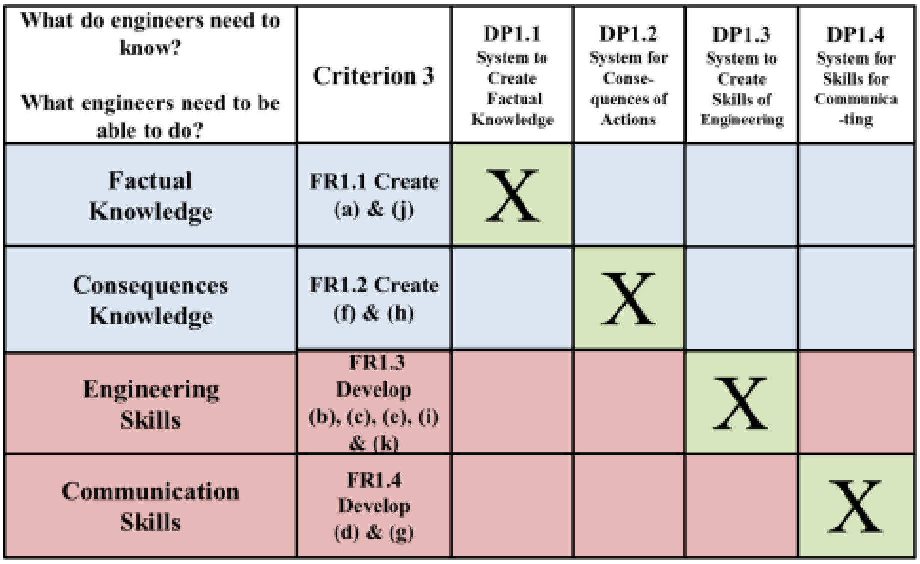
Information content is a measure of the probability of success of achieving the FRs. All of the FRs need to be considered in the total information content found by summing the individual ‘I’s that correspond to the set of FRs (Suh 1990). The probability of success is based on the congruence or overlapping of the design range, as designated by the designer and the system range of the manufacturing system intended to achieve the FRs. This describes the capability of the manufacturing system to achieve the FRs within given tolerances. The common range is the overlap between the design range and the system range. The common range determines the capability of the manufacturing system to achieve the FRs. This capability can be monitored over time and as the design and system ranges change, the probability of successfully fulfilling the FRs will increase or decrease.

4.6.6 Results of the second iteration of the design decomposition

The second iteration of the design uses as a decomposition theme the idea that engineers need to first know certain things and then be able to do certain things. An examination shows that all of the student outcomes (a) – (k) can be divided into four FRs. These new FRs are shown in Figure 25.

- Knowledgeable about the physical world
- Knowledgeable about the consequences of taking action
- Skillful in applying knowledge about the physical world
- Skillful in communicating, broadly defined

A design decomposition is able to be created by substituting these four new FRs for the original student outcomes (a) – (k) in the design hierarchy.



What do engineers need to know? What engineers need to be able to do?	Criterion 3	DP1.1 System to Create Factual Knowledge	DP1.2 System for Consequences of Actions	DP1.3 System to Create Skills of Engineering	DP1.4 System for Skills for Communicating
Factual Knowledge	FR1.1 Create (a) & (j)	X			
Consequences Knowledge	FR1.2 Create (f) & (h)		X		
Engineering Skills	FR1.3 Develop (b), (c), (e), (i) & (k)			X	
Communication Skills	FR1.4 Develop (d) & (g)				X

Figure 25 - Second iteration FRs reduced into knowledge and skill domains

Axiomatic design requires that the parent FR is equal to the sum of the children such that $FR_{1.1} + FR_{1.2} + FR_{1.3.} + FR_{1.4} = FR_1$ and FR_2 is equal to the sum of $FR_{2.1}$ through $FR_{2.9}$.

Figure 26 shows that the combining of FRs yield a design that is independently adjustable and controllable.

No coupling exists between the DPs and FRs in the second iteration of the design, with the exception of DP_2.

DP_2, which seeks to minimize cost conflicts with FR_1 which seeks to maximize value-added. The FR of maximizing value-added needs to be satisfied prior to the FR of minimizing cost. If this were not the case then closing the school would be the easiest way to accomplish FR_2.

This design matrix can be the basis for further development of manufacturing system design for the engineering education system.

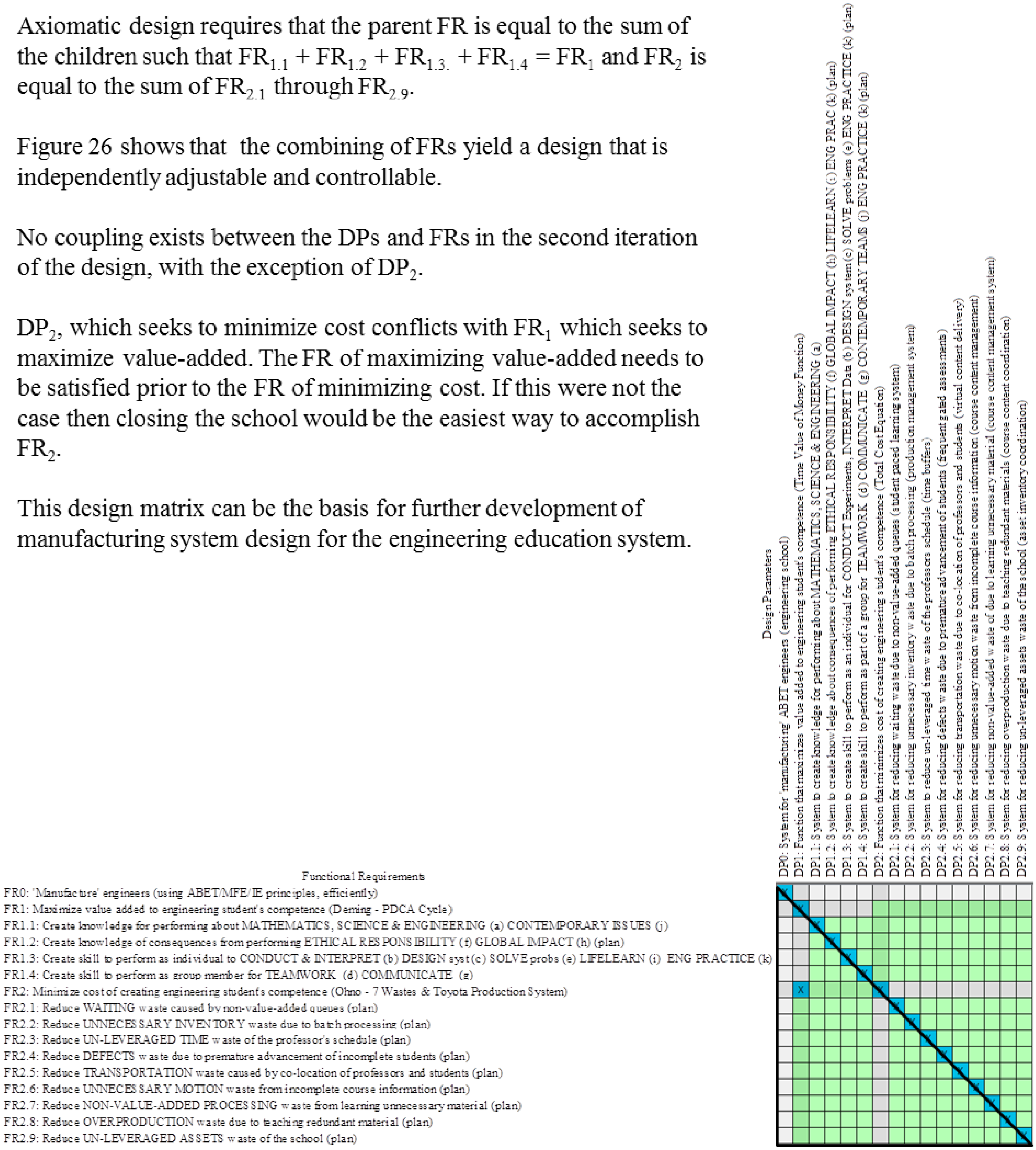


Figure 26 - FR and DP interactions for the second design iteration

4.7 Discussion

The need to examine the efficiency of engineering education was argued. A search of the literature found information about how to do manufacturing system design using Axiomatic Design. Nothing was found about designing engineering education as a manufacturing system.

A detailed design of an engineering education system was presented. The hierarchy of the design had as its top functional requirement the goal of producing engineers efficiently and the system's ability to progress towards this goal can be measured directly from values on the school's financial statements. The design is transparent allowing for the designer's intent to be known and subsequent revisions to any component of the design can be performed.

The initial design decomposition used the manufacturing principles of maximizing value-added and minimizing production cost as the decomposition theme. The first iteration of the design decomposed the theme of maximizing value-added using Criterion 3. The initial design violates Axiom One; maintain the independence of the functional requirements. The wastes in manufacturing were used to decompose the functional requirement of minimizing waste. The design also included a continuous improvement cycle.

Axiom Two; minimize the information content, showed that metrics can be developed for each for the FRs in the design. These suggested metrics can be further refined for specific school needs. The FRs for waste elimination have metrics that can be found for specific school needs such as throughput, classroom or technology use.

The probability of successfully fulfilling the FRs was also described. A comparison of the desired output of the design, i.e. the design range, with what the system is capable of producing, i.e. the system range was shown. As the system range overlaps the design range with increasing frequency, the amount of information required to operate the system is reduced thereby increasing the probability of successfully fulfilling the design's functional requirements.

The results of the first iteration showed DPs that influence multiple FRs. A description of how each DP influences the FRs was given. The resulting design matrix was found to be coupled and was not able to be rearranged to form a triangular matrix that allows the design to be adjusted without affecting previously set FRs.

A second iteration of the design decomposition was generated. It used what engineers need to know and what they need to be able to do in the workplace as additional decomposition themes. The second design decomposition yielded a design matrix that did not have any coupling and is therefore adjustable and controllable.

In order to create new FRs for the education system design, each Criterion 3 outcome was listed separately and when it was necessary to perform the outcome was listed. Some outcomes are required before attempting an engineering task. Other outcomes imply anticipatory knowledge is necessary to predict the results or outcomes of a task.

In this way engineers' knowledge is categorized as to what is known up to and including the present time and how that knowledge might be used in the future if acted upon. For example, an action resulting in the pollution of a water supply or if an action would cause a building to collapse should be known in advance. The second kind of knowledge is anticipatory in nature and may not happen depending upon a particular course of action. The first type of knowledge does not change whether acted upon or not, like celestial mechanics. The present time is a dividing line between the two types of knowledge.

With regard to skills-based actions being taken by an engineer, an engineer can function well without being able to communicate if there is a mechanism in place to act as an intermediary for the technical output of the engineers results. Engineers who are able to communicate well, but lack the ability to perform engineering processes like solving a problem or designing a system will not be effective in the engineering profession. The dividing line between these two major skill sets of solving and designing oriented skills must be present at least at the same time that before the communication skills are used in the field. Improper use of engineering design and experimentation skills cannot be compensated with communication skills. But the reverse could be true.

Criterion 3 distills down to these four elements that an engineer is expected to have as outcomes. What does an engineer need to know before starting work and what the outcome will likely be after the work is completed? Engineers can solve complex problems and be effective in the field even without good communication skills, but the latter will not make up for the lack of the former. Criterion 3 does not have any outcomes that do not fall along these lines for categorizing what outcome should be expected after graduating from engineering school.

A one-piece-flow model an appropriate production model because each part in the system is able to proceed at its own pace without regard to the status of the other parts in the system is coupling of the major processes is only reasonable way to eliminate the non-value-added time.

Other methods could be used like the ASTP model use during WWII. In this model strict adherence to a production schedule and expected outcomes was able to be enforced with little regard to each student's learning style or pace. Modern universities are not able to dictate pacing to their degree or be able to micromanage the student like during wartime. It is up to the individual student to put the effort into eliminating the non-value-added time in their education if they are given the opportunity to do. Without a one-piece-flow system, it is unlikely that increasing the rate of production will result in more students learning at a faster rate because it is imposed on them and not a desired choice.

Other metrics used to determine the fulfillment of the FRs could be developed.

4.8. Conclusions

The premise for this chapter is that improvements can be made to the engineering education process based on manufacturing principles and using Suh's axiomatic design method. A design hierarchy was decomposed based on the manufacturing engineering principles of maximizing the value added and minimizing the cost of production. The academic portion of engineering education is driven by ABET Criterion 3 and, Deming's Plan-Do-Check-Act continuous improvement methodology. Waste analysis was examined from the seven wastes in manufacturing processes perspective. Clearly, the new design has met these goals.

There are four major findings generated from the axiomatic design decomposition used to design engineering education as a manufacturing system:

First, the most important finding is that through the examination of waste in the production process it was found that an engineering education system creates queues in production that unnecessarily extend the students time in school. These queues can be remedied by using a mass customization one-piece-flow production system. In order for a one-piece-flow system to work, especially if the number of students in courses is expected to grow, a way of leveraging the professor's time by means of technology or teaching assistants is required.

Second, decomposing ABET Criterion 3 student outcomes (a) - (k) in a hierarchical design structure revealed that the eleven outcomes have at their root four simple requirements that engineers need to meet in order to be effective in the field:

1. Knowledge about the physical world
2. Knowledge about the consequences of actions
3. Skill in applying knowledge
4. Skill in communicating

Additionally, it was found that Criterion 3, when used as the FRs of an engineering education system, exhibits high level coupling that makes it difficult to fulfill each FR independently.

Third, all of the production system FRs can have metrics to know how the system is performing over time. The metrics can become universally accepted to compare all schools because they are easily calculated. The quantities needed are found on the financial statements of a school, from tuition and earning data and developed in the classroom.

Finally, the probability of successful operation of a system can be predicted if the design ranges of the functional requirements have a high degree of congruence with the system ranges used to satisfy them.

Chapter 5 - Simulation of Engineering Education as a Manufacturing Process

5.1. Introduction

The premise of this chapter is that industrial engineering process modeling software can generate data from a one-piece-flow model of an engineering school course that allows multiple times the current number of students to pass through a course without adding to the professor's work.

The objective of this chapter is to show the results from the computer simulation of a one-piece-flow model of an engineering school course.

The rationale is that computer simulation of manufacturing processes and value stream maps add the dimension of time (Donatellli and Harris 2001). Computer simulations provide for reconfiguring and simulating manufacturing processes quickly and inexpensively. Simulations help to illustrate how a process operates.

5.1.1 State-of-the-Art

The method of value stream mapping when used in conjunction with process simulation software allows a process designer the ability to experiment with new systems (Lian and Van Landeghem 2007) (McDonald et al. 2012). Simulation, in conjunction with value stream mapping, is a powerful analysis method that can be used to quantify the benefits of lean manufacturing (Gurumurthy and Kodali 2011) (Detty and Yingling 2000).

Computer simulation of production systems yield good estimates of the improvements possible in time-based performance statistics from implementing lean (Detty and Yingling 2000). The resulting performance measures allow management to make financial, strategic and competitive decisions for process redesign and implementation of lean process improvement (Detty and Yingling 2000).

The literature contains many examples of process simulation of manufacturing and service production systems such as industrial logistics (Blanco Rivero 2004) and apparel assembly cells (Black and Schroer 1993). Examples of health care emergency departments are found as well (Butcher et al. 2010). Simulating large and complex manufacturing environment has been a challenge to overcome facilitated by process simulation (Xu et al. 2000).

A search of the academic literature, as well as broader search engines, produced little usable material for simulating learning or academic course environments using industrial process automation software.
An example of simulating a web based course architecture using a low level modeling language was found (Rokou et al. 2004).

The Arena^{TM} simulation web site contains papers for manufacturing, packaging and supply chain solutions (Rockwell Automation 2012). The web site also contains solutions for defense, security and other process reengineering activities. The simulation model that is most similar to education might be that of a call center or help desk. This is because students enter a queue in order to get their questions answered similar to a call center or help desk. Call centers and help desks have hierarchical levels of support depending on the type of information needed by the user.

Models of education systems could have been developed by consultants and school administrators and students, but these results do not appear in the literature. A general model of students progressing through a course using industrial engineering process modeling software is not evident.

5.1.2 Approach

Simulating the engineering education process in the Arena^{TM} simulation software requires modeling how the course ‘processes’ students flowing through an academic course. The model begins with a predefined number of students in the course. After each student passes through a course activity, the simulation software uses a triangular probability distribution with a low-likely-high estimate of which students will progress to the next activity in the course. A predetermined percentage of students are diverted into a queue and held there until they have been supported by the professor in the order that they entered the queue.

The queues in the course have a low-likely-high triangular probability distribution for self-help, professor supported help and for graded coursework. Limits are placed on the amount of time that a professor has available for the process.

5.2 Methods

5.2.1 Design of the simulation model

To fulfill the objective of simulating a one-piece-flow model of engineering education as manufacturing system the first step is to define the sequence of activities in the process. A simple model illustrating that students might not experience delays in queues if they are able to avoid process steps that add non-vlaue-added time to the course is shown in Figure 27.

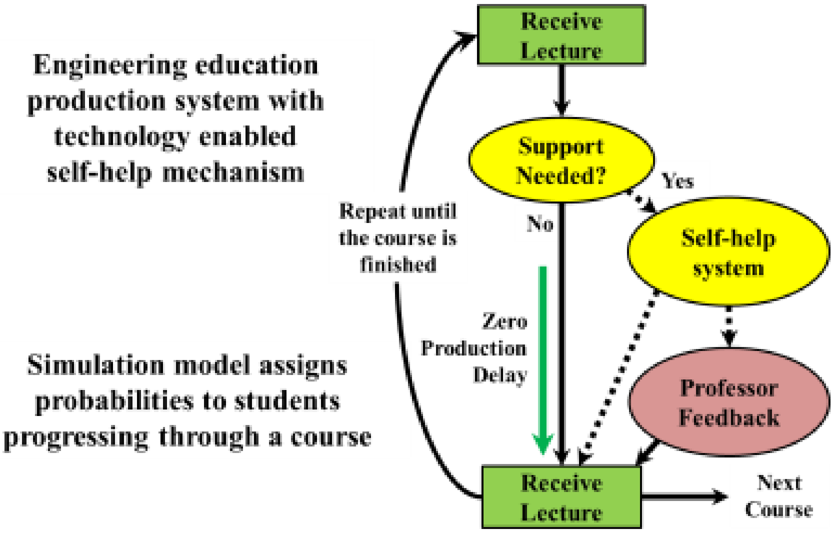


Figure 27 - Base Model of the One-piece-flow Production System

The process that is modeled is a course that meets twice per week for a total of fourteen class meetings. The course lectures are two hours long and meet on two different days. At the end of each week, either a homework assignment is due, or an exam is completed. The process steps for the students and the professor are shown in Figure 28.

The mechanics of the course include recorded lecture materials that are available on-demand by the students. Students receive answers to questions by first consulting a self-help mechanism that has a question and answer database or wiki and could also be supported by an intelligent tutor system (ITS) (Kehrer et al. 2013).

The course support database has written or video feedback that has been captured from the current and previous courses (Kelly et al. 2013). The information is cross referenced and maintained by teaching assistants (TAs). The processing of homework over the internet can include an artificial intelligence feedback mechanism (Kelly, et al. 2013). A human tutor might not be better than a computer based tutor (Rosé and Torrey 2005).

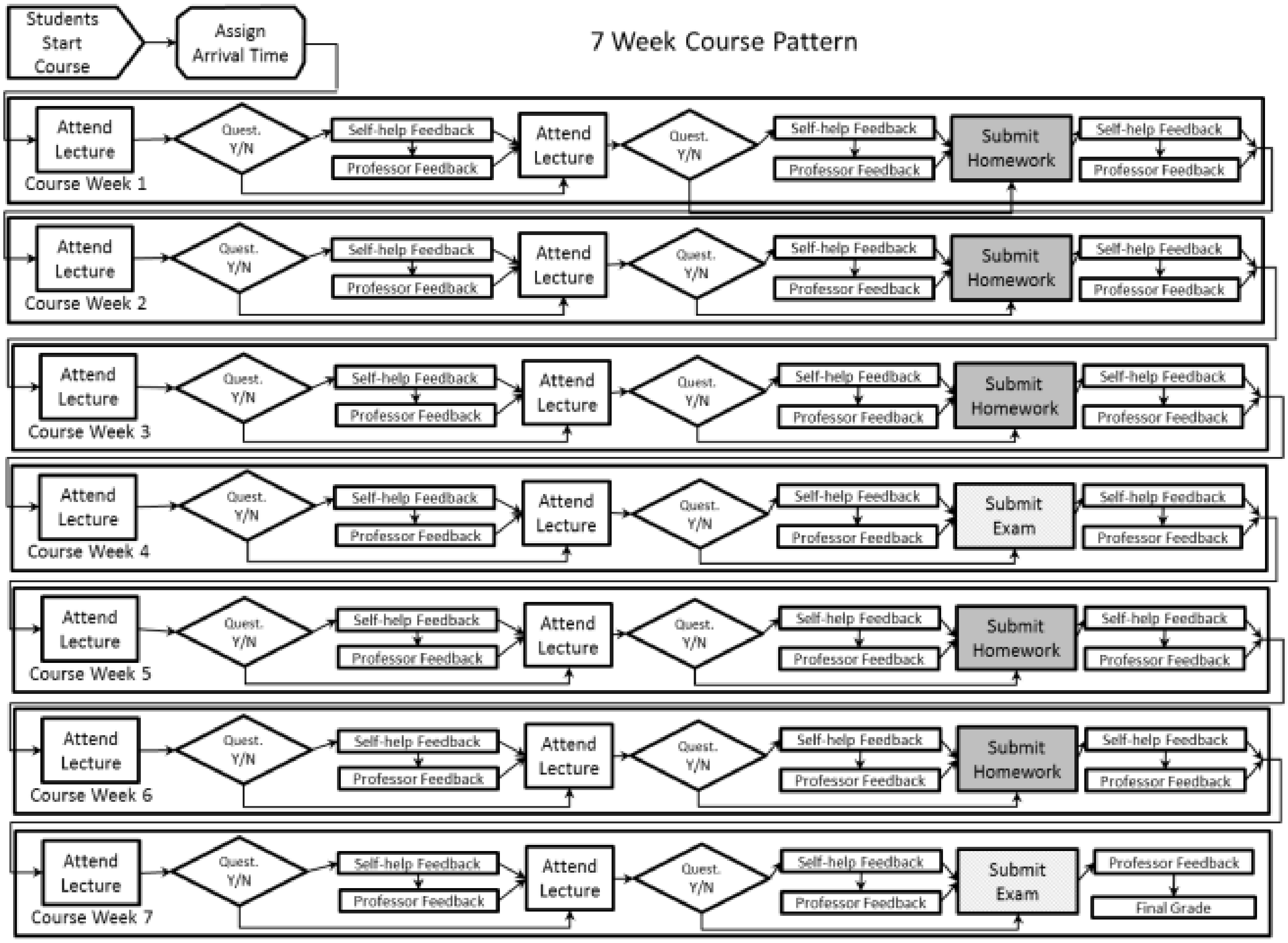


Figure 28 - Sequence of activities for a fourteen session seven week course

5.2.2 Process simulation in Arena^{TM}

The following graphics show the processing sequence of students in the new system using Arena^{TM}. A description of every activity and the subsequent output is contained in Appendix F.

The first step is to set the number of students. As an example, Worcester Polytechnic Institute (WPI) courses average 15-25 students per course (www.wpi.edu 2013). For the purpose of the simulation, a large group of 1500 students was chosen to illustrate the effect of leveraging the professor's time using the one-piece-flow model shown in Figure 30.

The model of students taking a course in a one-piece-flow system is also similar to a waiting line at a bank. Customers arrive randomly and require different service times. Similar to the bank waiting line, students arrive at each activity in the course in a stochastic manner. The amount of time that the students consume as they are completing the activity is also stochastic with upper and lower limits placed on the time it takes to complete each activity.

The available time of the professor is a limited resource which is fixed and deterministic in nature. The self-help mechanism for student support has random service times, but as a resource it is unlimited because it is primarily technology driven and maintained by teaching assistants, and is available on demand.

A flowchart model showing the percentage of students who are diverted away from the main path progressing through the course without requiring any support from the professor is shown in Figure 30. A probability distribution of how long each student participates in the support activity is also shown.

In the absence of real data, the teaching experience of the author is used to determine the upper and lower bounds on this support time, as well as a most likely time required to support the student. The Arena^{TM} software used to model the system uses a random number generator to draw samples and apply them to the entities in the simulation model. The arrival time, position in sequence and the duration of every activity the student performs is recorded by the software. The total time the professor is providing to the system is also tracked. Arena^{TM} reports when all of the professor's resource time is consumed, the system stops processing students and the simulation ends.

The goal of the simulation is to model a typical seven week undergraduate class at WPI. Each course has two lectures with the opportunity, if needed, for a student to get two levels of support after each lecture session. The students submit a deliverable at the end of each week for a total of five graded homework assignments and two graded exams that also have two levels of support. While the simulation appears to focus on the student's activity, the real focus is on the professor's time as it is the limiting factor in the simulation. Previously recorded lectures could be made available to the students who are progressing faster than the normal course schedule. There might also be limitations on when the professor is available to respond to students which will cause non-value-added time to accumulate in the system.

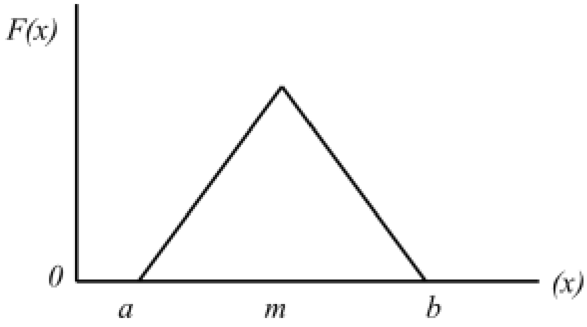


Figure 29 - Triangular probability distribution

Figure 29 shows the triangular probability distribution used in the simulation because the actual distribution is not known. Estimates can be made for minimum (*a*), maximum (*b*) and most-likely values (*m*) for a process time (Kelton et al. 2010).

The simulation model allows students who do not require support to complete each course activity sequentially without interruption. A main goal of the design of engineering education as a manufacturing system is to model a one-piece-flow system. Minimizing the students non-value-added time in between lecture sessions and deliverable submissions allows the student to progress at their own pace through the course.

The student’s total time in the system is not a major concern. What is a concern is that they do not have to wait in a non-value-added queue for the next course activity to start. The professor on the other hand has limited time to prepare and teach the lecture material and respond to student requests for support and grade the deliverables. Once the professor’s time has been consumed, the system stops processing students and data can be collected to understand the state of the system. Students can finish the course at times independent from each other. Based on the assumptions made, a large percentage of the students could complete the course while others are still in the first few weeks.

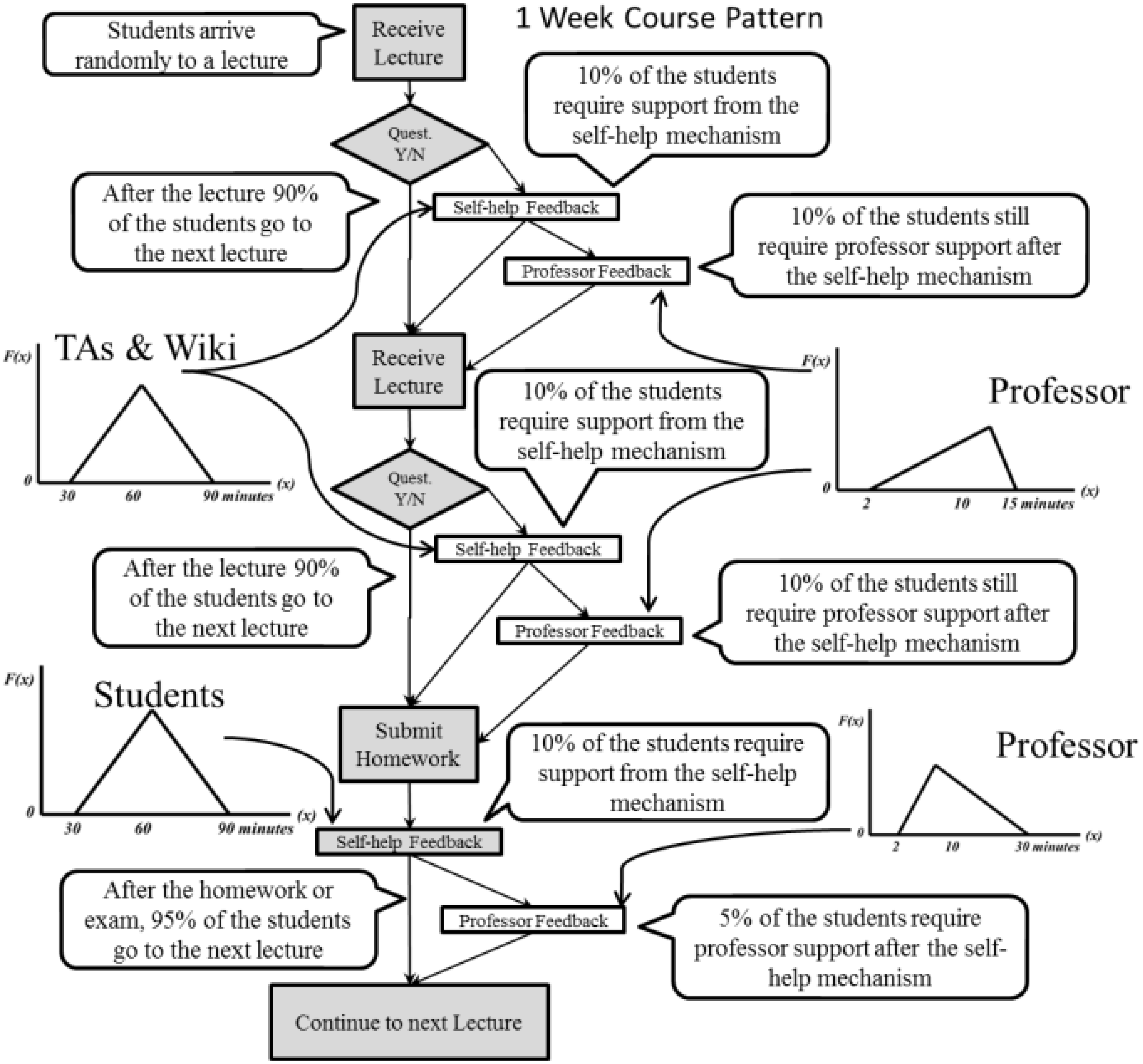


Figure 30 - Pattern of lecture, questioning, self-help, professor feedback

The basic pattern of students receiving a lecture, asking questions after internalizing the material, accessing the self-help mechanism and subsequently accessing the professor, if necessary, is shown in Figure 30. This pattern repeats fourteen times during the course's seven week period.

The flowchart in Figure 30 shows the path that the students take through one week of a seven week course. The proportion of students that are diverted to the self-help mechanism and the professor help mechanism is set at 10% for each of these activities. The probability distribution and its shape corresponding estimates of the length of time for each activity is shown on the flowchart as well. Waiting in a queue to access the professor for help is considered a non-value-added activity. The Arena^{TM} software records the time for each of the 1500 individual students in the system as they progress to the course. Summary statistics are calculated by the model software for analysis.

5.3 Results

Figure 31 shows student activity distributed throughout the course.

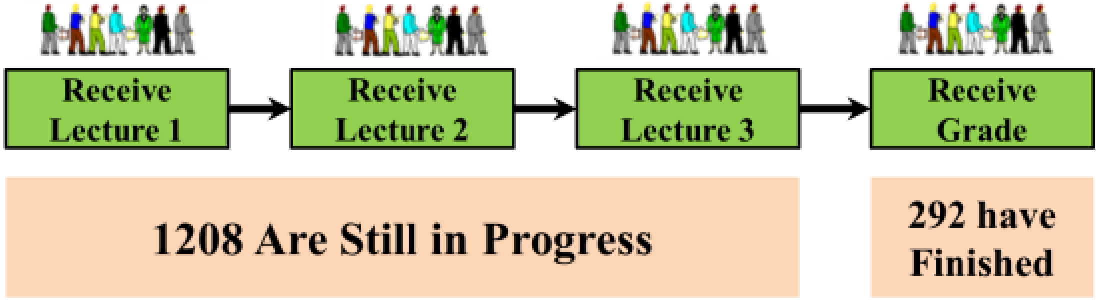


Figure 31 - Arena^{TM} model showing the students progressing through the course independently

The summary data shown in Table 39 indicates that a professor is preparing two hours for each lecture session and teaching two hours in each lecture session for a total of eight lecture related hours per week.

	Number in course	Total Hours Avail (49 days)	Total Lecture Prep Hours (14 X 2 hrs.)	Total Lecture Hours (14 X 2 hrs.)	Total Question Feedback Support Time	Total Homework Exam Feedback Support Time	Average Hours per week
Students (avg. values)	1500	1176	n/a	28	8.4	1.2	n/a
Professor (total values)	1	1176	28	28	25.5	82.4	23.4
Professor (avg. values)	1	168	4	4	3.6	11.8	23.4

Table 39 - Summary statistics for one-piece-flow course system

The time the professor spends in responding to the inquiries of 1500 students is about twelve hours for a total of twenty-four hours per week. For 750 students, this figure would be reduced to about six hours total time per week.

5.4 Discussion

The simulation showing 1500 students completing a seven week course with little additional time required by the professor provides impetus to work out the details of the self-support mechanism. The assumptions made that the professor will need to spend more time working with the students than the model allows is a valid concern. Unless the actual system is put into practice, the limits can only be theorized. The key finding for the simulation is that a compelling argument can be made that a one-piece-flow model reduces the non-value-added time for the student. Professors need a technology-based support system to gain leverage on their time or the system will not be feasible. The simulation allows any combination of professor time, percentage of students needing support, and the number of support activities available.

Computer simulation of industrial processes has limitations. For example, they are limited by the data set used to run the simulation which might not accurately reflect the real process. Data from an actual course would be desirable to compare with the computer model for accuracy. The model also does not address group work or projects that have a different learning pattern. Projects and courses that follow a different work structure than the one modeled might need their own simulation to run in parallel with the course simulation described. Development of the TAs and the system itself should be considered as well as the pattern of how and when professors respond to student requests for support.

5.5 Conclusions

The premise that a computer simulation model of a one-piece-flow production system for a course would provide meaningful data has been examined. The model shown is parametric which allows for any combination of lecture sessions, professor work time and other variables. Real data from an actual course can be inputted into the model for verification and refinement. The two key findings are:

1) Schools can keep operational costs down with an investment in TAs and the technology to minimize any duplication of effort in supporting student learning activities.

2) The support efforts that are delivered in person by the professor can be made scalable by the school.

Chapter 6 - Financial Analysis of the New Engineering Education Process

6.1 Introduction

One premise of this chapter is that it is possible to estimate the strategic financial results a university might receive using analysis similar to that used for a one-piece-flow production system. Another premise is that this analysis can be accomplished by using existing, accountant-prepared financial statements.

A third premise is that in order to meet these projected, strategic results for the production organization, i.e. the university, the process operators, i.e. the professors must have tactical managerial accounting methods which lean accounting can provide to know how the process is running. Strategic projections are too far removed from the tactical work of the professors, who deliver the educational product to the students, to be meaningful.

The first objective of this chapter is to show the potential impact on a school's financial results from increased tuition revenue received and reduced operating cost per student due to lean process improvement by using a one-piece-flow production system for the students.

The second objective is to show how lean accounting methods can be used to support process improvement whereas financial accounting methods cannot.

The first objective is important because a school that makes changes to its course management processes needs to know how the change will impact the strategic financial results. These changes might result from increased tuition revenue, decreased operating cost per student, or both. The reporting of pro-forma financial results at the highest level of an organization is useful for strategic planning.

The second objective is important because the high level financial reports described in the first objective do not support decision making for the day to day activities of the system participants, particularly the professors and department heads. An institution's financial statements prepared by CPAs have little relevance to the professor's day to day activities. What is required is a managerial accounting system that gives timely feedback on a set of user driven metrics designed for daily use. These kinds of metrics are used to support the tactical decisions in lean manufacturing processes. Lean accounting methods are necessary for successful process improvement in a production system, such as that targeted in the second objective.

6.1.1 State-of-the-Art

One use of traditional accounting procedures leading to professionally prepared financial results is for top level management to make strategic decisions. Financial accounting standards have been long established by the Financial Accounting Standards Board (FASB 2013). They are used to show the relationship of assets to liabilities, taxes and other amounts that have been modified through depreciation adjustments (Greer 1943). The information in the financial statements is important, not just to the day to day operations decisions of professors (Ansari and Euske 1995).

In contrast, the managerial accounting procedures that are used to support manufacturing are not as well defined as financial accounting standards. Lean accounting methods are situation specific and have process focused terms such as patients per hour, heats of metal per shift or students completing assessments today. Managerial accounting methods are developed in the environments that they support and are used by the people closest to the process. There is more than one generally accepted managerial accounting system in use today, some the more well-known systems are shown in Table 39.

Table 40 shows that some managerial accounting systems incorporate overhead calculations depending upon the methods underlying assumptions. In the engineering education system, overhead calculations and full absorption accounting obscure the information necessary for process improvement. The Lean Accounting Box Score Card is designed to show throughput and capacity metrics without burdening the user with large financial adjustments that have no bearing on how the process is performing.

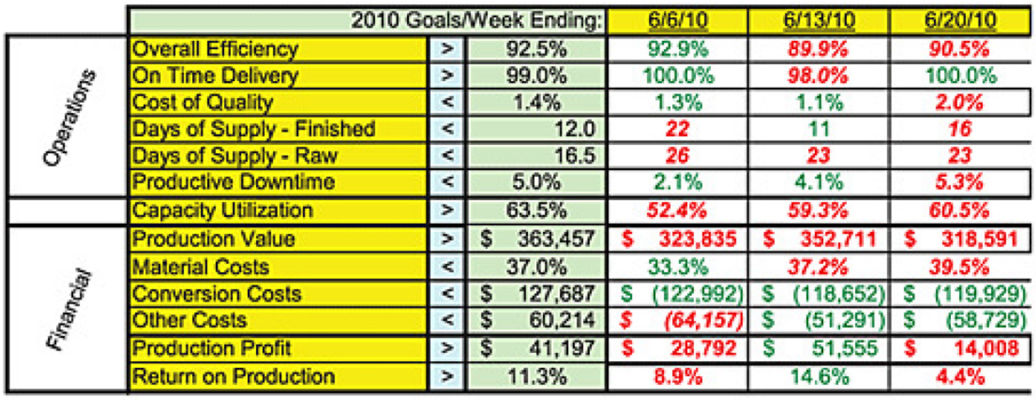
Managerial Accounting System (Lean)	Description
Activity based costing (ABC) (Moore 1998)	Attempts to attach each expense with the appropriate revenue flow, but also uses allocation of overhead
Resource Consumption Accounting (RCA) (Grasso 2006)	From a marginal costing system for manufacturing
Value Stream Costing (Sobczyk and Koch 2008) (Van Goubergen and Van Dijk 2011)	Derived from Goldratt's theory of constraints (TOC)
Lean Accounting Box Score Card (Kennedy and Huntzinger 2005) (van der Merwe and Thomson 2007) (Maskell et al. 2012)	Shows actual costs and not standard costs. Helps to detect bottlenecks. Operations, capacity and financial metrics for value stream accounting relationships

Table 40 - Managerial accounting systems

Lean accounting is designed to support daily, even hourly decisions in a production system (Maskell et al. 2012). Lean accounting can to be adapted to the engineering education system and utilizes a Box Score Card. The Box Score Card informs the production system operators how their decisions are affecting the production system results without waiting for accountants to prepare them. The information provided is timely and relevant to the people on the production floor. The Box Score Card can be adapted to manage and improve the course throughput and results.

Examples of manufacturing companies using lean accounting to support process improvement can be found at Jacobs, Inc. (DeLuzio 1993), Wiremold Inc. (Fiume 2004) and in Dahaner Inc.'s Danaher Business System (www.danaher.com 2013). Each of these companies achieved positive results by using production metrics close to the process and without financial accounting's full absorption methods being applied.

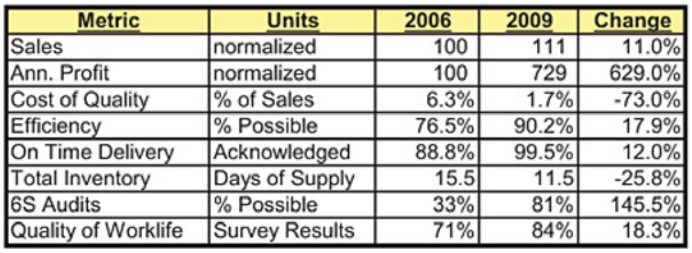
Figure 32 and Figure 33 show an actual Box Score Card and the resulting process improvement metrics from a manufacturing company, Currier Plastics, Inc.



	2010 Goals/Week Ending:			6/6/10	6/13/10	6/20/10
Operations	Overall Efficiency	>	92.5%	92.9%	89.9%	90.5%
	On Time Delivery	>	99.0%	100.0%	98.0%	100.0%
	Cost of Quality	<	1.4%	1.3%	1.1%	2.0%
	Days of Supply - Finished	<	12.0	22	11	16
	Days of Supply - Raw	<	16.5	26	23	23
	Productive Downtime	<	5.0%	2.1%	4.1%	5.3%
	Capacity Utilization	>	63.5%	52.4%	59.3%	60.5%
Financial	Production Value	>	$ 363,457	$ 323,835	$ 352,711	$ 318,591
	Material Costs	<	37.0%	33.3%	37.2%	39.5%
	Conversion Costs	<	$ 127,687	$ (122,992)	$ (118,652)	$ (119,929)
	Other Costs	<	$ 60,214	$ (64,157)	$ (51,291)	$ (58,729)
	Production Profit	>	$ 41,197	$ 28,792	$ 51,555	$ 14,008
	Return on Production	>	11.3%	8.9%	14.6%	4.4%

Figure 32 - Lean Box Score Card example from Currier Plastics, Inc.

The specific details in the calculations were not included with the source, but the direct costs and simple measures of days of supply and capacity utilization are shown. The Box Scores allow for a non-accountant to understand how the system is performing in real time.



Metric	Units	2006	2009	Change
Sales	normalized	100	111	11.0%
Ann. Profit	normalized	100	729	629.0%
Cost of Quality	% of Sales	6.3%	1.7%	-73.0%
Efficiency	% Possible	76.5%	90.2%	17.9%
On Time Delivery	Acknowledged	88.8%	99.5%	12.0%
Total Inventory	Days of Supply	15.5	11.5	-25.8%
6S Audits	% Possible	33%	81%	145.5%
Quality of Worklife	Survey Results	71%	84%	18.3%

Figure 33 - Currier Plastics, Inc. actual improvement from the use of a Box Score Card

The purpose of a Box Score Card is to simplify and publicize how an operation is performing so the operators can easily understand how they are affecting a production system. An example of making the production metrics available to the process operators is shown in Figure 34 below.

Figure 34 - Currier Plastics, Inc. employees discuss efficiency trends using an area board

A key finding is that accountant-prepared financial statements, while necessary to manage an organization, are backward looking (Watson 2011). Accountant prepared financial statements not only become available

much later than the time period they report on, but they do not offer any information about what is happening in the period they are received.
As a consequence, process operators should have accounting tools that are quick to prepare and do not require special training to understand. Lean accounting methods avoid the complexity of full absorption accounting and can be used for immediate feedback on the course process improvement activities for professors.

6.1.2 Approach

The objective of showing the potential operating results from the new system is accomplished using traditional accounting and engineering economy methods. Similar to what was noted above about aggregate financial statements, historical trend ratios are developed from the Worcester Polytechnic Institute (WPI) fiscal year ending (FYE) 2007 through 2012 financial statements that are publically available on the school's web site (www.wpi.edu 2013). The current tuition revenue and instruction expense line items from the financial statements are divided by current enrollment numbers to find the average tuition revenue per student as well as the average instruction cost per student.

The projected tuition revenue and expense figures are calculated by inflating the corresponding 2012 line items using assumptions about the potential number of students entering the system. Assumptions about the initial startup and ongoing costs for instruction expense are included. Trend data is shown comparing the ratio of tuition to cost coverage for both the existing and new system. To facilitate the understanding of the impact of the assumptions a sensitivity analysis is performed. The sensitivity analysis shows a present worth calculation for a ten year time horizon related through a discount rate equivalent to the tuition increase for the WPI 2012-2013 school year of 3.4% (Berkey 2012).

Aggregated financial data, as described in objective one, is too far removed from the day to day operation of a course to be of any use to the professor. The second objective of using a lean accounting system with key performance metrics is shown. In contrast to what is found in the literature, the current work illustrates that examples of key performance measures for a course that could be developed in concert with the professor from an operations throughput and quality stand point. The metrics appear on a Lean Box Score Card for the day to day support of improving the course management system.

6.2 Methods

Meeting the first objective of improving the schools overall financial performance can be accomplished in one of two ways. The first is for the school to receive more tuition per student either through tuition increases or increasing the number of enrolled students or both. The second way is to lower the cost of instruction on a per student basis. An ideal case to generate discretionary cash would be to have both a tuition increase and an instruction cost decrease simultaneously, but this option might be constrained.

Reducing the instruction cost per student necessitates leveraging the professor's time. This can be accomplished through the use of teaching assistants (TAs), but there are practical limits to this approach. If a large number of students are taking a course, then the number of TAs, who are surrogate professors, will also need to be large in order to properly support the course, presenting training and overhead challenges.

In order to leverage and scale up what can be accomplished with their time, professors can easily record their lectures as this technology is ubiquitous in universities today. The professor, or the TAs, can build a database where essentially any question that was ever asked in the course and its corresponding responses are retained. This database can be in a written or video form or a combination of both. The idea is to capture the response when it happens to avoid duplicating the effort again later. This information can be cross referenced in a database built to support student learning. Course support systems of this type have been fully developed for corporate training and can easily be adapted to the university environment (Retrieve Technology Inc. 2013).

If the students are not able to get their questions answered, a combination of the next steps will further add leverage to the professor’s time. The students may poll the other course participants though the course site, then seek the help of a teaching assistant and then, ultimately, when the interrogatory has not been satisfied, they will then have access to the professor. This method of course support has been simulated in industrial engineering process modeling software, demonstrating for specific assumptions, that one professor can support 1500 students without much additional time or effort on the part of the professor being required.

A computer science professor at WPI experimented with a Box Score Card and course management system. It was created as a spreadsheet that was populated and maintained by the course teaching assistants (Fisler 2012). An example of this course management system is shown in Figure 35.

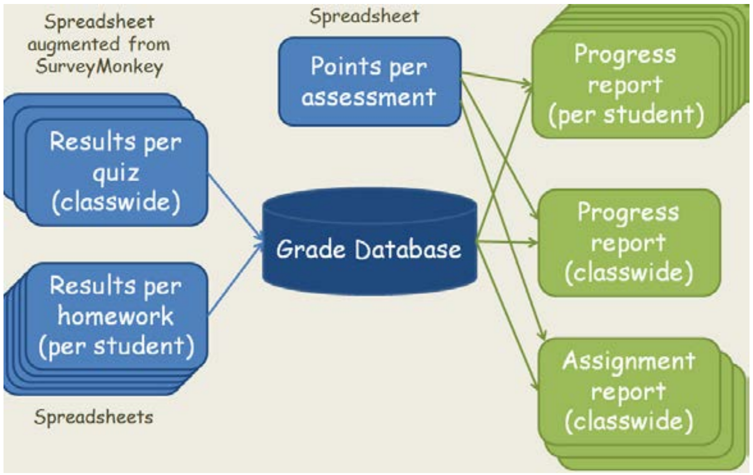
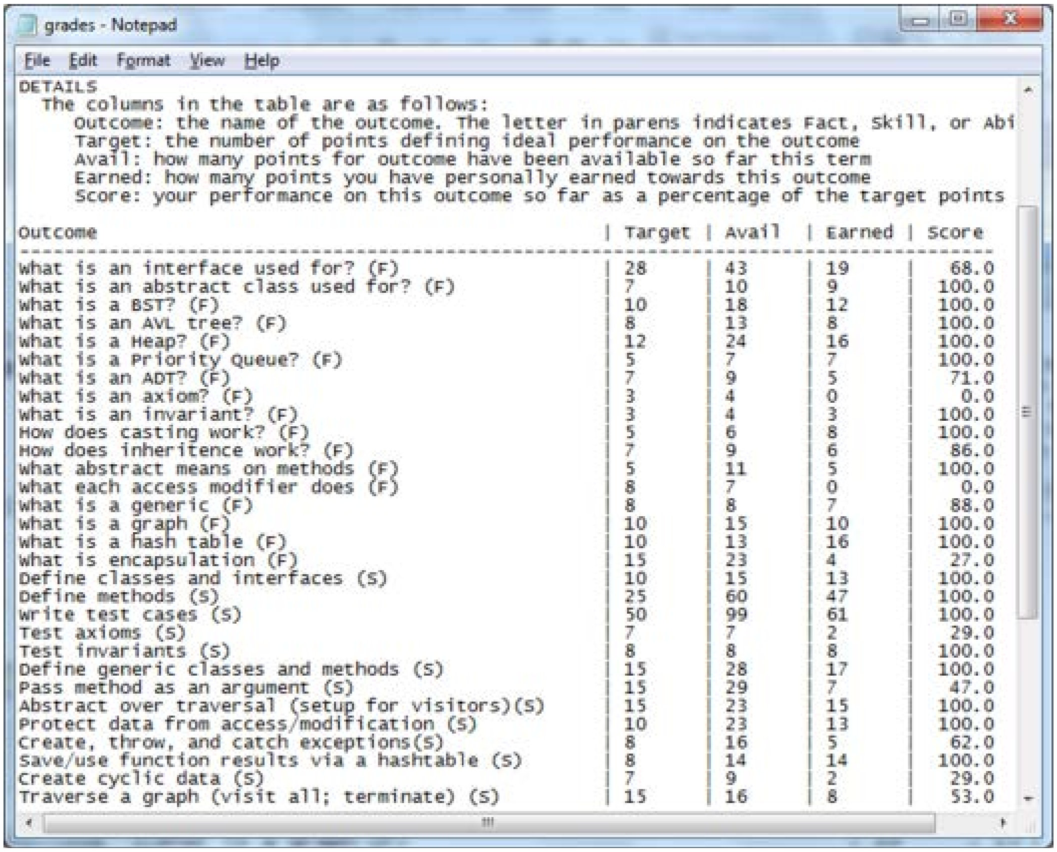


Figure 35 - Course management system on a per student basis

A running total is kept showing how each student is able to demonstrate mastery of each course concept. Individuals and summary metrics for a point in the course are shown in Figure 36.

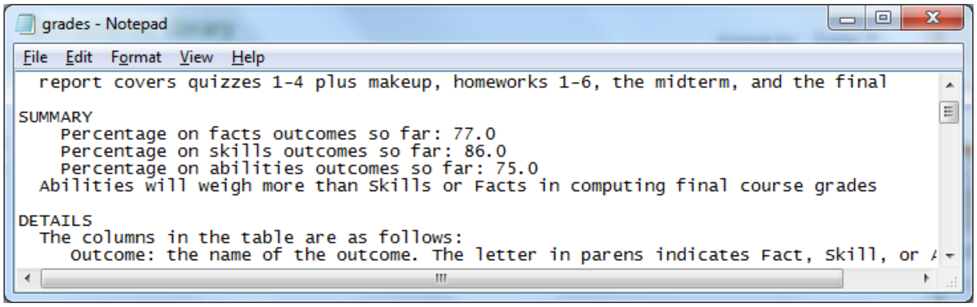


```
DETAILS
  The columns in the table are as follows:
     Outcome: the name of the outcome. The letter in parens indicates Fact, Skill, or Abi
     Target: the number of points defining ideal performance on the outcome
     Avail: how many points for outcome have been available so far this term
     Earned: how many points you have personally earned towards this outcome
     Score: your performance on this outcome so far as a percentage of the target points

Outcome                                              | Target | Avail  | Earned | Score
----------------------------------------------------------------------------------------
What is an interface used for? (F)                   | 28     | 43     | 19     |   68.0
What is an abstract class used for? (F)              | 7      | 10     | 9      |  100.0
What is a BST? (F)                                   | 10     | 18     | 12     |  100.0
What is an AVL tree? (F)                             | 8      | 13     | 8      |  100.0
What is a Heap? (F)                                  | 12     | 24     | 16     |  100.0
What is a Priority Queue? (F)                        | 5      | 7      | 7      |  100.0
What is an ADT? (F)                                  | 7      | 9      | 5      |   71.0
What is an axiom? (F)                                | 3      | 4      | 0      |    0.0
What is an invariant? (F)                            | 3      | 4      | 3      |  100.0
How does casting work? (F)                           | 5      | 6      | 8      |  100.0
How does inheritence work? (F)                       | 7      | 9      | 6      |   86.0
What abstract means on methods (F)                   | 5      | 11     | 5      |  100.0
What each access modifier does (F)                   | 8      | 7      | 0      |    0.0
What is a generic (F)                                | 8      | 8      | 7      |   88.0
What is a graph (F)                                  | 10     | 15     | 10     |  100.0
What is a hash table (F)                             | 10     | 13     | 16     |  100.0
What is encapsulation (F)                            | 15     | 23     | 4      |   27.0
Define classes and interfaces (S)                    | 10     | 15     | 13     |  100.0
Define methods (S)                                   | 25     | 60     | 47     |  100.0
Write test cases (S)                                 | 50     | 99     | 61     |  100.0
Test axioms (S)                                      | 7      | 7      | 2      |   29.0
Test invariants (S)                                  | 8      | 8      | 8      |  100.0
Define generic classes and methods (S)               | 15     | 28     | 17     |  100.0
Pass method as an argument (S)                       | 15     | 29     | 7      |   47.0
Abstract over traversal (setup for visitors)(S)      | 15     | 23     | 15     |  100.0
Protect data from access/modification (S)            | 10     | 23     | 13     |  100.0
Create, throw, and catch exceptions(S)               | 8      | 16     | 5      |   62.0
Save/use function results via a hashtable (S)        | 8      | 14     | 14     |  100.0
Create cyclic data (S)                               | 7      | 9      | 2      |   29.0
Traverse a graph (visit all; terminate) (S)          | 15     | 16     | 8      |   53.0
```

Figure 36 - Data for each student by course concept

Running totals of calculated student metrics are shown in Figure 37. Absent from this example are course throughput measures that might have been calculated. Another consideration that is unknown about this particular course is whether the students were allowed to finish the course early as would be the case in a one-piece-flow system. This metric does not appear to be designed into the current Box Score Care example but could have been.



```
  report covers quizzes 1-4 plus makeup, homeworks 1-6, the midterm, and the final

SUMMARY
    Percentage on facts outcomes so far: 77.0
    Percentage on skills outcomes so far: 86.0
    Percentage on abilities outcomes so far: 75.0
  Abilities will weigh more than Skills or Facts in computing final course grades

DETAILS
  The columns in the table are as follows:
     Outcome: the name of the outcome. The letter in parens indicates Fact, Skill, or
```

Figure 37 - Running totals of student metrics

Meeting the second objective of using a Box Score Card to support lean process improvement can be accomplished by course management software that provides real-time production results. Some course management software systems such as Blackboard Analytics®, (currently a provider to WPI), are partially or fully capable of doing this now. Feature enhancements or add-ons requested by a school would allow for customization to produce desired process metrics (www.blackboard.com 2013).

Other examples of potential Box Score Card metrics, as well as financial projections showing the potential increased tuition revenue from process improvement resulting from the new engineering education system are presented later.

6.3 Results

Addressing objective one, financial projections display the improved financial performance using data from the WPI website. To get a sense of what might be accomplished by improving the engineering education system, only a few operational and financial data are necessary. These data include revenue and cost figures such as how many students are in the system in addition to some derived growth rates based on historical data from the public financial statements. Summary data from the WPI website shows that the number of students in the system is 4900 where 4000 are undergraduates and 900 are graduate students (www.wpi.edu 2013). The undergraduate and graduate students will be treated in the same manner for any calculations for the following reasons. 1) it is not possible to tell the percentage of undergraduate versus graduate tuition from the school’s financial statements, and 2) students often take classes together, making differentiation difficult.

The WPI financial statements included in Appendix G contain the following information:

- The total tuition and fee revenue for FYE 2012 is $176 million, which has been increasing at 3% per year from 2007 to 2012.
- The cost of instruction for FYE 2012 was $67 million and has been increasing at 10% per year from 2007 to 2012.

The fact that costs are rising faster than revenue indicates the margin coverage is decreasing slowly over time. The graph in Figure 39 illustrates this trend.

The average class size is assumed to be twenty-five students, which is at the high end of a range from the school website data. By dividing FYE 2012’s tuition revenue and the instruction cost figures by the current student population a per student average can be found for revenue and expense. These averages can then be inflated by an assumed percentage increase for the purposes of showing how the new system financial results benefit the school. The information required to perform these calculations was gathered from the WPI website and is summarized in Table 41 (www.wpi.edu 2013).

WPI Data for FYE 2012		Annual Average Increase from 2007-2012	Averages Per Student	
Operating Revenues				
Tuition & fees	$176,528,000	3%	$36,026	Income
Operating Expenses				
Instruction & department research	$67,526,000	10%	$13,781	Cost/year of direct labor
Number of students	4900			Manufacturing cost has no cost of material
Average class size (15-25)	25			

Table 41 - Select WPI financial results

The publically available data regarding WPI's financial condition is aggregated at a high level, so only summary measures can be developed from the published financial statements.

The industrial engineering simulation shown in Chapter 5 showed that 1500 students could progress through a course based upon the above described process management system with specific assumptions about its effectiveness. The financial projections are assumed to include a modest 5% increase in new students each year. This amounts to 245 new students paying tuition starting in 2013, which is far from the 1500 students shown in the one-piece-flow simulation from the previous chapter. The new engineering education course management system will require support to perform training of the professors and their TAs.

An additional expense of 2% above and beyond the existing instruction & research cost shown on the financial statements for computer hardware and software upgrades is estimated for each year. In the initial year only, $1 million is allocated for major computer and software upgrades. The grand total of the first year expenses is found by adding the normally projected base amount of $74 million in instruction cost, plus the 2% additional annual operating expense of $1.48 million as well as the additional $1 million upgrade cost for the first year infrastructure improvement, resulting in a combined total of $76.7 million.

The $1.48 million amount consists of ten new employees used for the training of the professors and TAs salaried at $100,000 each, and $480,000 in annual computer and software expense. Since most of the infrastructure exists at WPI already, the one-piece-flow trainers, groomed at WPI, are the bulk of the ongoing expense.

The financial projection in Figure 38 shows an additional 5% of students per year are admitted beginning in 2013, and the cost of operating the one-piece-flow system is estimated at 2% per year as described above. Mentioned previously, the 2% additional expense is used for the teaching assistants and computer support systems necessary to leverage the professor's time to accommodate more students and develop courses for the new system.

The following spread sheet includes the potential result of adding only 5% more students to the enrollment by leveraging time productivity methods for the benefit of the professors.

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Base Tuition (increases at 3%)	$ 176,528,000	$ 181,823,840	$ 187,278,555	$ 192,896,912	$ 198,683,819	$ 204,644,334	$ 210,783,664	$ 217,107,174	$ 223,620,389	$ 230,329,001	$ 237,238,871	$ 244,356,037
Instruct & Rsrch (increases at 10%)	67,526,000	74,278,600	81,706,460	89,877,106	98,864,817	108,751,298	119,626,428	131,589,071	144,747,978	159,222,776	175,145,053	192,659,559
	$ 109,002,000	$ 107,545,240	$ 105,572,095	$ 103,019,806	$ 99,819,003	$ 95,893,036	$ 91,157,236	$ 85,518,103	$ 78,872,411	$ 71,106,225	$ 62,093,817	$ 51,696,478
Per Student Revenue	$ 36,026	$ 37,107	$ 38,220	$ 39,367	$ 40,548	$ 41,764	$ 43,017	$ 44,308	$ 45,637	$ 47,006	$ 48,416	$ 49,869
Per Student Costs	$ 13,781	$ 15,159	$ 16,675	$ 18,342	$ 20,176	$ 22,194	$ 24,414	$ 26,855	$ 29,540	$ 32,494	$ 35,744	$ 39,318
Current Margin Coverage for 4900 students + 0% growth	2.61	2.45	2.29	2.15	2.01	1.88	1.76	1.65	1.54	1.45	1.35	1.27
2012 Enrollment Level of 4000 ugrad + 900 grad	4,900	4,900	4,900	4,900	4,900	4,900	4,900	4,900	4,900	4,900	4,901	4,902
If 5% More Students Admitted		5,145	5,402	5,672	5,956	6,254	6,566	6,895	7,240	7,602	7,982	8,381
Base Tuition (increases at 3%)		$ 190,915,032	$ 206,474,607	$ 223,302,288	$ 241,501,424	$ 261,183,790	$ 282,470,269	$ 305,491,596	$ 330,389,161	$ 357,315,878	$ 386,437,122	$ 417,931,747
Instruct & Rsrch (incr 10%)		74,278,600	81,706,460	89,877,106	98,864,817	108,751,298	119,626,428	131,589,071	144,747,978	159,222,776	175,145,053	192,659,559
2% for one-piece-flow		2,485,572	1,634,129	1,797,542	1,977,296	2,175,026	2,392,529	2,631,781	2,894,960	3,184,456	3,502,901	3,853,191
		$ 114,150,860	$ 124,768,147	$ 133,425,182	$ 142,636,607	$ 152,432,492	$ 162,843,841	$ 173,902,525	$ 185,641,183	$ 198,093,102	$ 211,292,068	$ 225,272,188
Projected Margin Coverage for 4900 students + 5% growth		2.49	2.48	2.44	2.39	2.35	2.31	2.28	2.24	2.20	2.16	2.13
Net existing and new system results		$ 6,605,620	$ 19,196,052	$ 30,405,376	$ 42,817,605	$ 56,539,456	$ 71,686,605	$ 88,384,422	$ 106,768,772	$ 126,986,877	$ 149,198,251	$ 173,575,710

Figure 38 - Projected financial results for new engineering education system

An important point that can be taken from the above projected results is shown in Figure 39. The new system slows the current decrease in margin coverage of the tuition to expense ratio that WPI has been experiencing from 2007 to 2012.

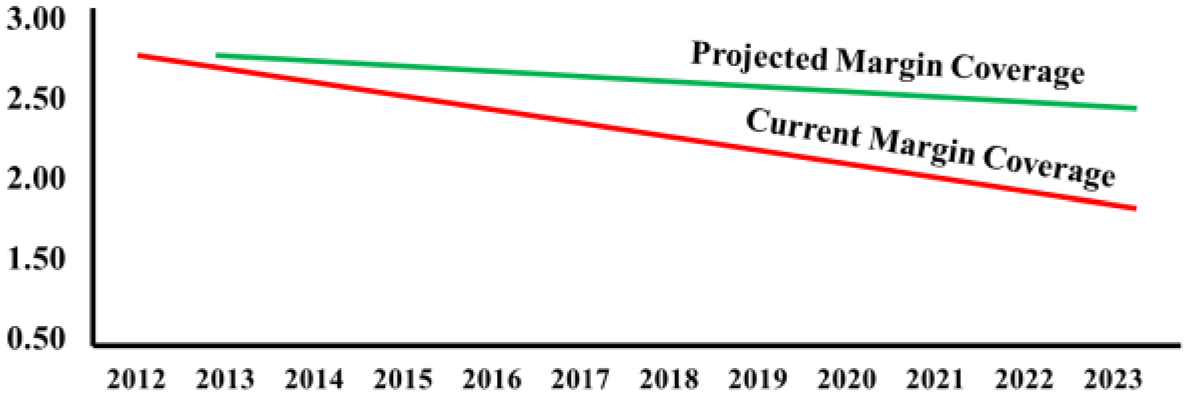


Figure 39 - Graph of 10 year tuition-to-instruction cost comparison

The average tuition per student used in the projection of $37,107 was found by dividing the total tuition and fee revenue found on the 2012 financial statement and by the average number of students reported on the schools web site. This calculation results in a figure that is not exactly the same as the published amount, which is $41,380 for 2013 (Berkey 2012). The reason for this is due to the effect of the financial statements aggregating all of the tuition revenue from every source and then dividing by the 4900 students reported on the school's website to find the average tuition per student. The figures presented here are based on a more conservative $37,107 to remain consistent with the financial statements and other referenced data.

A modest increase of 245 new students multiplied by tuition of $37,107 in 2013 brings in an additional $9 million in tuition revenue. Using the published tuition figure of $41,380 would result in higher tuition received by the school. The cost per student due to instruction and research is only available on the financial statements; hence it is the only figure that can be divided by the student population to get an average annual cost per student of $15,139 meaning that more detailed financial information could be used to more accurately complete the projection.

Most of the figures used are estimates derived from the public financial statements. It is for this reason that a sensitivity analysis is performed to more clearly show what quantities have the most impact on the financial results of the projections. The following sensitivity analysis shown in Figure 40 is used to understand how changes in base case assumptions affect performance results (Eschenbach 1992).

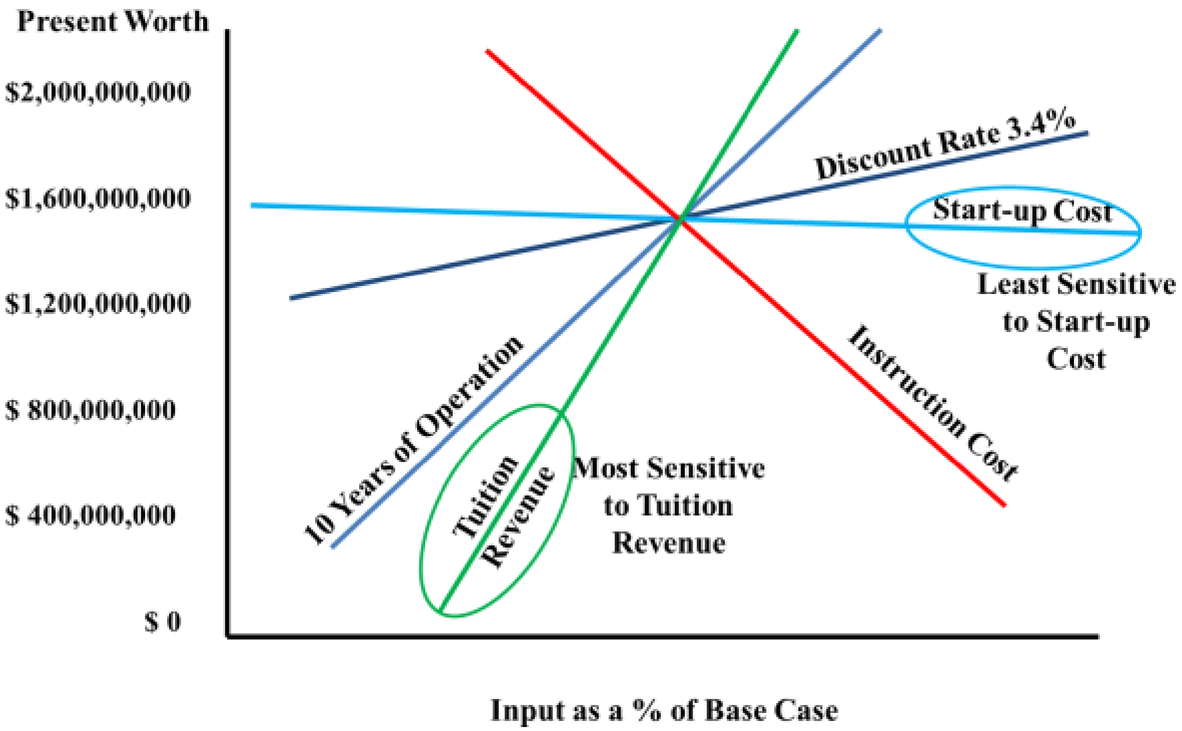


Figure 40 - Sensitivity analysis of the new system based on WPI 2012 data

Interpretation of Figure 40 indicates the horizontal lines have less impact than the lines with a higher slope. Changes in the initial start-up expenses have the least influence on the system because they are small in comparison to the other amounts. Tuition and fee revenue has the highest impact as they are by far the largest amount shown in the projection. The sensitivity analysis uses a fixed time frame; in this case it is 10 years.

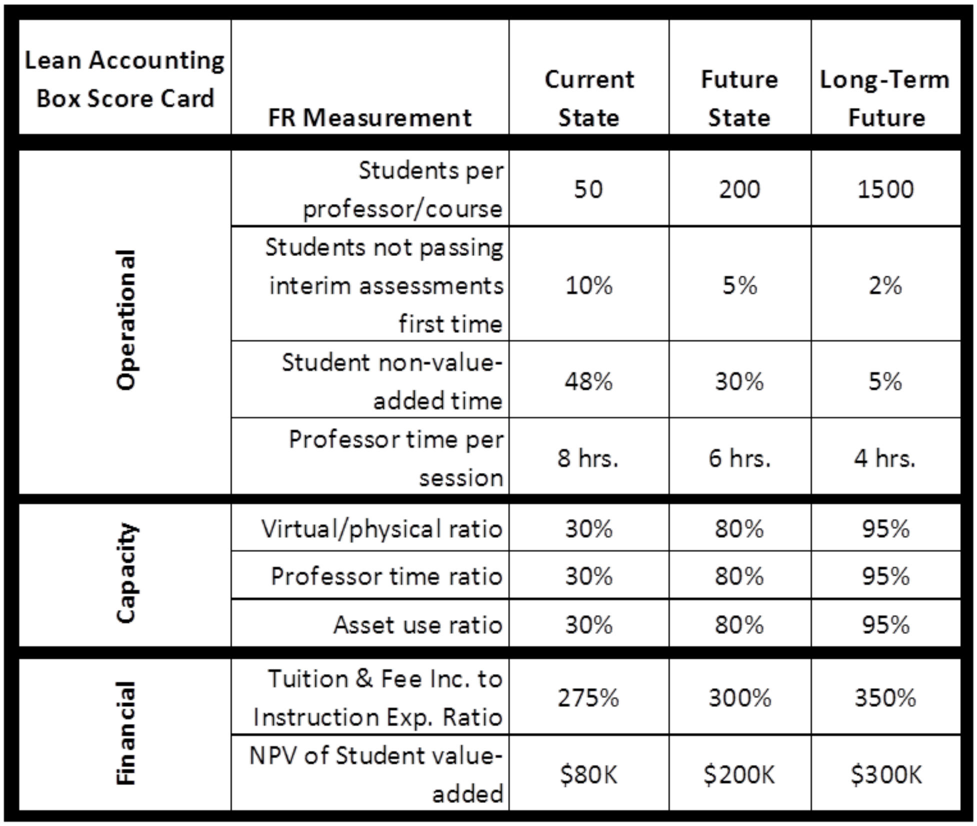
All quantities are related through a discount rate which is set at 3.4%, which is equal to the percentage increase for tuition for 2013 in order to determine the present worth of the stream of payments.

The interest rate (tuition rate increase) has some bearing on the overall performance, but not as much as how the system performs relative to tuition revenue and corresponding expense.

The main conclusion from the projection is that the results are conservative, and they show that changes in the initial costs and the discount rate have less effect on the outcome than do the tuition revenue to income coverage ratio.

To meet the objective of improving financial performance, the more students paying tuition relative to the small amount of extra expense it takes to educate them WPI is a strong argument for increasing the efficiency of the professors so they can educate more students in less time and with fewer resources. To make this a reality, the professors need to behave differently, in a way that benefits themselves as well as the students.

The second objective is to show how a new lean accounting system supports improvement of the teaching system. To address the second objective, professors can use a Box Score Card to track the progress of students in their courses. The Box Score Card contains operational, financial and capacity metrics useful in improving throughput and reducing non-value-added time in the course shown in Figure 41 (Maskell et al. 2012).



Lean Accounting Box Score Card	FR Measurement	Current State	Future State	Long-Term Future
Operational	Students per professor/course	50	200	1500
	Students not passing interim assessments first time	10%	5%	2%
	Student non-value-added time	48%	30%	5%
	Professor time per session	8 hrs.	6 hrs.	4 hrs.
Capacity	Virtual/physical ratio	30%	80%	95%
	Professor time ratio	30%	80%	95%
	Asset use ratio	30%	80%	95%
Financial	Tuition & Fee Inc. to Instruction Exp. Ratio	275%	300%	350%
	NPV of Student value-added	$80K	$200K	$300K

Figure 41 - Example of a Box Score Card for a course

Professors usually use course management software to keep records during the courses that they teach. They know who is passing and who is not. They know course concepts that are giving the students the most trouble. What professors have not been doing is seeing each student as an independent learning entity that is progressing at a rate independent of the other students. Viewing students in this way will allow them to process the course material at the student's own pace in a one-piece-flow system of course management.

Certainly, there are time limits on how long it should take to pass a course, but there are also implied minimums of how long it should take. This is faulty thinking, in that more students moving through the system at a faster pace allow for more time for the professor to do other things. This is a main tenant lean process improvement: find a better way.

Professors cannot know how much value-added time they personally have invested in a course unless it is tracked and evaluated. If one of the professor's roles is to make the degree as valuable as they can make it for the student, a system needs to be in place to evaluate throughput and be able to improve it.

Professors can get real time information on how students are progressing though the course with a Box Score Card. Professors would know, essentially in real time, whether there are bottlenecks developing in the production of the course as queues will build up ahead of the problem course concept or deliverable. This might lead to a topic being broken down into smaller steps or additional explanatory material being developed. Professors would know the quality metric from accumulated smaller assessments, similar to those used in MOOCs and corporate training as well as from larger assessments like exams and project submissions. An overall picture of the flow of the course can be developed and adjustments can be made.

Department heads could assist faculty who are have trouble structuring a course for one-piece-flow. A review of the students' progress in the course would yield not only production metrics, but assurance of learning results that can be addressed proactively.

Accountant prepared statements take a long time to produce and the information contained in them is not of a nature that can easily be used to improve a process. Important information is on them, but with hundreds of professors activities captured in the prepared statements, it is not possible to know how a single person is doing with reference to the organization's goals.

This idea parallels the elimination of non-value-added time such that the professors need data on how the students in the process are doing very soon after any activity has taken place. By using a Box Score Card, the non-value added time of waiting for others to report on the process is eliminated.

6.4 Discussion

To accomplish the main objective of improving the overall financial performance, published financial data for WPI, an engineering school, was analyzed. This analysis showed the potential effect of increased tuition revenue for the school with a modest increase in operating expense. Regarding the objective of actually improving the financial performance of a school, the professors are too far removed from the aggregate financial result to know how they are influencing its outcome. Also, waiting for CPA prepared financial statements takes too long to be of much use.

The simulation was focused on modeling a course that the students might take where group or other work does not impact the pace of learning. Consideration should be given to the new systems impact on physical plant resources including but not limited to housing, classroom space and information technology infrastructure.

Considering the second objective of increasing tuition revenue through more efficient operation thus allowing for increased enrollment numbers will not be realized unless the professors are able to better manage their courses. The professor cannot do this without some metrics that indicate how many students have finished a lecture, how many have completed various assessments, and what the flow time is for the course. A Box Score Card can be used to accomplish this task. The Box Score Card may be an electronic spread sheet and will have throughput metrics designed for and by the professor who will be using them.

The Box Score Card can be updated daily, either automatically from the course management system, or manually if the course management system is not setup to do so. Without this information, it is difficult to make changes in real time to increase throughput and improve quality. The Box Score Card enables real time decision making to meet the goal of reducing the non-value-added time for the students and increasing the quality of the education for student outcomes.

Some metrics that the professors will be interested in to accomplish objective two are: How many students are enrolled? What numbers of students have completed which lectures and assessments? How many students have completed the course? What is the pace of those remaining who have not finished? What needs to be done to get them through the course faster? Additionally, metrics on the grade distribution that are tied to specific questions or problems indicate where students are having difficulty and which students might not pass the course. Calculations of value-added and non-value-added time could be made with additional input from the students who experience the system. While not all data can be shared with the class, the overall production metrics will be of interest to both the students and professors for additional process improvement efforts.

The implementation of the proposed system will likely take place over a period of years due to the difficulty of simultaneously preparing and executing these steps across many courses in an institution. Professors who are among the first to develop their courses will be a resource for those that follow. The results from operations should show a gradual increase in the number of students attending the school. Even before the student population increases, the positive effects of mass customization and one-piece-flow will emerge as professors have more time while simultaneously more efficiently processing more students. The students will have an increase in their value-added time from more freedom to either take more courses, or pursue other interests.

6.5 Conclusions

The teaching and learning activity taking place in a university is substantially the same kind of activity across all departments. It is for this reason that the premise of it being possible to estimate the strategic financial results that a university might receive using one-piece-flow production can be accomplished by using existing, accountant-prepared financial statements. Manufacturing companies have too many different kinds of processes that prevent the scaling of top line revenue or cost figures to project future results. A university is homogeneous in this respect and allows one to project future operating results from existing, accountant-prepared financial statements.

Universities, like factories, cannot expect to achieve strategic projected results without providing the tactical process operators a way to know how they are influencing production output. The professors need to know how to manage a one-piece-flow system and the Lean Accounting Box Score Card is the tool for the job.

Chapter 7 – Summary, Critique and Generalizations

7.1 Introduction

This chapter has four objectives, the first of which is to summarize the high level concepts shown in this dissertation. The second objective is to critique the conclusions from each chapter. A third objective is to show how manufacturing engineering can improve a non-manufacturing process, often without great expense. And the fourth objective is to discuss impediments to implementation. The rationale is to examine the reasonableness of the premises and combined meaning of their conclusions.

7.1.1 Approach

This chapter ties together the methods used in this dissertation to design a one-piece-flow production system for engineering education. Each chapter is critiqued for its methods and results leading to the chapter's conclusion where counter arguments are presented.

7.2 Summary and critique of the chapters

7.2.1 Chapter 1 summary and critique

Chapter 1, Introduction, introduced the premise that a manufacturing system can be designed to educate engineers and it should be based on mass customization. The rationale for developing such a system is based on financial, national competitiveness and technological reasons. The financial cost of higher education has risen at four times the rate of inflation and the debt burden has become so great that a potential student debt bubble exists (Augustine 2007) (Schumpeter 2011) (Mote 2004). U.S. competitiveness is challenged, similar to the automobile industry in the 1980's and engineering education has become a commodity allowing global companies to employ engineers at 20% of the cost of U.S. engineers (NSF 2009). The technology of MOOCs using newly developed artificial intelligence software makes the professor scalable and can allow students to go at their own pace (Kelly et al. 2013) (Martin 2012) (Koller 2012) (Severance 2012).

This dissertation began on the premise that tuition cannot rise indefinitely due to an impending student loan bubble and that the rate of college tuition rising at twice the rate of inflation is unsustainable as evidenced by record delinquencies (Simon and Ensign 2013). This implies that either the operational costs of the school need to decrease, or the student's ability to pay the tuition is made more achievable. Additionally, public support for higher education in the form of grants and guaranteed student loans could begin to be curtailed. Recent remarks by the current administration have alluded to his possibility (Obama 2012).

Healthcare has been the latest major sector of the economy that is responding to societal pressure for value analysis and waste reduction (Orszag and Emanuel 2010). The Patient Protection and Affordable Care Act, signed into law on March 10 2010, penalizes hospitals for patient readmissions (Kamerow 2013). This is a form of value-added analysis that seeks to make the patient fit upon discharge to avoid costly readmission to the hospital for a condition that should have been fixed the first time around. Government action could require colleges and universities to demonstrate how their graduates are able to pay back their government backed student loans (Staley and Trinkle 2011).

A counter argument is that process improvement to benefit higher education students will not take place because it is not necessary. If the value proposition offered to higher education graduates is sufficiently high, and if consumer demand continues to be elastic, then there might not be a need for process improvement.

7.2.2 Chapter 2 summary and critique

Chapter 2, Literature Review for the Design of Engineering Education as a Manufacturing System, investigated four premises. The first is that a value-added function for engineering education can be defined, second, that value stream mapping can be used to design a higher education system, third, the new design can be simulated by a computer, and fourth that both financial and managerial accounting would be needed to make the system a reality.

A value-added function explaining the relationship between an engineering student’s tuition and graduate income was not found, but similar functions do exist (Cunha and Darwin 2009). Value stream maps of the higher education learning process itself were called for, but not found (Emiliani 2006). The lack of industrial engineering simulation modeling of higher education systems results from the view that student learning is not a true production process. Lean accounting is the link between the strategic direction and tactical controls necessary to accomplish process improvement (Kennedy and Widener 2008) (Albright and Lam 2006).

The literature search could have overlooked research and education modeled as a production system because the keywords used were not appropriate to the search. It is also reasonable to assume that an institution of higher education has used value stream mapping for improvement of the learning process itself, but that the work is not available to search databases.

7.2.3 Chapter 3 summary and critique

Chapter 3, An Examination of “Value-Added” in Engineering Education, laid the foundation for the design of engineering education as a manufacturing system. Chapter 3 offered the three premises about knowing the customer’s economic value-added received from a production process is vital in designing the production system which is accomplished by a value-added function, value stream maps, and a process chart (Rother and Shook 1999) (Raisinghani et al. 2005) (Graham 2004). The rationale for defining a value-added function is to relate monetary input and market value output. (Davis and Novack 2012) (Gopinath and Freiheit 2009). A value stream map is needed to reduce production lead time (Wilson 2009) (Rother and Shook 1999) (Graham 2012).

It is difficult to argue that a time value money based value-added function is not important. Students often speak about what they sacrifice in the form of tuition paid in the present for the income gains that are expected to come in the future. It is also difficult argue that a value stream map that shows how student daily activity is translated into valuable knowledge and skills is not important. The fractal nature of engineering education could be related to an existing learning science discipline, but none was located during the literature search.

7.2.4 Chapter 4 summary and critique

The premise of Chapter 4, Manufacturing System Design of New Engineering Education Process, is that the manufacturing principles of maximizing value added and minimizing production cost, along with ABET Criterion 3, Ohno's seven wastes and Suh's axiomatic design method can produce a new system for engineering education (Brown 2011b) (ABET 2012) (Ohno 1988) (Suh 1990) SUH. A new system is needed because the U.S. system might be unsustainable due to high operating costs and the potential inability of students to fund tuition (Wood 2011). The objective to develop a value-added function, a value stream map, and a process chart was achieved. A university is now able to evaluate the value-adding and non-value-adding activities under their control. Professors can evaluate their courses to increase the value that the student receives.

The process of decomposing a system's FRs to understand exactly what and how it is trying to be accomplished is a high value activity for the designer. Axiomatic design is unique in that the designer is required to apply the axioms to the design. Designs that violate the Independence and Information Axioms have been shown to exhibit sub-optimal results causing unnecessary iterations to either control the design or to improve it. In addition, the calculation of the information content in the design leads to a beneficial reevaluation of the FRs and DPs to find new ones that can reduce the system information. Important processes, such as operating an engineering school, should be subjected to this scrutiny if nothing else to ensure the goals of the system are being met or to cause a reduction in operating expenses. The selection of process metrics used to calculate the probability of success in an education system is a potential area for further study. Metrics for the assurance of learning could benefit from detailed definitions to be useful in this production system.

7.2.5 Chapter 5 summary and critique

Chapter 5, Simulation of Engineering Education as a Manufacturing Process, presents the premise that industrial simulation software can generate data from a one-piece-flow model of engineering education. This is important because the simulation of value stream maps adds the dimension of time to provide for understanding a process quickly and inexpensively (Donatellli and Harris 2001). Simulation adds effect of resource dependencies (Kelton, Sadowski and Swets 2010).

The broader limitations include estimating some parameters which could be done by sensitivity analysis. The simulation showed that 1500 students can progress through a course with one professor. This is possible as long as there is an information technology based support system for the students. The percentage of students that need personally delivered support can be found through operating the one-piece-flow system. Operating the system will produce data on what percentage of the students need help, and the simulation can be updated. The author's personal experience was used to develop the simulation model. No data was found about what percentage of students will need direct support from the professor in this type of course system.

7.2.6 Chapter 6 summary and critique

Chapter 6, Financial Analysis of the New Engineering Education Process, starts with three premises. The first is that it is possible to estimate the strategic financial results of a university using a one-piece-flow production system. The second is that this analysis can be accomplished by using existing financial statements. A third premise is that in order to meet these projected results, the professors can rely on lean accounting. The teaching and learning process in a university follows a similar pattern shown in a value stream map, regardless of the department, thus allowing for a scaling of the financial projections which might otherwise not be possible.

The argument was made that the figures in the financial statements are able to be scaled up to show potential future results. This assumes that all teaching activity will respond in the same manner and impact the financial results equally. Only after trying to operate the one-piece-flow system in different courses will a school be able to gauge the actual result. The proposed analysis is a starting point

7.3 How manufacturing engineering can improve a non-manufacturing process

The third objective of this chapter is to show how manufacturing and industrial engineering can improve a process, often without great expense. Manufacturing engineering accomplishes this by employing two basic principles. The basic principles of manufacturing engineering are to 1) maximize the value added and 2) minimize the cost (Brown 2011b). By using these principles as the theme of decomposing manufacturing production design problems new solutions can be developed for education processes.

Axiomatic design has previously been applied to the education process itself (Thompson, Thomas and Hopkins 2009). It has also been applied to the design of courses that teach axiomatic design (Cha and Lee 2004), (Odom, et al. 2005), (Park 2011), (Tate and Lu 2004) and (Dickinson and Brown 2009).

The field of industrial engineering is actively involved in applying production metrics to field's other than manufacturing such as healthcare (de Mast, et al. 2011). UMass Memorial Hospital has saved $13 million in the first year of adopting manufacturing engineering process improvement methods (Eckelbecker 2012).

Business process engineering methods use a hierarchical approach to improvement (Adesola and Baines 2005). Business process improvement methods grounded in industrial engineering show the need for sustainability (Bateman and David 2001). The plan-do-check-act cycle developed by Deming is often cited as the basis for work in this area (Deming 2000). Examples in the literature of manufacturing principles and industrial engineering applied designing the production aspects of education were not found.

There are references to the "manufacturing model of education" as being the antithesis of good educational practice (Astin 1993) (Emiliani 2004). Education writers might not have the fine knowledge to be able to discern what manufacturing is and is not. If their description of manufacturing includes repeatable processes and known outputs servicing the needs of the customer, then their description of manufacturing is accurate. Unfortunately, there are few flattering descriptions using the words manufacturing and education in the same sentence. If what is meant is rigidity in the process to the point of it being able to be automated, then the negative connotation as applied to education would be accurate. This would certainly be a bad way to run any higher education system. This generalization of manufacturing often refers only to the physical processing part of manufacturing. Manufacturing is more encompassing than that.

Manufacturing is about fulfilling customer needs in a reliable and predictable way that minimizes waste and maximizes the value-added for the customer. Any other description of manufacturing does not encompass a systems perspective or is a derivative of the system and certainly does not represent the overall goals or functioning of the manufacturing system in its entirety.

7.4 Impediments to implementation

7.4.1 Do colleges and universities recognize the problem?

Universities might not see the magnitude of their inefficiency problem. U.S. universities employed more than 230,000 administrators in 2009, up 60% from 1993, or 10 times the rate of growth of tenured faculty according to the U.S. Department of education (Hechinger 2012).

In a recent interview J. Paul Robinson, chairman of Purdue University's faculty senate, strode through the halls of a 10- story concrete-and-glass administrative tower. "I have no idea what these people do," said Robinson, waving his hand across a row of offices, his voice rising. Did the education experience at the university improve because of these admissions by Robinson? (Hechinger 2012). This might be a different issue than reducing the non-value- added time in education, but might be indicative of how universities lose sight of connecting value to the student's education.

Production processes are never as lean as they can be unless a constant vigil is kept to examine how the operation is performing. The automobile business was forced to respond to this when the Toyota machine "changed the world". Colleges and universities have not been forced to retool their academic manufacturing system because the money has not stopped flowing. But substitute education products are becoming available. Competition could come in the form of an ABET accredited school in South America that has new facilities, no debt, and offers a degree for twenty thousand dollars (Rice 2012).

Even if these schools are not a threat to the top tier schools, prudent management dictates that cost containment by school management is a major responsibility.

7.4.2 Organizational issues when implementing lean process improvement

Recognizing that there is problem is a necessary step in process improvement but lean process improvement does not always work. A 2007 Industry Week survey showed that only 2% of companies achieved their lean goals and that 24% had significant results (Pay 2008). This leaves three quarters of organizations that have tried to implement lean process improvement still struggling with improving their operations.

Implementing a production system of this nature requires that broad institutional leadership, commitment and understanding be present. Organizations that attempt to implement lean manufacturing techniques have mixed results. Part of the problem of not achieving the desired results is that the managers and employees do not understand clearly what constitutes lean manufacturing (Anand and Rambabu 2010).

This problem can be solved using lean improvement departments that educate and assist in implementing lean process improvement in organizations. Examples include the highly successful department of Toyota Production Systems (Liker and Rother 2011) and The University of Massachusetts Memorial Hospital Center for Innovation and Transformational Change (Cooney, Roche and Xarras 2011).

College administrators and faculty might not have the training to see the degree granting process as a production system. They also might not have the skill set to implement a change of this magnitude.

The American automobile industry’s history in response to competitive threats from the 1950’s to the 1990’s was very slow (Anand and Rambabu 2010). The single biggest impediment to achieving the goals set forth here is that the system operators are not taking the time to analyze the academic manufacturing system that they are currently operating.

7.5 Overall Summary and Conclusions

7.5.1 Substitution of goods in engineering education

The nature of the world economy brings to bear two competitive realities. The first is that history has shown that the costs or revenues of any industry cannot increase indefinitely and substitute products will balance the supply and demand equation. Since the fourteenth century, scholars such as Mamluk Ibn Taymiyyah have written about supply and demand equilibrium. “If desire for goods increases while its availability decreases, its price rises. On the other hand, if availability of the good increases and the desire for it decreases, the price comes down (Hosseini 1995) (Biddle, Davis and Samuels 2006). This has been manifest recently with global corporations able to hire non US educated engineers at 20% of the cost of a US educated engineer.

A goal of the design of engineering education as a manufacturing system is to show that one-piece-flow production in education produces two main benefits. One is for the student and the other is for the school.

The first benefit is that the student gains more control over progress towards his or her degree. The student’s ability to increase the financial value of their degree will allow the best and brightest to achieve much more during the time they are attending engineering school.

The second benefit is that universities will have more options to increase or decrease tuition because they are more efficient (Belkin and Thurm 2012). Schools that operate less efficiently will eventually go out of existence in a competitive market (Harney 2012). Conversely, small schools will gain market share because of efficient degree programs (King and Nanfito 2012).

These concepts are not new. Worcester Polytechnic Institute (WPI), has already operated in a one-piece-flow manner with its Individually Prescribed Instruction (IPI) courses from the early 1980’s (Sisson 2011). Other schools experimented with similar programs.

One area that is applicable to MOOCs is one-piece-flow and leveraging the time of the professor. Technology based methods exist that currently enable this to happen (Andrews 2012). Residential colleges offer a different, but not better or worse education experience (Tucker 2001). A student who has access to a live professor as a resource is invaluable but the professor cannot personally attend to the needs of the great number of students enrolled in a MOOC. A different method of responding to student inquiries and grading that uses teaching assistants and technology is required. MOOCs are able to process large numbers of students efficiently, but the financial model has not been sorted out yet (Korn and Levitz 2012). Giving the MOOC away for free and then accepting credit from the MOOC towards a degree does not make economic sense. And there is the question of accepting MOOC credit towards a degree. This is especially important where the degree leads to professional life as a medical doctor or a professional engineer.

Students could seek alternative schools to offset the effect of rising tuition relative to their earning potential after graduation. The economic failure of a school could be the result of increasing tuition beyond graduates’ perceived earning potential. In a competitive market with similar goods, the producer is not able to raise prices at will to compensate for increasing internal costs (Sraffa 1926). For example, General Motors lost the ability to keep production costs below what the market would pay for their products leading to bankruptcy during the financial crisis of 2008 (Economist 2009).

Could a parallel be drawn between the history of the automotive industry and the higher education system in the United States? The United States was overtaken as the largest automobile producer first by Japan in the 1980s and subsequently by China in 2008 (OICA 2012). The U.S. automobile industry began losing its dominance starting in the 1950’s but this was not obvious until the 1980’s. Lean manufacturing or more clearly, the elimination of waste in production processes, is a primary reason for this phenomenon (Womack et al. 1991).

The Chronicle of Higher Education offers some support for the automobile industry U.S. education system analogy:

> ‘The American share of "highly influential" papers published in peer-reviewed journals fell to 58 percent in 2003, from 63 percent in 1998. Just 4 percent of American college graduates major in engineering, compared with 13 percent of European students and 20 percent of those in Asia’ (K. Fischer 2009).

From 1976 to 2010 the prices of all commodities rose 280 percent, housing 40% and private education 1000% (Davies and Harrigan 2012). Posted on the WPI website, the president of the college discusses national rankings for WPI and that a major infusion of cash needs to be sought prompting the school’s most ambitious fund raising campaign (Berkey, Ranking 2013). The same posting mentions that in 2006 WPI was listed as having the second highest student debt load of all US universities. WPI was listed at number 8 of colleges that leave students in massive debt (Huffington Post 2010). Improving the operational performance of the school is not mentioned as a part of that goal.

Engineering education today would be well served by knowing the how and why of its value proposition and work to reverse the trend. Process analysis tools focusing on value-added are necessary to eliminate non-value-added time in order for higher education programs in engineering in the United States to remain competitive. Design of production systems, in general, should be informed by data in how value is created and measured (Cochran and Dobbs 2001).

7.5.2 Higher education modeled as a manufacturing process

University education is similar to a manufacturing job shop (Black, 1997). There are many paths through the education process and the resultant outputs are substantially similar, like being able to perform mathematical calculations, design an experiment or analyze results. Each system output in the form of graduate engineers is unique and has varying levels of quality and performance capabilities associated with it, just like the output of a manufacturing job shop. Students could excel at one or another skill set while being educated and no two outputs would be exactly the same.

If the education system is able to be modeled as a manufacturing system, then improvement could be accomplished by examining the seven wastes in manufacturing (Ohno, 1988). Eliminating or reducing waste through kaizen events and process improvement while creating engineers will make the education system less costly to operate. The system's responsiveness to customer demand is improved by eliminating or reducing non-value-added activities.

Suh's axiomatic design method was used to decompose the functional requirements in order to design an education system that produces graduate engineers with the least amount of waste. The new system is generic in the sense that no subject matter is suggested; rather, the method of how the 'raw material' in the form of a student progresses through the 'academic manufacturing system' is shown. The system is designed from an idealized point of view as a goal to be achieved and not an end in itself.

The design presented used the axiomatic design method to decompose the FRs according to Criterion 3. It was determined that a high degree of coupling between the DPs and FRs prompted a second iteration of the design. The second decomposition of Criterion 3 showed that engineers should possess at least two types of knowledge and two major skills they should be able to perform. The resulting new design was completely uncoupled with the exception of maximizing value added to the student before minimizing the cost.

The waste analysis in the design pointed out that non-value-added time accumulated in-between the learning process steps. This led to a one-piece-flow production system that decoupled the major process steps to allow for individual learning pacing. Metrics were developed for use with the FRs and to allow the calculation of information content in the design.

Many different types of education systems exist today such as traditional lecture format, asynchronous and synchronous online courses, massive open online courses (MOOCs) apprenticeships and internships, among others. These various education systems have been effective over long stretches time, and in the absence of economic pressure, any given method could continue to meet the needs of a school, students and future employers.

Current education models are shifting away from traditional scheduled instruction formats in classroom settings for a variety of reasons. They include limitations due to physical resources, geographic considerations and the increasing improvements in delivery education through online and blended formats.

In a production sense, education systems are based on "push" type production systems and as such, they deliver the course content at a prescribed rate. Students may or may not be able to complete the requirements in advance of the course schedule even if they have the ability to do so.

Analysis of this type has been performed on production lines that create physical products but little has been done to use manufacturing engineering principles to evaluate the knowledge transfer and skill creating process at an engineering university. Operation of the university system is subject to the same types of production constraints as in a factory.

7.6 Discussion

Universities, like WPI have experimented with these production processes in the past. The author was fortunate to participate in two courses in freshman physics delivered in a self-paced, self-quality controlled method with success (Sisson 2011). These courses, known as individually prescribed instruction or IPI courses, were the paper based versions of what might be described as precursors to today's massive open online courses or MOOCs.

At a recent summit titled "Online Learning and the Future of Residential Education," MOOCs are described as "[…] simply a tool" (Reuter 2013). Some MOOCs have lots of small, low-risk assessments built in to them. The author has participated in many MOOC type courses to satisfy continuing education (CE) requirements in order to maintain securities licenses.

Specifically, CE courses for money laundering and bank fraud, which the author has also participated in, have a lecture component that has both written material supported by video vignettes that need judgmental answers. The student is asked questions during the learning experience and if the assessment is not satisfactory, other written material and vignettes are presented. When the student demonstrates understanding of the material he or she can move on to the next topic. At the end of the session is a comprehensive exam that covers all of the material and makes a record of it for reporting purposes. University professors can now easily record their lectures. They are aided by course management software provided by vendors such as Blackboard® (www.blackboard.com 2013). This type of software offers the ability to create online assessments that contain all of the above process steps and much more.

When WPI offered IPI courses in the past, keeping the content fresh would have been difficult as productive data management methods, internet communication and video capability did not exist. Also, the IPI courses were essentially all or nothing in terms of the student having access to a professor for extra help. There was a teaching assistant assigned to the course to help students, but the inability of students to answer their own questions at three in the morning prior to the advent of the internet was not an option, so the pacing was still controlled by the professor and teaching assistants.

Another example of leveraging the professor's time is the instruction method used in WPI course ME1800 Manufacturing Science, Prototyping, and Computer-Controlled Machining. This course has existed at WPI for over 40 years and now has the benefit of CNC machine tools being made available to the entire campus. The course teaches over 1000 students per year to setup and run vertical mills, and lathes among other machine tools (Bergstrom 2012). One professor and a group of TAs teaching the course in a traditional manner could find it difficult to prepare over 1000 students per year in the course. The course process is to "teach one-learn one-observe one" (Brown 2012). That is to say, the last student who learned how to program and run the machine tools teaches the next student how to do it. A third student is observes the first two students and gets ready to become the learner and then the teacher.

These multiple levels of reinforcement benefit everyone in the course as students proceed at their own pace. The professor is available for consultation, but the bulk of the work is performed by students who teach each other. A more modest version of this method has been adapted in WPI undergraduate course BUS3020 Achieving Effective Operations. This course is also a lab course that teaches the basics of one-piece-flow. The lab instructors are students who took the course previously. They run and grade the labs independent of the course lectures (Johnson 2009).

WPI has graduated at least one student who was able to earn a B.S.M.E and an M.S.M.E in four years while participating in varsity sports and other activities (J. M. 2012). An academic manufacturing system that allowed for more students of this caliber to attend an engineering school seems to be a goal worth pursuing.

By applying manufacturing engineering principles to the engineering education process an engineering school will be able to know how its education system is performing relative to the needs of its professors, students and the ultimate customers who are the employers of the graduate engineers. The knowledge and skill set of a graduate engineer is the output of engineering school. The axiomatic design method is able to define the FRs of the engineering education system and show how the FRs are measured. Axiomatic design can incorporate continuous improvement methods into the design to improve its performance over time as well incorporate new required FRs. This can be accomplished using manufacturing and industrial engineering principles.

This work might be limited by the need to better understand the learning model presented. There is no analysis presented here on student's cognitive function and the simulation is based on sequential steps that might or might not reflect how students learn. Assumptions in the simulation model did not address collaborative group work that can be incorporated into the simulation potentially in a different form.

In addition to the aggressive reengineering process targets shown in the financial analysis additional adept levers could be should be employed such as (Hall et al. 1993):

- Top level administrators and faculty should allocate sufficient time to a project of this magnitude.
- A more detailed review of the stakeholders needs such as employers, students and faculty administration should be performed.
- One person should be held responsible for the entire value stream to ensure the best results in the system should be piloted before large-scale rollout.

A process redesign of this potential magnitude is not likely to succeed according to the following criteria:

- Assign average performers to implement the project.
- Measure only the output of the plan and not avoid other measurements in the system.
- Settle for the status quo meaning that a radical redesign is never fully achieved because it is watered down upon implementation.

And potentially most critical item to overlook is the amount of communication required between all of the stakeholders so that the message is clear and unequivocal about what is trying to be achieved.

Future directions of this work could include gathering data on different types of actual courses and refine the simulation model. The metrics used to measure the FRs could be further developed and expand the detail in the axiomatic design. A way of thinking and analysis technique was presented. Future work might include an empirical study that could test several hypotheses about the design and operation of the new system.

7.7 Conclusions

This work demonstrated that manufacturing and industrial engineering is able to design a new system for engineering education that functions like a manufacturing system.

The key findings are:

1. A value proposition was defined in terms of the financial inputs and outputs for the students.
2. The fractal nature of engineering education led to a minimum amount of learning that could be used to construct a value stream map of the engineering education process.
3. Metrics from the value stream map quantified student value-added time.
4. Value-added time metrics were incorporated into a system that maximizes the value-added and minimize cost.
5. An axiomatic design hierarchy of the new system based on manufacturing principles was developed
6. Simulation of the new system showed how students can progress through a course with modest increases in support through technology.
7. Financial analysis gave indication of the magnitude of the impact of the new system and how to use lean accounting for process improvement.

The new design of engineering education as a manufacturing system is shown to be adjustable, controllable, cost efficient and able to be put into operation.

Afterword

One thing that struck me, when I mentioned my ideas to a few faculty members on the WPI campus, was the immediate, not quite visceral, but strong reaction to the topic of the design of engineering education as a manufacturing system.

Two of the responses, without making direct references to the professors that said them, are below.

Without asking me any further questions, their reactions to my dissertation topic were something to the effect of:

“There is no *non-value-added* time in what I do” and “you’re not going to industrialize *my* teaching.”

Interestingly, the industrial engineering professors who are working on hospitals and factories thought the idea was perfectly reasonable. This calls to mind a saying popularized by English Presbyterian minister and writer Matthew Henry (1662-1714) “None so blind as those that will not see.”

So therein lies the problem. Upper level management is often blind to process improvement and is not able to get the message out to the organization. A university populated with independent thinkers makes process improvement even more challenging.

A much more efficiently run engineering school is entirely possible. The key is to start with one or two one-piece-pilot cells scattered throughout the school and the students will demand more of them. This potential new future is easier to achieve than ever before.

The popular press has an article on MOOCs nearly every day. MOOCs are just another method of delivering academic material and they are subject to the same manufacturing and industrial engineering principles as any other production process. Creating higher value for stakeholders is what changes markets and methods of production.

Peter Drucker wrote the following about Fredrick Winslow Taylor’s contribution to management science in his 1973 book, *Management; tasks, responsibilities, practices*:

> "On Taylor's 'scientific management' rests, above all, the tremendous surge of affluence in the last seventy-five years which has lifted the working masses in the developed countries well above any level recorded, even for the well-to-do. Taylor, though the Isaac Newton (or perhaps the Archimedes) of the science of work, laid only first foundations, however. Not much has been added to them since--even though he has been dead all of sixty years."

Writing the dissertation was an enjoyable experience that I would do again, especially with Professor Brown as my advisor. The simple logic and potential end result of *The Design of Engineering Education as a Manufacturing System* was obvious from the outset.

Walter. T. Towner, Jr.
April 2013

Appendix A - Army Special Training Program

ASTP student academic schedule

Individuals who passed above the acceptable level were sent to an Army Specialized Training Program, which included intensive courses, approximately 25 class-time hours per quarter, in engineering, science, medicine, dentistry, personnel psychology, and 34 different foreign language at 227 land-grant universities around the country.

These programs were accelerated; students were expected to complete the program in 18 months with a four-year degree and a commission. This included many volunteers from the civilian echelons who were at least 17 but less than 18 years of age.

The soldiers' week was made up of 59 hours of "supervised activity," including at least 24 hours of classroom and lab work, 24 hours of required study, six hours of physical instruction, and five hours of military instruction. At its height in December 1944, about 140,000 men were enrolled in the program.

Utilizing major colleges and universities across the country, the Army provided what was supposedly the equivalent technical content a four-year college education combined with specialized Army technical training over a period of one and one-half years to those enlisted men who were accepted into the program.

The Army Specialized Training Program was formally established in December 1942. It differed from some of the preliminary proposals in placing attention not so much on the production of officers as on the production of specialists who might or might not ultimately be commissioned. The specialties were chiefly scientific, engineering, medical, and linguistic.

9,000 engineers earned degrees in 18 months

The stated need for 1944 was 52,404 men, distributed among types of specialized training shown in Table 42.

ASTP Program	Engineering	Scientific & Mathematical	Languages	Field Immaterial	Total AGF Requirements
Advanced (4 yrs. College)	9,263		2,311	4,529	16,103
Basic (2 yrs. College)		26,181	5,419	4,701	36,301
Total	9,263	26,181	7,730	9,230	52,404

Table 42 - Total personnel trained in ASTP Program

Appendix B - Value Stream Maps and Process Chart

This appendix contains the following value stream maps and charts:

Eng. Education VSM: At The Session Level:
A session is defined to be one class session, represented as two hours in this example.

Eng. Education VSM: At The Course Level:
A course is defined to be one course of fourteen sessions in this example.

New Eng. Education VSM: At The Term Level
A term is defined to be three courses in this example.

New Eng. Education VSM: At The Academic Year Level
An academic year is defined to be four terms in this example.

New Eng. Education VSM: Degree Level
A degree is defined to be four academic years in this example.

New Eng. Education VSM: User Data Input Sheet
The user data input sheet allows the user to adjust any of the definitions above, such as three terms in an academic year instead of four. Data is tabulated to determine the amount of value-added to total time to degree in an education system.

Process Chart
The process chart shows the responsibilities of the student and professor in the system.

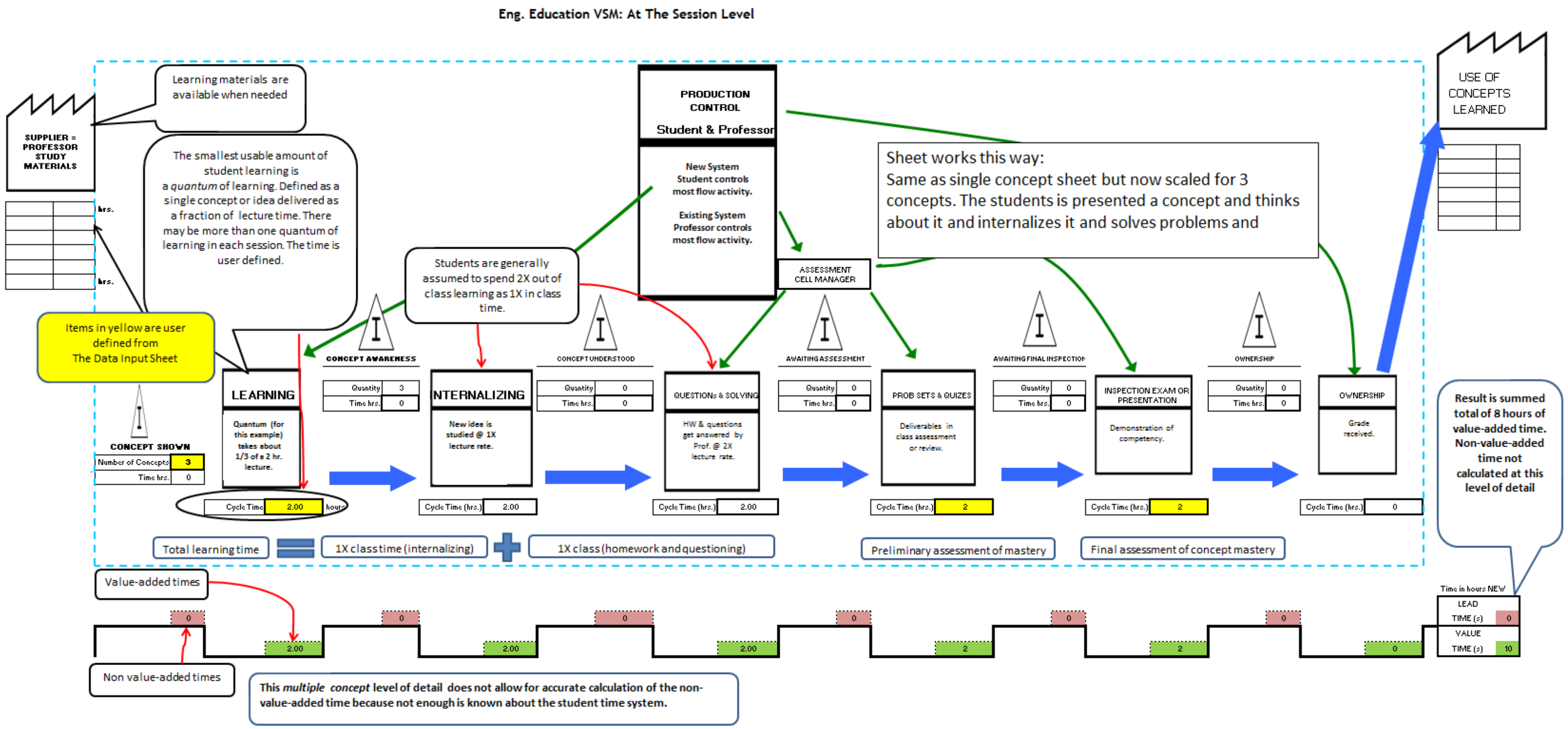
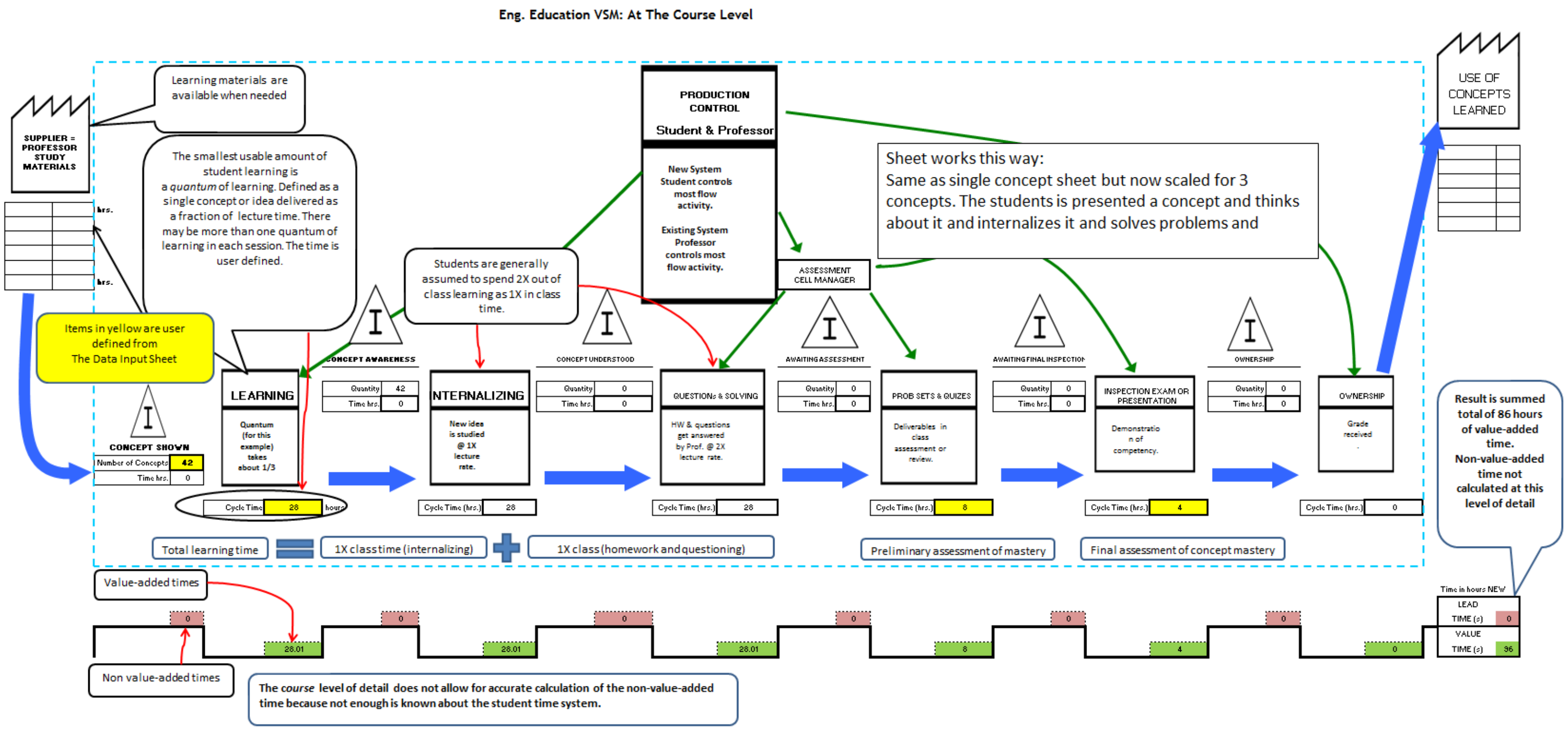


Figure 42 - Engineering education value stream map for the session level



Learning materials are available when needed

The smallest usable amount of student learning is a *quantum* of learning. Defined as a single concept or idea delivered as a fraction of lecture time. There may be more than one quantum of learning in each session. The time is user defined.

Items in yellow are user defined from The Data Input Sheet

Students are generally assumed to spend 2X out of class learning as 1X in class time.

Sheet works this way:
Same as single concept sheet but now scaled for 3 concepts. The students is presented a concept and thinks about it and internalizes it and solves problems and

Result is summed total of 86 hours of value-added time. Non-value-added time not calculated at this level of detail

The *course* level of detail does not allow for accurate calculation of the non-value-added time because not enough is known about the student time system.

Figure 43 - Engineering education value stream map for the course level

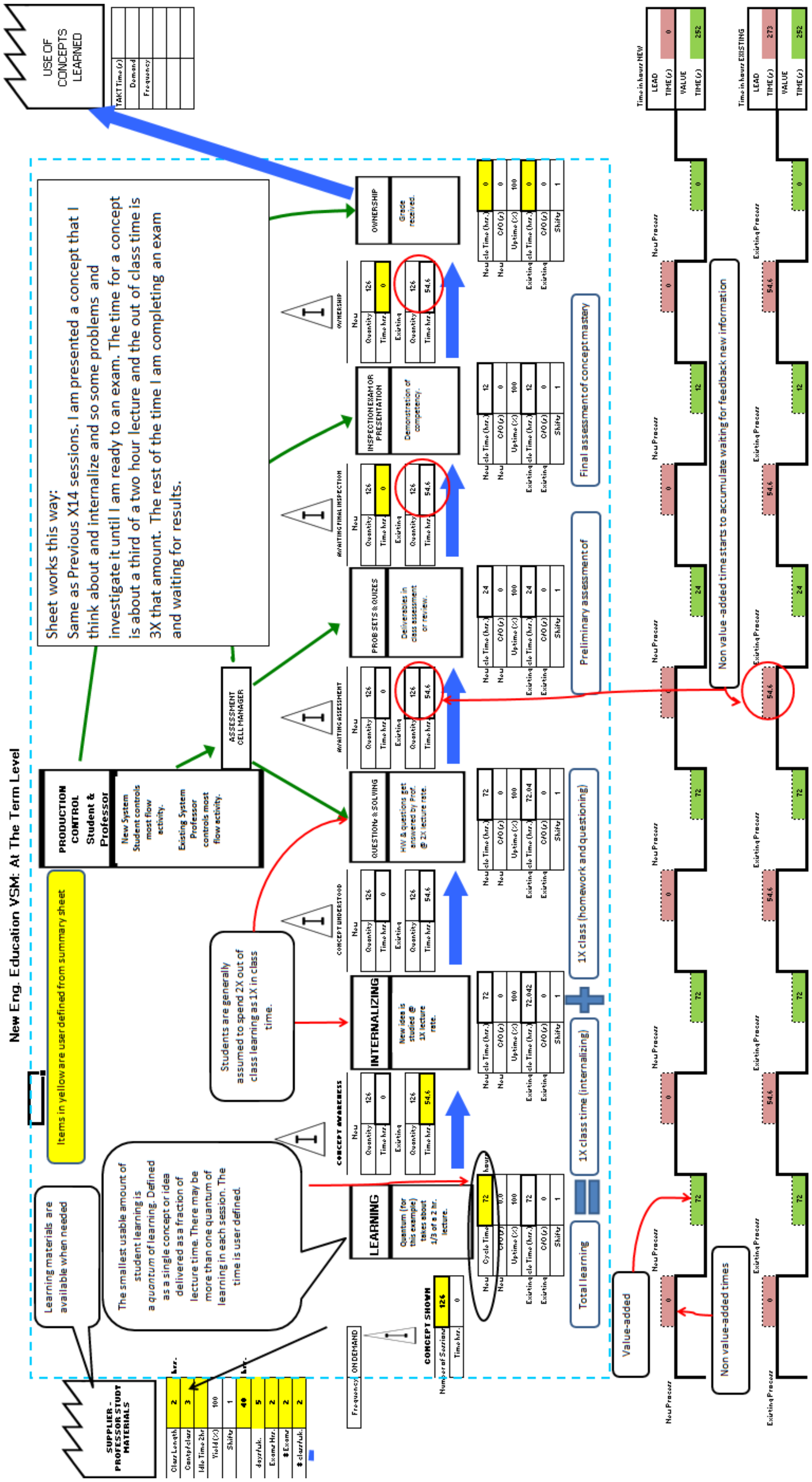


Figure 44 - Engineering education value stream map for the term level

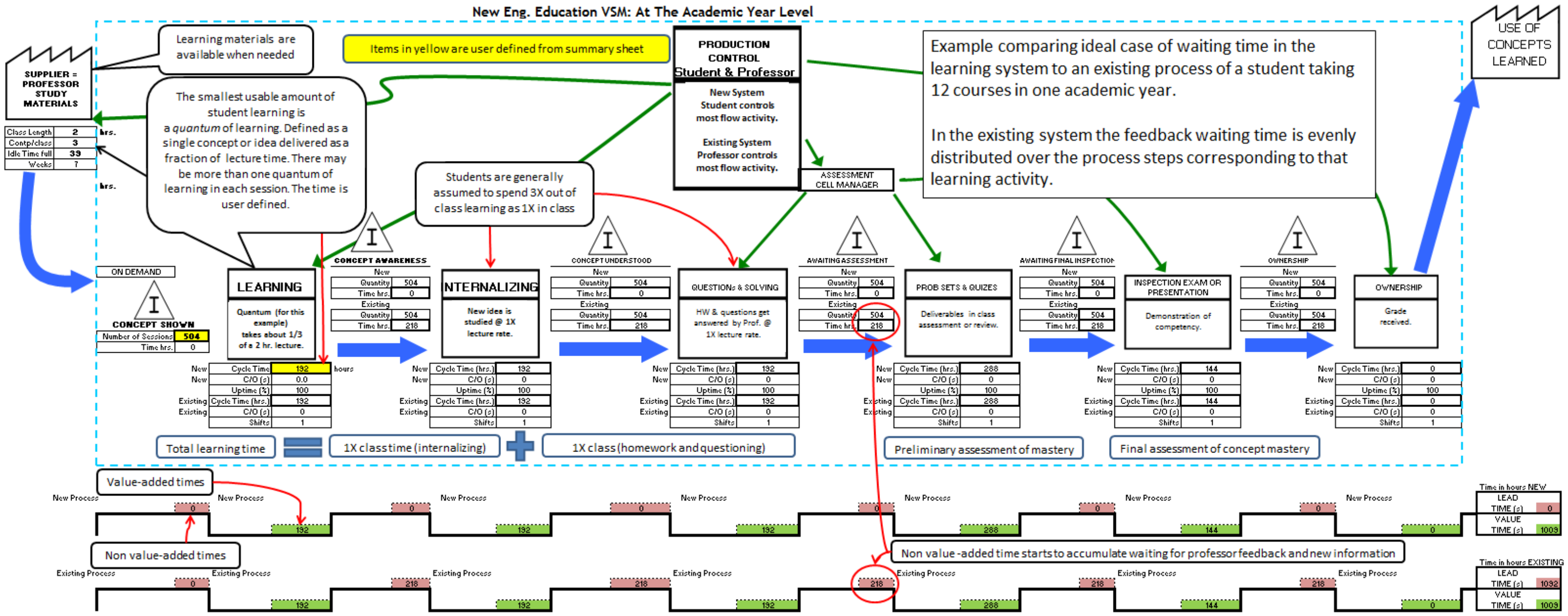
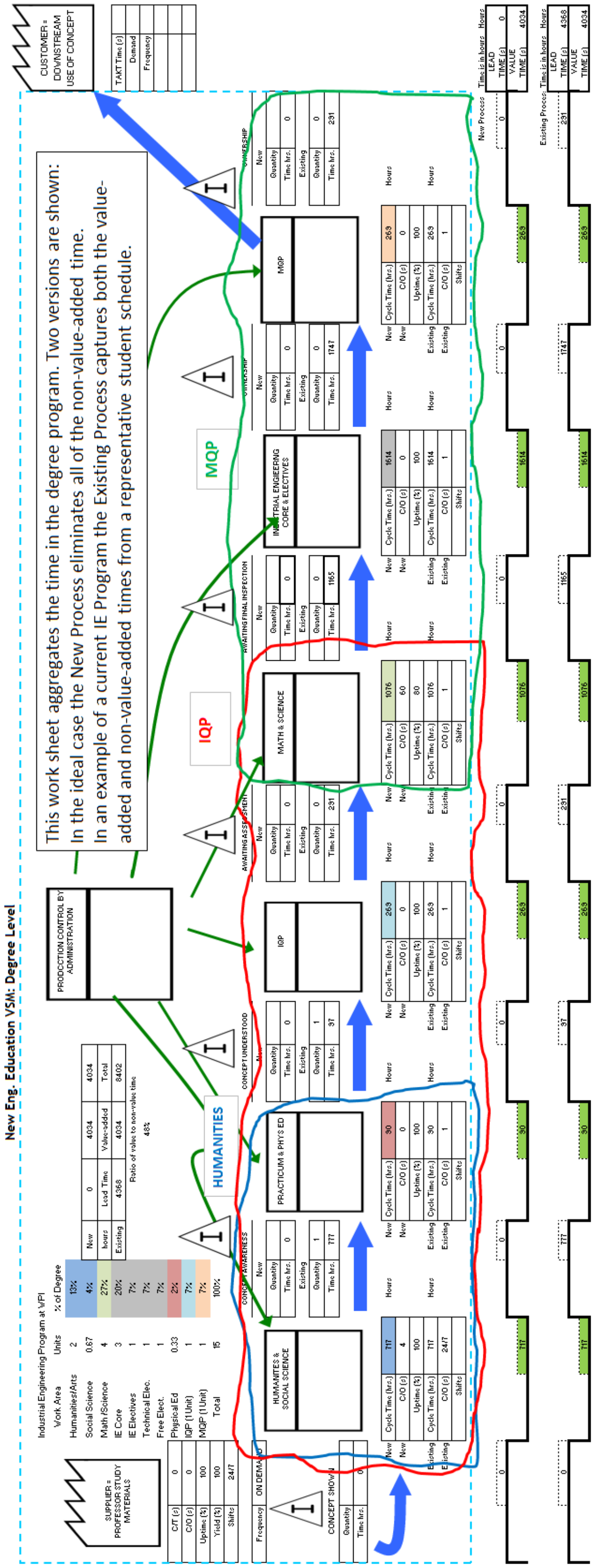
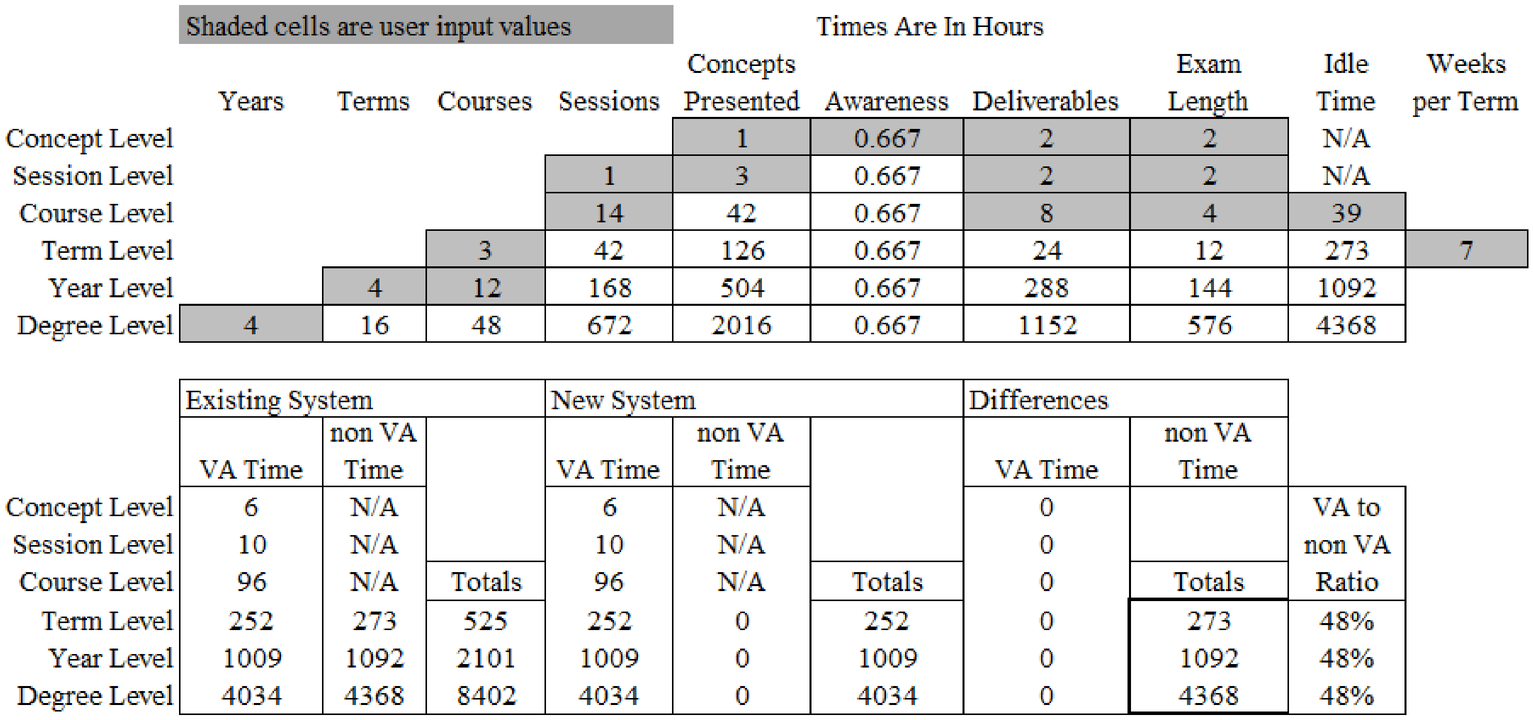


Figure 45 - Engineering education value stream map for the academic year level



This work sheet aggregates the time in the degree program. Two versions are shown: In the ideal case the New Process eliminates all of the non-value-added time. In an example of a current IE Program the Existing Process captures both the value-added and non-value-added times from a representative student schedule.

Figure 46 - Engineering education value stream map for the degree level



Shaded cells are user input values

Times Are In Hours

	Years	Terms	Courses	Sessions	Concepts Presented	Awareness	Deliverables	Exam Length	Idle Time	Weeks per Term
Concept Level					1	0.667	2	2	N/A	
Session Level				1	3	0.667	2	2	N/A	
Course Level				14	42	0.667	8	4	39	
Term Level			3	42	126	0.667	24	12	273	7
Year Level		4	12	168	504	0.667	288	144	1092	
Degree Level	4	16	48	672	2016	0.667	1152	576	4368	

	Existing System			New System			Differences		
	VA Time	non VA Time		VA Time	non VA Time		VA Time	non VA Time	
Concept Level	6	N/A		6	N/A		0		VA to non VA Ratio
Session Level	10	N/A		10	N/A		0		
Course Level	96	N/A	Totals	96	N/A	Totals	0	Totals	
Term Level	252	273	525	252	0	252	0	273	48%
Year Level	1009	1092	2101	1009	0	1009	0	1092	48%
Degree Level	4034	4368	8402	4034	0	4034	0	4368	48%

Figure 47 - Master input table for the value stream maps

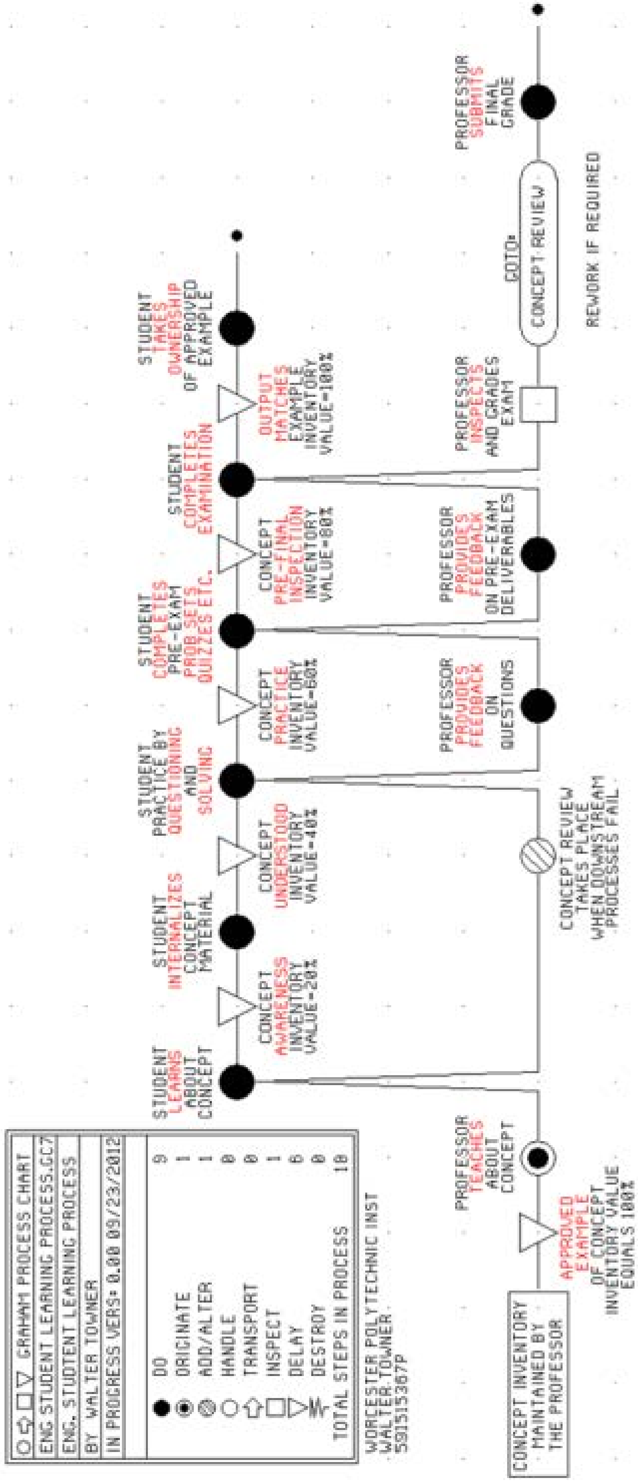


Figure 48 - Process chart showing responsibilities of each participant in the learning process

Appendix C - ABET Criteria for Accrediting Engineering Programs 2013-2014

2013-2014 Criteria for Accrediting Engineering Programs

Criterion 1. Students

Student performance must be evaluated. Student progress must be monitored to foster success in attaining student outcomes, thereby enabling graduates to attain program educational objectives. Students must be advised regarding curriculum and career matters.

The program must have and enforce policies for accepting both new and transfer students, awarding appropriate academic credit for courses taken at other institutions, and awarding appropriate academic credit for work in lieu of courses taken at the institution. The program must have and enforce procedures to ensure and document that students who graduate meet all graduation requirements.

Criterion 2. Program Educational Objectives

The program must have published program educational objectives that are consistent with the mission of the institution, the needs of the program's various constituencies, and these criteria. There must be a documented, systematically utilized, and effective process, involving program constituencies, for the periodic review of these program educational objectives that ensures they remain consistent with the institutional mission, the program's constituents' needs, and these criteria.

Criterion 3. Student Outcomes

The program must have documented student outcomes that prepare graduates to attain the program educational objectives.

Student outcomes are outcomes (a) through (k) plus any additional outcomes that may be articulated by the program.

(a) an ability to apply knowledge of mathematics, science, and engineering
(b) an ability to design and conduct experiments, as well as to analyze and interpret data
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
(d) an ability to function on multidisciplinary teams
(e) an ability to identify, formulate, and solve engineering problems
(f) an understanding of professional and ethical responsibility
(g) an ability to communicate effectively
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
(i) a recognition of the need for, and an ability to engage in life-long learning
(j) a knowledge of contemporary issues
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Appendix D - Axiomatic Design Primer

Design as a science

Designing is a central part of engineering. The goal of the designer is to create a design that fulfills the functional requirements of the customer with the least amount of iterations of the design. Suh's work at MIT continuing from the 1970's proposes that an optimal design may be reached by satisfying his two un-provable laws of design activity. No exceptions to the axioms are known to exist which are shown in Table 43 (Suh 1990):

Axiom 1 The Independence Axiom	Maintain the independence of functional requirements (FRs)
Axiom 2 The Information Axiom	Minimize the information content

Table 43 - The design axioms

A design equation and subsequent design matrix can be created that allows objective critique of both simple and complex structures and systems. The design matrix can be used to formally work through the elements of a production system and deduce its behavior while satisfying the conditions of the functional requirements.

Suh's Axiomatic Design Method

According to Suh, the axiomatic design method makes use of mapping of "what we want to achieve" into "how we want to achieve it" as shown in Figure 49 (2001).

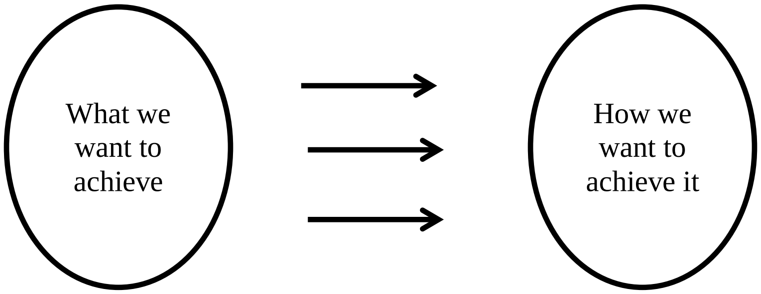


Figure 49 - Mapping of design goals into methods of how to achieve them

There are four domains in the design space. First, the needs of the customers, known as "CNs" are found and then translated into functional requirements "FRs" that fulfill these CNs. The FRs are then translated into design parameters, known as “DPs” that will fulfill the FRs. The last mapping is that of the DPs into process variables known as “PVs that fulfill the DPs shown in Figure 50 (Suh 1990).

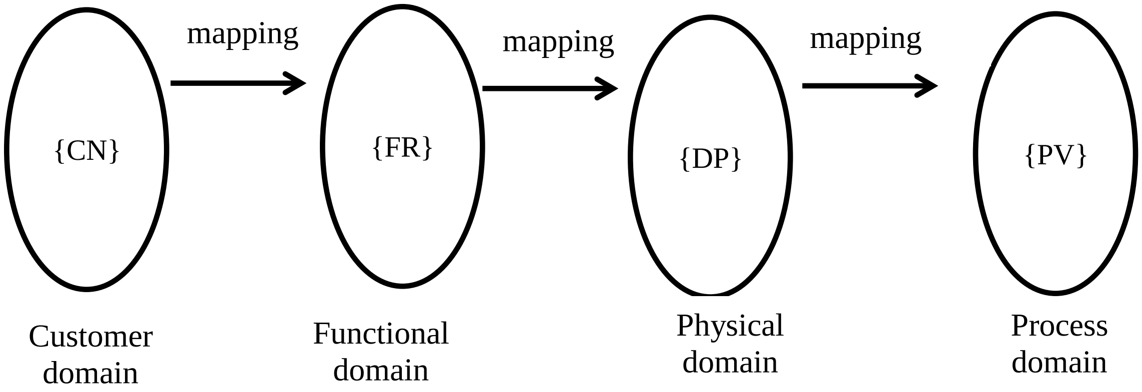


Figure 50 - Domains of the design space

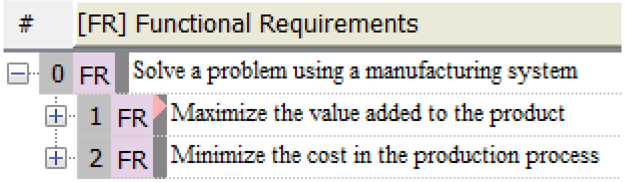
The mapping process results in a design matrix that may be optimized to achieve the design’s goals according to the design axioms. The design resulting design equation is of the form shown in Equation 21.

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \end{Bmatrix} = \begin{pmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{pmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \end{Bmatrix}$$

Equation 21 - Axiomatic design equation

Axiomatic design decomposition demands that the list of FRs satisfying the customer needs be collectively exhaustive, mutually exclusive and stated in a minimum form. This is to prevent the unnecessary duplication or overlapping of design requirements leading to redundancy in the design. The functional requirements are the foundation for the resulting design effort. As stated by Rasial in his book *The McKinsey Way*, McKinsey’s problem solving process has three major attributes: the solution will be 1) rigidly structured, 2) hypothesis driven, and 3) facts are friendly. The list of facts will be *mutually exclusive* and *collectively exhaustive* (1999). Additionally, the design axioms are also subject to additional theorems and corollaries that are described by Suh to further support an analysis.

The first step in applying the axiomatic design method to decomposing engineering education is to define a hypothesis or a theme for the decomposition. In the present case the goal is to design a new system for educating graduate engineers based on manufacturing engineering principles. Brown proposes that the most basic function of any manufacturing system is to maximize value to the customer and minimize the cost. Stated in a design matrix the decomposition begins with this premise shown in Figure 51 (2011b):



#	[FR] Functional Requirements
0 FR	Solve a problem using a manufacturing system
1 FR	Maximize the value added to the product
2 FR	Minimize the cost in the production process

Figure 51 - The top level FRs for understanding manufacturing engineering as a science

FR_1 and FR_2, and sometimes many more FRs, set the theme for the overall design decomposition.

Appendix E - Axiomatic Design Decomposition Output

Completed axiomatic design decomposition

The design decomposition on the following pages is based upon manufacturing engineering principles, capturing the proper FRs and corresponding DPs.

The FRs have metrics for evaluation on whether they are improving or not. The design system is transparent by retaining the design intent and it is able to be modified with new FRs if necessary.

Functional Requirements	FR Measurement
FR0: 'Manufacture' engineers (using ABET/MFE/IE principles, efficiently)	max %=Tuition Inc./Instruction Exp.
FR1: Maximize value added to engineering student's competence (Deming - PDCA Cycle)	max VA=NPV Sum Rt/(1+i)^t
FR1.1: Create an ability to apply knowledge of MATHEMATICS, SCIENCE & ENGINEERING ABET(a) (plan)	Assurance of Learning Results
FR1.1.1: Teach knowledge of mathematics, science, and engineering (do)	Assurance of Learning Results
FR1.1.2: Measure the ability to apply knowledge of math, science, & eng (check)	Assurance of Learning Results
FR1.1.3: Improve the ability to apply knowledge of math, science & eng (adjust)	Feedback Analysis Results
FR1.1.3.1: Improve a student's ability to apply knowledge of math, science & eng (adjust)	Rework Analysis Results
FR1.1.3.2: Improve the teaching system for knowledge of math, science & eng (adjust)	Kaizen Event Results
FR1.2: Create an ability to DESIGN/CONDUCT Experiments, ANALYZE/ INTERPRET DATA ABET(b) (plan)	Assurance of Learning Results
FR1.2.1: Teach how to design/conduct experiments, analyze/interpret data (do)	Assurance of Learning Results
FR1.2.2: Quality Assurance of the ability to design/conduct experiments, analyze/interpret data (check)	Assurance of Learning Results
FR1.2.3: Improve the ability to design/conduct experiments, analyze/interpret data (adjust)	Feedback Analysis Results
FR1.2.3.1: Improve a student's ability to design/conduct experiments, analyze/interpret data	Rework Analysis Results
FR1.2.3.2: Improve the teaching of design/conduct experiments, analyze/interpret data	Kaizen Event Results
FR1.3: Create an ability to DESIGN a system, component, process w/ realistic constraints ABET(c) (plan)	Assurance of Learning Results
FR1.3.1: Teach how to design a system, component, or process w/ realistic constraints (do)	Assurance of Learning Results
FR1.3.2: Quality Assurance of the ability to design a system, component, or process w/ constraints (check)	Assurance of Learning Results
FR1.3.3: Improve an ability to design a system, component, or process w/ realistic constraints ABET(adjust)	Feedback Analysis Results
FR1.3.3.1: Improve a student's ability to design a system, component, or process w/ constraints (adjust)	Rework Analysis Results
FR1.3.3.2: Improve the teaching system for design a system, component, or process w/ constraints (adjust)	Kaizen Event Results
FR1.4: Create an ability to function on Multidisciplinary TEAMS ABET (d) (plan)	Assurance of Learning Results
FR1.4.1: Teach how to function on multidisciplinary teams (do)	Assurance of Learning Results
FR1.4.2: Verify how to function on multidisciplinary teams (check)	Assurance of Learning Results
FR1.4.3: Improve the ability to function on multidisciplinary teams (adjust)	Feedback Analysis Results
FR1.4.3.1: Improve a student's ability to function on multidisciplinary teams	Rework Analysis Results
FR1.4.3.2: Improve the teaching system for functioning on multidisciplinary teams	Kaizen Event Results
FR1.5: Create an ability to identify, formulate & SOLVE ENGINEERING PROBLEMS ABET(e) (plan)	Assurance of Learning Results
FR1.5.1: Teach the ability to identify, formulate, and solve engineering problems (do)	Assurance of Learning Results
FR1.5.2: Quality Assurance of the ability to identify, formulate & solve eng problems (check)	Assurance of Learning Results
FR1.5.3: Improve the ability to identify, formulate & solve engineering problems (adjust)	Feedback Analysis Results
FR1.5.3.1: Improve an ability to identify, formulate & solve engineering problems (adjust)	Rework Analysis Results
FR1.5.3.2: Improve the teaching system to identify, formulate & solve eng problems (adjust)	Kaizen Event Results
FR1.6: Create an understanding of professional & ETHICAL RESPONSIBILITY ABET(f) (plan)	Assurance of Learning Results
FR1.6.1: Teach an understanding of professional and ethical responsibility (do)	Assurance of Learning Results
FR1.6.2: Verify the understanding of professional and ethical responsibility (check)	Assurance of Learning Results
FR1.6.3: Improve the teaching system for understanding of professional and ethical responsibility (adjust)	Feedback Analysis Results
FR1.6.3.1: Improve a student's understanding of professional and ethical responsibility	Rework Analysis Results
FR1.6.3.2: Improve the teaching system for understanding of professional and ethical responsibility	Kaizen Event Results
FR1.7: Create an ability to COMMUNICATE EFFECTIVELY ABET(g) (plan)	Assurance of Learning Results
FR1.7.1: Teach how to communicate effectively (do)	Assurance of Learning Results
FR1.7.2: Verify the ability to communicate effectively (check)	Assurance of Learning Results
FR1.7.3: Improve the teaching system for communicating effectively (adjust)	Feedback Analysis Results
FR1.7.3.1: Improve a student's ability to communicate effectively (adjust)	Rework Analysis Results
FR1.7.3.2: Improve the teaching system for communicating effectively (adjust)	Kaizen Event Results
FR1.8: Create an understanding of eng. on GLOBAL IMPACT, economic, environ'l, soc'l context ABET(h) (plan)	Assurance of Learning Results
FR1.8.1: Teach an understanding of the impact of engineering solutions (do)	Assurance of Learning Results
FR1.8.2: Verify an understanding of the impact of engineering solutions (check)	Assurance of Learning Results
FR1.8.3: Improve an understanding of the impact of engineering solutions (adjust)	Feedback Analysis Results
FR1.8.3.1: Improve a student's understanding of the impact of engineering solutions (adjust)	Rework Analysis Results
FR1.8.3.2: Improve the teaching system for understanding of the impact of engineering solutions (adjust)	Kaizen Event Results
FR1.9: Create a recognition of the need for & an ability to engage in LIFE-LONG LEARNING ABET(i) (plan)	Assurance of Learning Results
FR1.9.1: Teach the recognition and ability to engage in life-long learning (do)	Assurance of Learning Results
FR1.9.2: Quality Assurance of the recognition and an ability to engage in life-long learning (check)	Assurance of Learning Results
FR1.9.3: Improve the teaching system for the recognition of life-long learning (adjust)	Feedback Analysis Results
FR1.9.3.1: Improve a student's recognition of an ability to engage in life-long learning (do)	Rework Analysis Results
FR1.9.3.2: Improve the teaching system for the ability for in life-long learning (do)	Kaizen Event Results
FR1.10: Create a knowledge of CONTEMPORARY TEAMS ABET(j) (plan)	Assurance of Learning Results
FR1.10.1: Teach about contemporary teams ABET(do)	Assurance of Learning Results
FR1.10.2: Quality Assurance of the knowledge of contemporary teams ABET(check)	Assurance of Learning Results
FR1.10.3: Improve the knowledge of contemporary teams (adjust)	Feedback Analysis Results
FR1.10.3.1: Improve a student's knowledge of contemporary teams(adjust)	Rework Analysis Results
FR1.10.3.2: Improve the teaching system for contemporary teams (adjust)	Kaizen Event Results
FR1.11: Create an ability to use the techniques, skills, & eng. tools for ENGINEERING PRACTICE ABET(k) (plan)	Assurance of Learning Results
FR1.11.1: Teach the techniques, skills, and modern engineering tools necessary for engineering practice (do)	Assurance of Learning Results
FR1.11.2: Verify the ability to use techniques, skills, and modern engineering tools necessary for engineering	Assurance of Learning Results
FR1.11.3: Improve the ability to use techniques, skills, and modern engineering tools necessary for engineering	Feedback Analysis Results
FR1.11.3.1: Improve a student's ability to use techniques for engineering practice (adjust)	Rework Analysis Results
FR1.11.3.2: Improve the teaching system for using techniques for engineering practice (adjust)	Kaizen Event Results

Table 44 - Initial decomposition (does not comply with Axiom One) FR_0 through $FR_{1.11}$

FR Measurement	Design Parameters				
max %=Tuition Inc./Instruction Exp.	DP0: System for 'manufacturing' ABET engineers (engineering school)				
max VA=NPV Sum Rt/(1+i)^t		DP1: Function that maximizes value added to engineering student's competence (Time Value of Money Function)			
Assurance of Learning Results			DP1.1: System for creating knowledge of math, science & eng (learning activity mngt syst)		
Assurance of Learning Results				DP1.1.1: System for teaching math, science, & eng (learning activity)	
Assurance of Learning Results				DP1.1.2: System for measuring the ability to apply math, science, & eng (inspection/grading)	
Feedback Analysis Results				DP1.1.3: System for improving the ability to apply math, science, & eng (feedback system)	
Rework Analysis Results					DP1.1.3.1: System for reworking a student's ability to apply math, science, and eng (rework)
Kaizen Event Results					DP1.1.3.2: System for redesigning the teaching system of math, science, and eng (Kaizen event)
Assurance of Learning Results			DP1.2: System for creating how to design/conduct experiments (learning activity mngt syst)		
Assurance of Learning Results				DP1.2.1: System for teaching how to design/conduct experiments, analyze/interpret data (learning activity)	
Assurance of Learning Results				DP1.2.2: System for measuring the ability to design/conduct experiments, analyze/interpret data (inspection/grading)	
Feedback Analysis Results				DP1.2.3: System for improving the ability to design/conduct experiments, analyze/interpret data (feedback system)	
Rework Analysis Results					DP1.2.3.1: System for improving a student's ability to design/conduct experiments, analyze/interpret data (rework)
Kaizen Event Results					DP1.2.3.2: System for improving the teaching of design/conduct experiments, analyze/interpret data (Kaizen event)
Assurance of Learning Results			DP1.3: System for creating the ability to design w/ constraints (learning activity mngt syst))		
Assurance of Learning Results				DP1.3.1: System for teaching how to design a system, w/constraints (learning activity)	
Assurance of Learning Results				DP1.3.2: System for measuring the ability to design a system, w/ constraints (inspection/grading)	
Feedback Analysis Results				DP1.3.3: System for reworking the ability to design a system w/ constraints (feedback system)	
Rework Analysis Results					DP1.3.3.1: System for improving a student's ability to design a system w/ constraints (rework)
Kaizen Event Results					DP1.3.3.2: System for redesigning the teaching of designing a system w/ constraints (Kaizen event)
Assurance of Learning Results			DP1.4: System for creating the ability to function on multi-teams (learning activity mngt syst)		
Assurance of Learning Results				DP1.4.1: System for teaching how to function on multidisciplinary teams (learning activity)	
Assurance of Learning Results				DP1.4.2: System for measuring how to function on multidisciplinary teams (inspection/grading)	
Feedback Analysis Results				DP1.4.3: System for improving the ability to function on multi-teams (feedback system)	
Rework Analysis Results					DP1.4.3.1: System for improving a student's ability to function on multi-teams (rework)
Kaizen Event Results					DP1.4.3.2: System for redesigning the teaching system for how to function on multi-teams (Kaizen event)
Assurance of Learning Results			DP1.5: System for creating the ability to identify, formulate, solve eng probs (learning activity mngt syst)		
Assurance of Learning Results				DP1.5.1: System for teaching the ability to identify, formulate & solve eng problems (learning activity)	
Assurance of Learning Results				DP1.5.2: System for measuring the ability to identify, formulate & solve eng problems (inspection/grading)	
Feedback Analysis Results				DP1.5.3: System for improving the ability to identify, formulate & solve eng problems (feedback system)	
Rework Analysis Results					DP1.5.3.1: System for improving a student's ability to identify, formulate & solve eng problems (rework)
Kaizen Event Results					DP1.5.3.2: System for redesigning the teaching system to identify, formulate & solve eng problems (Kaizen event)
Assurance of Learning Results			DP1.6: System for creating the understanding professional/ethical responsibility (learning activity mngt syst)		
Assurance of Learning Results				DP1.6.1: System for teaching an understanding of professional/ethical responsibility (learning activity)	
Assurance of Learning Results				DP1.6.2: System for measuring the understanding of professional/ethical responsibility (inspection/grading)	
Feedback Analysis Results				DP1.6.3: System for improving the teaching system of professional/ethical responsibility (feedback syst)	
Rework Analysis Results					DP1.6.3.1: System for improving a student's understanding of professional/ethical responsibility (rework)
Kaizen Event Results					DP1.6.3.2: System for redesigning the teaching system of professional /ethical responsibility (Kaizen)
Assurance of Learning Results			DP1.7: System for creating the ability to communicate effectively (learning activity mngt syst)		
Assurance of Learning Results				DP1.7.1: System for teaching how to communicate effectively (learning activity)	
Assurance of Learning Results				DP1.7.2: System for measuring the ability to communicate effectively (inspection/grading)	
Feedback Analysis Results				DP1.7.3: System for improving the ability for communicating effectively (feedback system)	
Rework Analysis Results					DP1.7.3.1: System for improving a student's ability to communicate effectively (rework)
Kaizen Event Results					DP1.7.3.2: System for improving the teaching system for communicating effectively (Kaizen)
Assurance of Learning Results			DP1.8: System for creating an understanding of impact eng global context (learning activity mngt syst)		
Assurance of Learning Results				DP1.8.1: System for teaching an understanding of the impact of engineering solutions (learning activity)	
Assurance of Learning Results				DP1.8.2: System for measuring an understanding of the impact of engineering solutions (inspections/grading)	
Feedback Analysis Results				DP1.8.3: System for reworking an understanding of the impact of engineering solutions (feedback syst)	
Rework Analysis Results					DP1.8.3.1: System for improving a student's understanding of the impact of engineering solutions (rework)
Kaizen Event Results					DP1.8.3.2: System for improving the teaching of the impact of engineering solutions (Kaizen event)
Assurance of Learning Results			DP1.9: System for creating recognition of need & ability life-long learning (learning activity mngt syst)		
Assurance of Learning Results				DP1.9.1: System for teaching the recognition and ability to engage in life-long learning (learning activity)	
Assurance of Learning Results				DP1.9.2: System for measuring the recognition and ability to engage in life-long learning (inspection/grading)	
Feedback Analysis Results				DP1.9.3: System for improving the teaching of the need for and ability to engage in life-long learning	
Rework Analysis Results					DP1.9.3.1: System for improving a student's recognition and ability to engage in life-long learning (rework)
Kaizen Event Results					DP1.9.3.2: System for improving the teaching of the need and ability to engage in life-long learning (Kaizen event)
Assurance of Learning Results			DP1.10: System for creating knowledge of contemporary teams (learning activity mngt syst)		
Assurance of Learning Results				DP1.10.1: System for teaching about contemporary teams ABET (learning activity)	
Assurance of Learning Results				DP1.10.2: System for measuring the knowledge of contemporary teams (inspection/grading)	
Feedback Analysis Results				DP1.10.3: System for improving the knowledge of contemporary teams (feedback system)	
Rework Analysis Results					DP1.10.3.1: System for improving a student's knowledge of contemporary teams (rework)
Kaizen Event Results					DP1.10.3.2: System for improving the teaching system for contemporary teams (Kaizen event)
Assurance of Learning Results			DP1.11: System for creating the ability to use techniques for eng practice (learning activity mngt syst)		
Assurance of Learning Results				DP1.11.1: System for teaching the techniques for engineering practice (learning activity)	
Assurance of Learning Results				DP1.11.2: System for measuring the ability to use techniques for engineering practice (inspection/grading)	
Feedback Analysis Results				DP1.11.3: System for improving the ability to use techniques engineering practice	
Rework Analysis Results					DP1.11.3.1: System for improving a student's ability to use techniques for engineering practice (rework)
Kaizen Event Results					DP1.11.3.2: System for improving the teaching of techniques for engineering practice (Kaizen)

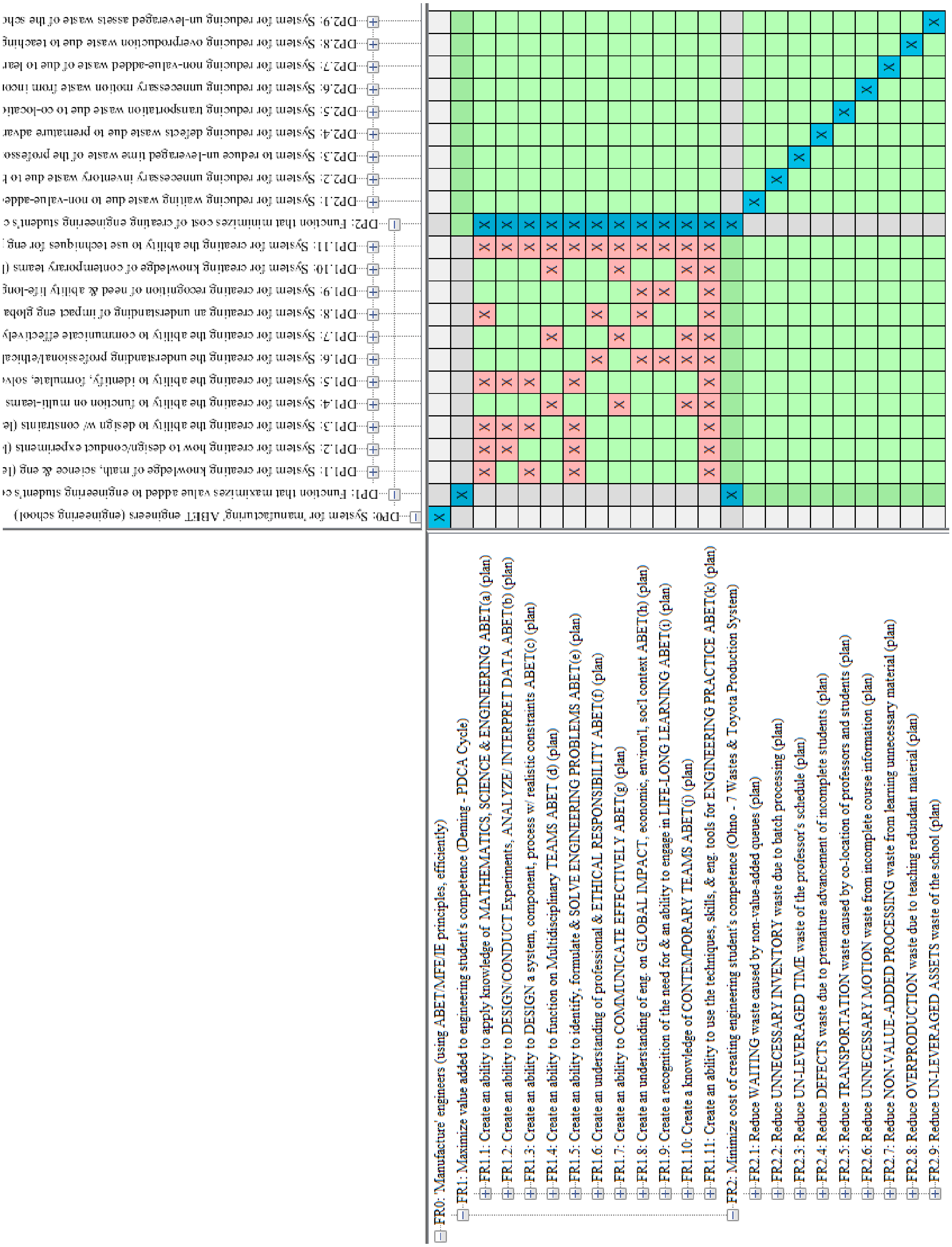
Table 45 - Initial decomposition (does not comply with Axiom One) DP$_0$ through DP$_{1.11}$

FR2: Minimize cost of creating engineering student's competence (Ohno - 7 Wastes & Toyota Production System)	min Total Instruction Expense
FR2.1: Reduce WAITING waste caused by non-value-added queues (plan)	min W=I/L
FR2.1.1: Identify waste due to waiting in non-value-added queues (do)	Student's Value Stream Map
FR2.1.2: Measure waste due to waiting in non-value added queues (check)	Student's Value Stream Map
FR2.1.3: Improve waste due to waiting in non-value-added queues (adjust)	Kaizen Event Results
FR2.2: Reduce UNNECESSARY INVENTORY waste due to batch processing (plan)	One-Piece-Flow Analysis
FR2.2.1: Identify UNNECESSARY INVENTORY waste due to batch processing (do)	One Piece Flow Analysis
FR2.2.2: Measure UNNECESSARY INVENTORY waste due to batch processing (check)	One Piece Flow Analysis
FR2.2.3: Improve UNNECESSARY INVENTORY waste due to batch processing (adjust)	Kaizen Event Results
FR2.3: Reduce UN-LEVERAGED TIME waste of the professor's schedule (plan)	Professor's Value Stream Map
FR2.3.1: Identify waste of UN-LEVERAGED TIME of the professors time (do)	Professor's Value Stream Map
FR2.3.2: Measure waste of UN-LEVERAGED TIME of the professors time (check)	Professor's Value Stream Map
FR2.3.3: Improve waste of UN-LEVERAGED TIME of the professors time (adjust)	Kaizen Event Results
FR2.4: Reduce DEFECTS waste due to premature advancement of incomplete students (plan)	Intra Course Progress Exams
FR2.4.1: Identify waste of defects due to premature advancement of incomplete students (do)	Assurance of Learning Results
FR2.4.2: Measure waste of defects due to premature advancement of incomplete students (check)	Assurance of Learning Results
FR2.4.3: Improve waste of defects due to premature advancement of incomplete students (adjust)	Kaizen Event Results
FR2.5: Reduce TRANSPORTATION waste caused by co-location of professors and students (plan)	Occupancy Ratio virtual/physical
FR2.5.1: Identify co-location caused transportation waste (do)	Asset Inventory Coordination
FR2.5.2: Measure co-location caused transportation waste (check)	Asset Inventory Coordination
FR2.5.3: Improve co-location caused transportation waste removal process (adjust)	Kaizen Event Results
FR2.6: Reduce UNNECESSARY MOTION waste from incomplete course information (plan)	Concept Inventory Coordination
FR2.6.1: Identify waste of unnecessary motion from incomplete course information (do)	Assurance of Learning Results
FR2.6.2: Measure waste of unnecessary motion from incomplete course information (check)	Assurance of Learning Results
FR2.6.3: Improve waste of unnecessary motion from incomplete course information (adjust)	Kaizen Event Results
FR2.7: Reduce NON-VALUE-ADDED PROCESSING waste from learning unnecessary material (plan)	Concept Inventory Coordination
FR2.7.1: Identify waste of NON-VALUE-ADDED PROCESSING from learning unnecessary material (do)	Concept Inventory Coordination
FR2.7.2: Measure waste of NON-VALUE-ADDED PROCESSING from learning unnecessary material (check)	Concept Inventory Coordination
FR2.7.3: Improve waste of NON-VALUE-ADDED PROCESSING from learning unnecessary material (adjust)	Kaizen Event Results
FR2.8: Reduce OVERPRODUCTION waste due to teaching redundant material (plan)	Concept Inventory Coordination
FR2.8.1: Identify redundant academic material (plan)	Concept Inventory Coordination
FR2.8.2: Measure redundant academic material (check)	Concept Inventory Coordination
FR2.8.3: Improve redundant academic material content (adjust)	Kaizen Event Results
FR2.9: Reduce UN-LEVERAGED ASSETS waste of the school (plan)	Capacity Analysis
FR2.9.1: Identify waste due to un-leveraged assets of the school (do)	Asset Inventory Coordination
FR2.9.2: Measure waste due to un-leveraged assets of the school (check)	Asset Inventory Coordination
FR2.9.3: Improve waste due to un-leveraged assets of the school (adjust)	Kaizen Event Results

Table 46 - Initial decomposition (does not comply with Axiom One) FR$_{2.1}$ through FR$_{2.9}$

DP2: Function that minimizes cost of creating engineering student's competence (Total Cost Equation)		
	DP2.1: System for reducing waiting waste due to non-value-added queues (student paced learning system)	
		DP2.1.1: System for Identifying waste due to waiting in non-value-added queues (course value stream map)
		DP2.1.2: System for measuring waste due to waiting in non-value added queues (course value stream map)
		DP2.1.3: System for improving waste due to waiting in non-value-added queues (course planning)
	DP2.2: System for reducing unnecessary inventory waste due to batch processing (production management system)	
		DP2.2.1: System for Identifying UNNECESSARY INVENTORY waste due to batch processing (production management system)
		DP2.2.2: System for measuring UNNECESSARY INVENTORY waste due to batch processing (production management system)
		DP2.2.3: System for Improving UNNECESSARY INVENTORY waste due to batch processing (Kaizen event)
	DP2.3: System to reduce un-leveraged time waste of the professors schedule (time buffers)	
		DP2.3.1: System to identify waste of UN-LEVERAGED TIME of the professors time (student support system)
		DP2.3.2: System to measure waste of UN-LEVERAGED TIME of the professors time (lean accounting)
		DP2.3.3: System to Improve waste of UN-LEVERAGED TIME of the professors time (student support system)
	DP2.4: System for reducing defects waste due to premature advancement of students (frequent gated assessments)	
		DP2.4.1: System to identify waste of defects due to premature advancement of incomplete students (frequent gated assessments)
		DP2.4.2: System to measure waste of defects due to premature advancement of incomplete students (frequent gated assessments)
		DP2.4.3: system to improve waste of defects due to premature advancement of incomplete students (assessment management system)
	DP2.5: System for reducing transportation waste due to co-location of professors and students (virtual content delivery)	
		DP2.5.1: System to identify co-location caused transportation waste (room schedule)
		DP2.5.2: System to measure co-location caused transportation waste (room schedule)
		DP2.5.3: System to improve the co-location caused transportation waste removal process (course planning)
	DP2.6: System for reducing unnecessary motion waste from incomplete course information (course content management)	
		DP2.6.1: System to identify waste of unnecessary motion from incomplete course information (course content management system)
		DP2.6.2: System to measure waste of unnecessary motion from incomplete course information (course management system)
		DP2.6.3: System to improve waste of unnecessary motion from incomplete course information (course management system)
	DP2.7: System for reducing non-value-added waste of due to learning unnecessary material (course content management system)	
		DP2.7.1: System for identifying waste of NON-VALUE-ADDED PROCESSING from learning unnecessary material (course content mgnt syst.)
		DP2.7.2: System to measure waste of NON-VALUE-ADDED PROCESSING from learning unnecessary material (lean accounting)
		DP2.7.3: System to improve waste of NON-VALUE-ADDED PROCESSING from learning unnecessary material (course content system)
	DP2.8: System for reducing overproduction waste due to teaching redundant materials (course content coordination)	
		DP2.8.1: System for identifying redundant academic material (course content coordination)
		DP2.8.2: System for measuring redundant academic material (course content coordination)
		DP2.8.3: System for improve redundant academic material content management (course content coordination)
	DP2.9: System for reducing un-leveraged assets waste of the school (asset inventory coordination)	
		DP2.9.1: System for identifying waste due to un-leveraged assets of the school (asset inventory coordination)
		DP2.9.2: System for measuring waste due to un-leveraged assets of the school (asset inventory coordination)
		DP2.9.3: System for improving waste due to un-leveraged assets of the school (Kaizen event)

Table 47 - Initial decomposition (does not comply with Axiom One) $DP_{2.1}$ through $DP_{2.9}$



DP0: System for 'manufacturing' ABET engineers (engineering school)
DP1: Function that maximizes value added to engineering student's co
DP1.1: System for creating knowledge of math, science & eng (le
DP1.2: System for creating how to design/conduct experiments (l
DP1.3: System for creating the ability to design w/ constraints (le
DP1.4: System for creating the ability to function on multi-teams
DP1.5: System for creating the ability to identify, formulate, solv
DP1.6: System for creating the understanding professional/ethical
DP1.7: System for creating the ability to communicate effectively
DP1.8: System for creating an understanding of impact eng globa
DP1.9: System for creating recognition of need & ability life-long
DP1.10: System for creating knowledge of contemporary teams (l
DP1.11: System for creating the ability to use techniques for eng
DP2: Function that minimizes cost of creating engineering student's c
DP2.1: System for reducing waiting waste due to non-value-adde
DP2.2: System for reducing unnecessary inventory waste due to l
DP2.3: System to reduce un-leveraged time waste of the professo
DP2.4: System for reducing defects waste due to premature advar
DP2.5: System for reducing transportation waste due to co-locatio
DP2.6: System for reducing unnecessary motion waste from incor
DP2.7: System for reducing non-value-added waste of due to lear
DP2.8: System for reducing overproduction waste due to teaching
DP2.9: System for reducing un-leveraged assets waste of the scho

	DP0	DP1	DP1.1	DP1.2	DP1.3	DP1.4	DP1.5	DP1.6	DP1.7	DP1.8	DP1.9	DP1.10	DP1.11	DP2	DP2.1	DP2.2	DP2.3	DP2.4	DP2.5	DP2.6	DP2.7	DP2.8	DP2.9
FR0: 'Manufacture' engineers (using ABET/MFE/IE principles, efficiently)	X																						
FR1: Maximize value added to engineering student's competence (Deming - PDCA Cycle)		X																					
FR1.1: Create an ability to apply knowledge of MATHEMATICS, SCIENCE & ENGINEERING ABET(a) (plan)			X	X	X		X			X			X	X									
FR1.2: Create an ability to DESIGN/CONDUCT Experiments, ANALYZE/ INTERPRET DATA ABET(b) (plan)				X	X		X						X	X									
FR1.3: Create an ability to DESIGN a system, component, process w/ realistic constraints ABET(c) (plan)			X		X		X						X	X									
FR1.4: Create an ability to function on Multidisciplinary TEAMS ABET (d) (plan)						X			X			X	X	X									
FR1.5: Create an ability to identify, formulate & SOLVE ENGINEERING PROBLEMS ABET(e) (plan)			X	X	X		X						X	X									
FR1.6: Create an understanding of professional & ETHICAL RESPONSIBILITY ABET(f) (plan)								X		X			X	X									
FR1.7: Create an ability to COMMUNICATE EFFECTIVELY ABET(g) (plan)						X			X			X	X	X									
FR1.8: Create an understanding of eng. on GLOBAL IMPACT, economic, environ'l, soc'l context ABET(h) (plan)								X		X	X		X	X									
FR1.9: Create a recognition of the need for & an ability to engage in LIFE-LONG LEARNING ABET(i) (plan)								X			X		X	X									
FR1.10: Create a knowledge of CONTEMPORARY TEAMS ABET(j) (plan)						X		X	X			X	X	X									
FR1.11: Create an ability to use the techniques, skills, & eng. tools for ENGINEERING PRACTICE ABET(k) (plan)			X	X	X	X	X	X	X	X	X	X	X	X									
FR2: Minimize cost of creating engineering student's competence (Ohno - 7 Wastes & Toyota Production System)		X												X									
FR2.1: Reduce WAITING waste caused by non-value-added queues (plan)															X								
FR2.2: Reduce UNNECESSARY INVENTORY waste due to batch processing (plan)																X							
FR2.3: Reduce UN-LEVERAGED TIME waste of the professor's schedule (plan)																	X						
FR2.4: Reduce DEFECTS waste due to premature advancement of incomplete students (plan)																		X					
FR2.5: Reduce TRANSPORTATION waste caused by co-location of professors and students (plan)																			X				
FR2.6: Reduce UNNECESSARY MOTION waste from incomplete course information (plan)																				X			
FR2.7: Reduce NON-VALUE-ADDED PROCESSING waste from learning unnecessary material (plan)																					X		
FR2.8: Reduce OVERPRODUCTION waste due to teaching redundant material (plan)																						X	
FR2.9: Reduce UN-LEVERAGED ASSETS waste of the school (plan)																							X

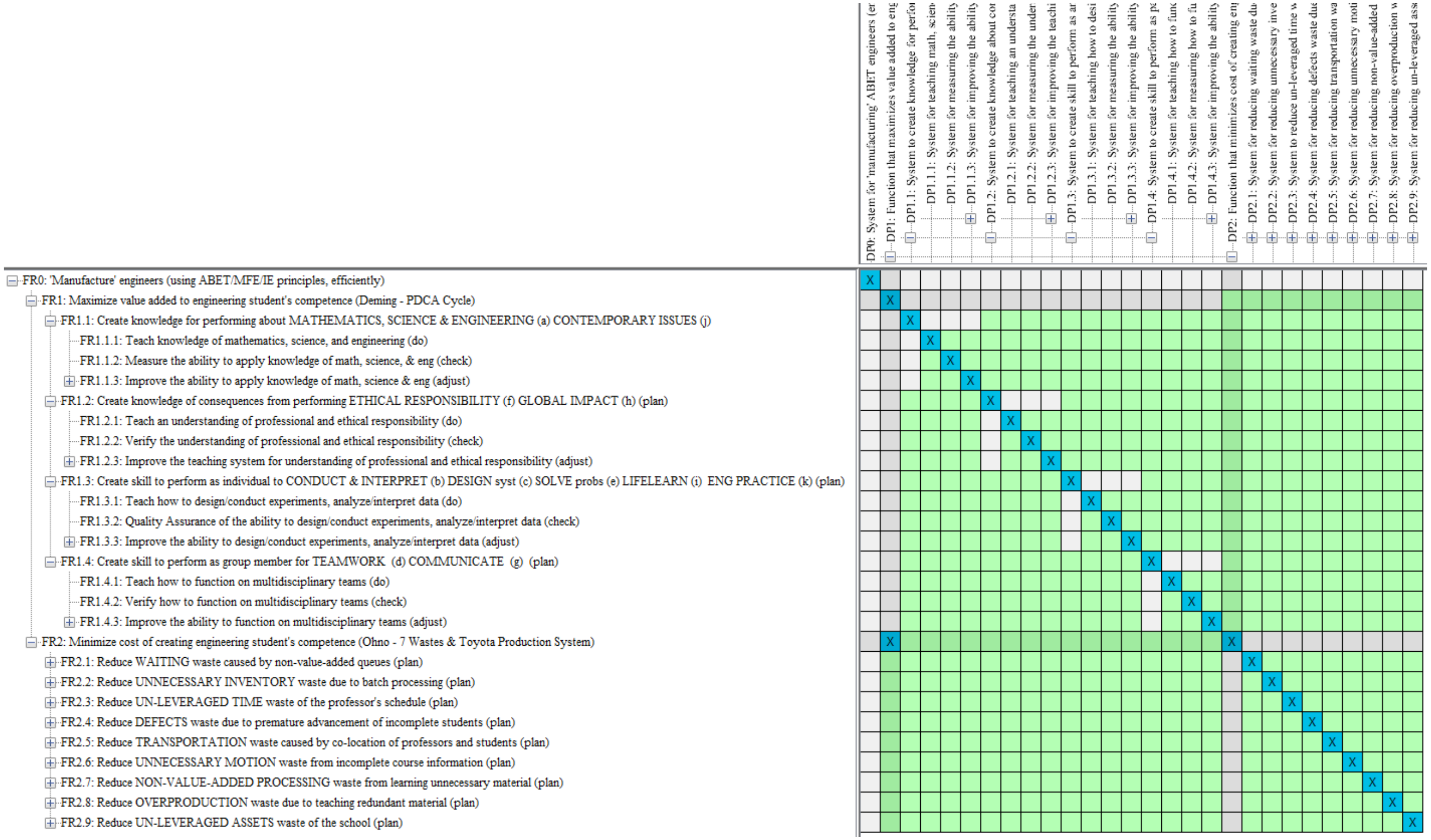
Figure 52 - Initial decomposition upper level design matrix (does not comply with Axiom One)

Functional Requirements	FR Measurement
FR0: 'Manufacture' engineers (using ABET/MFE/IE principles, efficiently)	max %=Tuition Inc./Instruction Exp.
FR1: Maximize value added to engineering student's competence (Deming - PDCA Cycle)	max VA=NPV Sum Rt/(1+i)^t
FR1.1: Create knowledge for performing about MATHEMATICS, SCIENCE & ENGINEERING (a) CONTEMPORARY ISSUES (j)	Assurance of Learning Results
FR1.1.1: Teach knowledge of mathematics, science, and engineering (do)	Assurance of Learning Results
FR1.1.2: Measure the ability to apply knowledge of math, science, & eng (check)	Assurance of Learning Results
FR1.1.3: Improve the ability to apply knowledge of math, science & eng (adjust)	Feedback Analysis Results
FR1.1.3.1: Improve a student's ability to apply knowledge of math, science & eng (adjust)	Rework Analysis Results
FR1.1.3.2: Improve the teaching system for knowledge of math, science & eng (adjust)	Kaizen Event Results
FR1.2: Create knowledge of consequences from performing ETHICAL RESPONSIBILITY (f) GLOBAL IMPACT (h) (plan)	Assurance of Learning Results
FR1.2.1: Teach an understanding of professional and ethical responsibility (do)	Assurance of Learning Results
FR1.2.2: Verify the understanding of professional and ethical responsibility (check)	Assurance of Learning Results
FR1.2.3: Improve the teaching system for understanding of professional and ethical responsibility (adjust)	Feedback Analysis Results
FR1.2.3.1: Improve a student's understanding of professional and ethical responsibility	Rework Analysis Results
FR1.2.3.2: Improve the teaching system for understanding of professional and ethical responsibility	Kaizen Event Results
FR1.3: Create skill to perform as individual to CONDUCT & INTERPRET (b) DESIGN syst (c) SOLVE probs (e) LIFELEARN (i) ENG PRACTICE (k) (plan)	Assurance of Learning Results
FR1.3.1: Teach how to design/conduct experiments, analyze/interpret data (do)	Assurance of Learning Results
FR1.3.2: Quality Assurance of the ability to design/conduct experiments, analyze/interpret data (check)	Assurance of Learning Results
FR1.3.3: Improve the ability to design/conduct experiments, analyze/interpret data (adjust)	Feedback Analysis Results
FR1.3.3.1: Improve a student's ability to design/conduct experiments, analyze/interpret data	Rework Analysis Results
FR1.3.3.2: Improve the teaching of design/conduct experiments, analyze/interpret data	Kaizen Event Results
FR1.4: Create skill to perform as group member for TEAMWORK (d) COMMUNICATE (g) (plan)	Assurance of Learning Results
FR1.4.1: Teach how to function on multidisciplinary teams (do)	Assurance of Learning Results
FR1.4.2: Verify how to function on multidisciplinary teams (check)	Assurance of Learning Results
FR1.4.3: Improve the ability to function on multidisciplinary teams (adjust)	Feedback Analysis Results
FR1.4.3.1: Improve a student's ability to function on multidisciplinary teams	Rework Analysis Results
FR1.4.3.2: Improve the teaching system for functioning on multidisciplinary teams	Kaizen Event Results
FR2: Minimize cost of creating engineering student's competence (Ohno - 7 Wastes & Toyota Production System)	min Total Instruction Expense
FR2.1: Reduce WAITING waste caused by non-value-added queues (plan)	min W=I/L
FR2.1.1: Identify waste due to waiting in non-value-added queues (do)	Student's Value Stream Map
FR2.1.2: Measure waste due to waiting in non-value added queues (check)	Student's Value Stream Map
FR2.1.3: Improve waste due to waiting in non-value-added queues (adjust)	Kaizen Event Results
FR2.2: Reduce UNNECESSARY INVENTORY waste due to batch processing (plan)	One-Piece-Flow Analysis
FR2.2.1: Identify UNNECESSARY INVENTORY waste due to batch processing (do)	One Piece Flow Analysis
FR2.2.2: Measure UNNECESSARY INVENTORY waste due to batch processing (check)	One Piece Flow Analysis
FR2.2.3: Improve UNNECESSARY INVENTORY waste due to batch processing (adjust)	Kaizen Event Results
FR2.3: Reduce UN-LEVERAGED TIME waste of the professor's schedule (plan)	Professor's Value Stream Map
FR2.3.1: Identify waste of UN-LEVERAGED TIME of the professors time (do)	Professor's Value Stream Map
FR2.3.2: Measure waste of UN-LEVERAGED TIME of the professors time (check)	Professor's Value Stream Map
FR2.3.3: Improve waste of UN-LEVERAGED TIME of the professors time (adjust)	Kaizen Event Results
FR2.4: Reduce DEFECTS waste due to premature advancement of incomplete students (plan)	Intra Course Progress Exams
FR2.4.1: Identify waste of defects due to premature advancement of incomplete students (do)	Assurance of Learning Results
FR2.4.2: Measure waste of defects due to premature advancement of incomplete students (check)	Assurance of Learning Results
FR2.4.3: Improve waste of defects due to premature advancement of incomplete students (adjust)	Kaizen Event Results
FR2.5: Reduce TRANSPORTATION waste caused by co-location of professors and students (plan)	Occupancy Ratio virtual/physical
FR2.5.1: Identify co-location caused transportation waste (do)	Asset Inventory Coordination
FR2.5.2: Measure co-location caused transportation waste (check)	Asset Inventory Coordination
FR2.5.3: Improve co-location caused transportation waste removal process (adjust)	Kaizen Event Results
FR2.6: Reduce UNNECESSARY MOTION waste from incomplete course information (plan)	Concept Inventory Coordination
FR2.6.1: Identify waste of unnecessary motion from incomplete course information (do)	Assurance of Learning Results
FR2.6.2: Measure waste of unnecessary motion from incomplete course information (check)	Assurance of Learning Results
FR2.6.3: Improve waste of unnecessary motion from incomplete course information (adjust)	Kaizen Event Results
FR2.7: Reduce NON-VALUE-ADDED PROCESSING waste from learning unnecessary material (plan)	Concept Inventory Coordination
FR2.7.1: Identify waste of NON-VALUE-ADDED PROCESSING from learning unnecessary material (do)	Concept Inventory Coordination
FR2.7.2: Measure waste of NON-VALUE-ADDED PROCESSING from learning unnecessary material (check)	Concept Inventory Coordination
FR2.7.3: Improve waste of NON-VALUE-ADDED PROCESSING from learning unnecessary material (adjust)	Kaizen Event Results
FR2.8: Reduce OVERPRODUCTION waste due to teaching redundant material (plan)	Concept Inventory Coordination
FR2.8.1: Identify redundant academic material (plan)	Concept Inventory Coordination
FR2.8.2: Measure redundant academic material (check)	Concept Inventory Coordination
FR2.8.3: Improve redundant academic material content (adjust)	Kaizen Event Results
FR2.9: Reduce UN-LEVERAGED ASSETS waste of the school (plan)	Capacity Analysis
FR2.9.1: Identify waste due to un-leveraged assets of the school (do)	Asset Inventory Coordination
FR2.9.2: Measure waste due to un-leveraged assets of the school (check)	Asset Inventory Coordination
FR2.9.3: Improve waste due to un-leveraged assets of the school (adjust)	Kaizen Event Results

Table 48 - Second decomposition (complies with Axiom One) FR$_{1.1}$ through FR$_{2.9}$

FR Measurement	Design Parameters				
max %=Tuition Inc./Instruction Exp.	DP0: System for 'manufacturing' ABET engineers (engineering school)				
max VA=NPV Sum Rt/(1+i)^t		DP1: Function that maximizes value added to engineering student's competence (Time Value of Money Function)			
Assurance of Learning Results			DP1.1: System to create knowledge for performing about MATHEMATICS, SCIENCE & ENGINEERING (a)		
Assurance of Learning Results				DP1.1.1: System for teaching math, science, & eng (learning activity)	
Assurance of Learning Results				DP1.1.2: System for measuring the ability to apply math, science, & eng (inspection/grading)	
Feedback Analysis Results				DP1.1.3: System for improving the ability to apply math, science, & eng (feedback system)	
Rework Analysis Results					DP1.1.3.1: System for reworking a student's ability to apply math, science, and eng (rework)
Kaizen Event Results					DP1.1.3.2: System for redesigning the teaching system of math, science, and eng (Kaizen event)
Assurance of Learning Results			DP1.2: System to create knowledge about consequences of performing ETHICAL RESPONSIBILITY (f) GLOBAL IMPACT (h) LIFELEARN (i) ENG PRAC (k) (plan)		
Assurance of Learning Results				DP1.2.1: System for teaching an understanding of professional/ethical responsibility (learning activity)	
Assurance of Learning Results				DP1.2.2: System for measuring the understanding of professional/ethical responsibility (inspection/grading)	
Feedback Analysis Results				DP1.2.3: System for improving the teaching system of professional/ethical responsibility (feedback syst)	
Rework Analysis Results					DP1.2.3.1: System for improving a student's understanding of professional/ethical responsibility (rework)
Kaizen Event Results					DP1.2.3.2: System for redesigning the teaching system of professional /ethical responsibility (Kaizen)
Assurance of Learning Results			DP1.3: System to create skill to perform as an individual for CONDUCT Experiments, INTERPRET Data (b) DESIGN system (c) SOLVE problems (e) ENG PRACTICE (k) (plan)		
Assurance of Learning Results				DP1.3.1: System for teaching how to design/conduct experiments, analyze/interpret data (learning activity)	
Assurance of Learning Results				DP1.3.2: System for measuring the ability to design/conduct experiments, analyze/interpret data (inspection/grading)	
Feedback Analysis Results				DP1.3.3: System for improving the ability to design/conduct experiments, analyze/interpret data (feedback system)	
Rework Analysis Results					DP1.3.3.1: System for improving a student's ability to design/conduct experiments, analyze/interpret data (rework)
Kaizen Event Results					DP1.3.3.2: System for improving the teaching of design/conduct experiments, analyze/interpret data (Kaizen event)
Assurance of Learning Results			DP1.4: System to create skill to perform as part of a group for TEAMWORK (d) COMMUNICATE (g) CONTEMPORARY TEAMS (j) ENG PRACTICE (k) (plan)		
Assurance of Learning Results				DP1.4.1: System for teaching how to function on multidisciplinary teams (learning activity)	
Assurance of Learning Results				DP1.4.2: System for measuring how to function on multidisciplinary teams (inspection/grading)	
Feedback Analysis Results				DP1.4.3: System for improving the ability to function on multi-teams (feedback system)	
Rework Analysis Results					DP1.4.3.1: System for improving a student's ability to function on multi-teams (rework)
Kaizen Event Results					DP1.4.3.2: System for redesigning the teaching system for how to function on multi-teams (Kaizen event)
min Total Instruction Expense		DP2: Function that minimizes cost of creating engineering student's competence (Total Cost Equation)			
min W=I/L			DP2.1: System for reducing waiting waste due to non-value-added queues (student paced learning system)		
Student's Value Stream Map				DP2.1.1: System for Identifying waste due to waiting in non-value-added queues (course value stream map)	
Student's Value Stream Map				DP2.1.2: System for measuring waste due to waiting in non-value added queues (course value stream map)	
Kaizen Event Results				DP2.1.3: System for improving waste due to waiting in non-value-added queues (course planning)	
One-Piece-Flow Analysis			DP2.2: System for reducing unnecessary inventory waste due to batch processing (production management system)		
One Piece Flow Analysis				DP2.2.1: System for Identifying UNNECESSARY INVENTORY waste due to batch processing (production management system)	
One Piece Flow Analysis				DP2.2.2: System for measuring UNNECESSARY INVENTORY waste due to batch processing (production management system)	
Kaizen Event Results				DP2.2.3: System for Improving UNNECESSARY INVENTORY waste due to batch processing (Kaizen event)	
Professor's Value Stream Map			DP2.3: System to reduce un-leveraged time waste of the professors schedule (time buffers)		
Professor's Value Stream Map				DP2.3.1: System to identify waste of UN-LEVERAGED TIME of the professors time (student support system)	
Professor's Value Stream Map				DP2.3.2: System to measure waste of UN-LEVERAGED TIME of the professors time (lean accounting)	
Kaizen Event Results				DP2.3.3: System to Improve waste of UN-LEVERAGED TIME of the professors time (student support system)	
Intra Course Progress Exams			DP2.4: System for reducing defects waste due to premature advancement of students (frequent gated assessments)		
Assurance of Learning Results				DP2.4.1: System to identify waste of defects due to premature advancement of incomplete students (frequent gated assessments)	
Assurance of Learning Results				DP2.4.2: System to measure waste of defects due to premature advancement of incomplete students (frequent gated assessments)	
Kaizen Event Results				DP2.4.3: system to improve waste of defects due to premature advancement of incomplete students (assessment management system)	
Occupancy Ratio virtual/physical			DP2.5: System for reducing transportation waste due to co-location of professors and students (virtual content delivery)		
Asset Inventory Coordination				DP2.5.1: System to identify co-location caused transportation waste (room schedule)	
Asset Inventory Coordination				DP2.5.2: System to measure co-location caused transportation waste (room schedule)	
Kaizen Event Results				DP2.5.3: System to improve the co-location caused transportation waste removal process (course planning)	
Concept Inventory Coordination			DP2.6: System for reducing unnecessary motion waste from incomplete course information (course content management)		
Assurance of Learning Results				DP2.6.1: System to identify waste of unnecessary motion from incomplete course information (course content management system)	
Assurance of Learning Results				DP2.6.2: System to measure waste of unnecessary motion from incomplete course information (course management system)	
Kaizen Event Results				DP2.6.3: System to improve waste of unnecessary motion from incomplete course information (course management system)	
Concept Inventory Coordination			DP2.7: System for reducing non-value-added waste of due to learning unnecessary material (course content management system)		
Concept Inventory Coordination				DP2.7.1: System for identifying waste of NON-VALUE-ADDED PROCESSING from learning unnecessary material (course content management system)	
Concept Inventory Coordination				DP2.7.2: System to measure waste of NON-VALUE-ADDED PROCESSING from learning unnecessary material (lean accounting)	
Kaizen Event Results				DP2.7.3: System to improve waste of NON-VALUE-ADDED PROCESSING from learning unnecessary material (course content system)	
Concept Inventory Coordination			DP2.8: System for reducing overproduction waste due to teaching redundant materials (course content coordination)		
Concept Inventory Coordination				DP2.8.1: System for identifying redundant academic material (course content coordination)	
Concept Inventory Coordination				DP2.8.2: System for measuring redundant academic material (course content coordination)	
Kaizen Event Results				DP2.8.3: System for improve redundant academic material content management (course content coordination)	
Capacity Analysis			DP2.9: System for reducing un-leveraged assets waste of the school (asset inventory coordination)		
Asset Inventory Coordination				DP2.9.1: System for identifying waste due to un-leveraged assets of the school (asset inventory coordination)	
Asset Inventory Coordination				DP2.9.2: System for measuring waste due to un-leveraged assets of the school (asset inventory coordination)	
Kaizen Event Results				DP2.9.3: System for improving waste due to un-leveraged assets of the school (Kaizen event)	

Table 49 - Second decomposition (complies with Axiom One) $DP_{1.1}$ through $DP_{2.9}$



DP0: System for 'manufacturing' ABET engineers (er
DP1: Function that maximizes value added to eng
DP1.1: System to create knowledge for perfor
DP1.1.1: System for teaching math, scien
DP1.1.2: System for measuring the ability
DP1.1.3: System for improving the ability
DP1.2: System to create knowledge about cor
DP1.2.1: System for teaching an understa
DP1.2.2: System for measuring the under
DP1.2.3: System for improving the teachi
DP1.3: System to create skill to perform as ar
DP1.3.1: System for teaching how to desi
DP1.3.2: System for measuring the ability
DP1.3.3: System for improving the ability
DP1.4: System to create skill to perform as pa
DP1.4.1: System for teaching how to func
DP1.4.2: System for measuring how to fu
DP1.4.3: System for improving the ability
DP2: Function that minimizes cost of creating eng
DP2.1: System for reducing waiting waste du
DP2.2: System for reducing unnecessary inve
DP2.3: System to reduce un-leveraged time w
DP2.4: System for reducing defects waste due
DP2.5: System for reducing transportation wa
DP2.6: System for reducing unnecessary moti
DP2.7: System for reducing non-value-added
DP2.8: System for reducing overproduction w
DP2.9: System for reducing un-leveraged ass

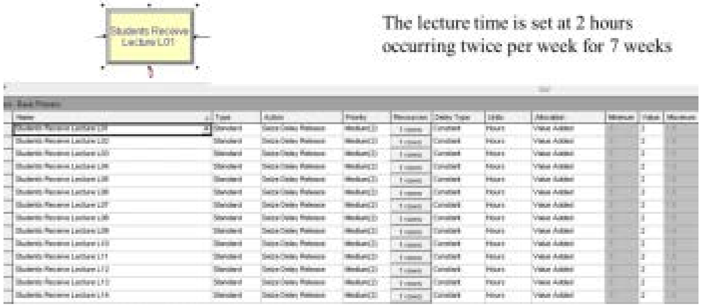
- FR0: 'Manufacture' engineers (using ABET/MFE/IE principles, efficiently)
  - FR1: Maximize value added to engineering student's competence (Deming - PDCA Cycle)
    - FR1.1: Create knowledge for performing about MATHEMATICS, SCIENCE & ENGINEERING (a) CONTEMPORARY ISSUES (j)
      - FR1.1.1: Teach knowledge of mathematics, science, and engineering (do)
      - FR1.1.2: Measure the ability to apply knowledge of math, science, & eng (check)
      - FR1.1.3: Improve the ability to apply knowledge of math, science & eng (adjust)
    - FR1.2: Create knowledge of consequences from performing ETHICAL RESPONSIBILITY (f) GLOBAL IMPACT (h) (plan)
      - FR1.2.1: Teach an understanding of professional and ethical responsibility (do)
      - FR1.2.2: Verify the understanding of professional and ethical responsibility (check)
      - FR1.2.3: Improve the teaching system for understanding of professional and ethical responsibility (adjust)
    - FR1.3: Create skill to perform as individual to CONDUCT & INTERPRET (b) DESIGN syst (c) SOLVE probs (e) LIFELEARN (i) ENG PRACTICE (k) (plan)
      - FR1.3.1: Teach how to design/conduct experiments, analyze/interpret data (do)
      - FR1.3.2: Quality Assurance of the ability to design/conduct experiments, analyze/interpret data (check)
      - FR1.3.3: Improve the ability to design/conduct experiments, analyze/interpret data (adjust)
    - FR1.4: Create skill to perform as group member for TEAMWORK (d) COMMUNICATE (g) (plan)
      - FR1.4.1: Teach how to function on multidisciplinary teams (do)
      - FR1.4.2: Verify how to function on multidisciplinary teams (check)
      - FR1.4.3: Improve the ability to function on multidisciplinary teams (adjust)
  - FR2: Minimize cost of creating engineering student's competence (Ohno - 7 Wastes & Toyota Production System)
    - FR2.1: Reduce WAITING waste caused by non-value-added queues (plan)
    - FR2.2: Reduce UNNECESSARY INVENTORY waste due to batch processing (plan)
    - FR2.3: Reduce UN-LEVERAGED TIME waste of the professor's schedule (plan)
    - FR2.4: Reduce DEFECTS waste due to premature advancement of incomplete students (plan)
    - FR2.5: Reduce TRANSPORTATION waste caused by co-location of professors and students (plan)
    - FR2.6: Reduce UNNECESSARY MOTION waste from incomplete course information (plan)
    - FR2.7: Reduce NON-VALUE-ADDED PROCESSING waste from learning unnecessary material (plan)
    - FR2.8: Reduce OVERPRODUCTION waste due to teaching redundant material (plan)
    - FR2.9: Reduce UN-LEVERAGED ASSETS waste of the school (plan)

Figure 53 - Second decomposition upper level design matrix (complies with Axiom One)

Appendix F - Arena^{TM} Simulation Computer Output

The following graphics are screen shots of the entities, data input forms and operation results from the computer simulation. The graphic are intended as a record of the setting used for the computer simulation.

Figure 54 shows the course lecture duration is set to two hours per session for student value-added time.

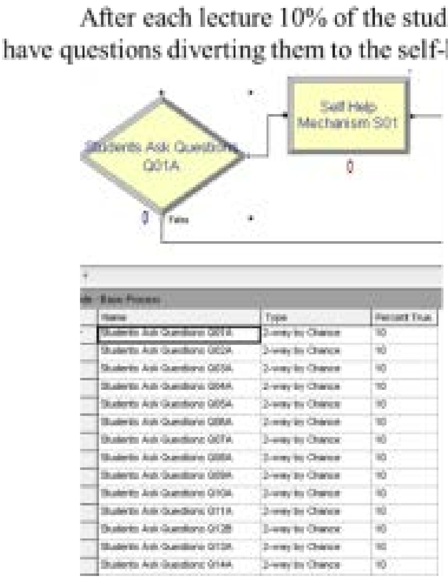


The lecture time is set at 2 hours
occurring twice per week for 7 weeks

Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Minimum	Value	Maximum
Students Receive Lecture L01	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Hours	Value Added	[illegible]	2	[illegible]
Students Receive Lecture L02	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Hours	Value Added	[illegible]	2	[illegible]
Students Receive Lecture L03	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Hours	Value Added	[illegible]	2	[illegible]
Students Receive Lecture L04	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Hours	Value Added	[illegible]	2	[illegible]
Students Receive Lecture L05	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Hours	Value Added	[illegible]	2	[illegible]
Students Receive Lecture L06	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Hours	Value Added	[illegible]	2	[illegible]
Students Receive Lecture L07	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Hours	Value Added	[illegible]	2	[illegible]
Students Receive Lecture L08	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Hours	Value Added	[illegible]	2	[illegible]
Students Receive Lecture L09	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Hours	Value Added	[illegible]	2	[illegible]
Students Receive Lecture L10	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Hours	Value Added	[illegible]	2	[illegible]
Students Receive Lecture L11	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Hours	Value Added	[illegible]	2	[illegible]
Students Receive Lecture L12	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Hours	Value Added	[illegible]	2	[illegible]
Students Receive Lecture L13	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Hours	Value Added	[illegible]	2	[illegible]
Students Receive Lecture L14	Standard	Seize Delay Release	Medium(2)	1 rows	Constant	Hours	Value Added	[illegible]	2	[illegible]

Figure 54 - Setting for student value-added time from lecture is two hours for fourteen sessions

An estimated proportion of the students will need the self-help mechanism. This number is set to 10 percent of the students. The self-help-mechanism does not consume any resources of the professor while the course is in operation. The management of the recording of the lecture material and constructing the self-help database is managed by the teaching assistants.

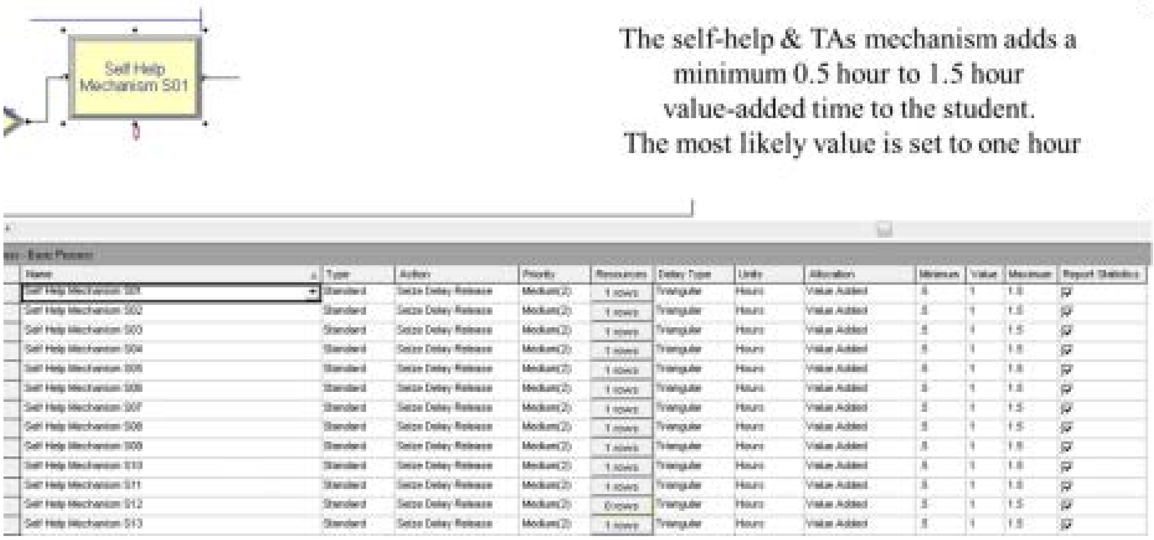


After each lecture 10% of the students
have questions diverting them to the self-help & TAs

Name	Type	Percent True
Students Ask Questions Q01A	2-way by Chance	10
Students Ask Questions Q02A	2-way by Chance	10
Students Ask Questions Q03A	2-way by Chance	10
Students Ask Questions Q04A	2-way by Chance	10
Students Ask Questions Q05A	2-way by Chance	10
Students Ask Questions Q06A	2-way by Chance	10
Students Ask Questions Q07A	2-way by Chance	10
Students Ask Questions Q08A	2-way by Chance	10
Students Ask Questions Q09A	2-way by Chance	10
Students Ask Questions Q10A	2-way by Chance	10
Students Ask Questions Q11A	2-way by Chance	10
Students Ask Questions Q12B	2-way by Chance	10
Students Ask Questions Q13A	2-way by Chance	10
Students Ask Questions Q14A	2-way by Chance	10

Figure 55 - Setting for percentage of students accessing the self-help system for support is 10%

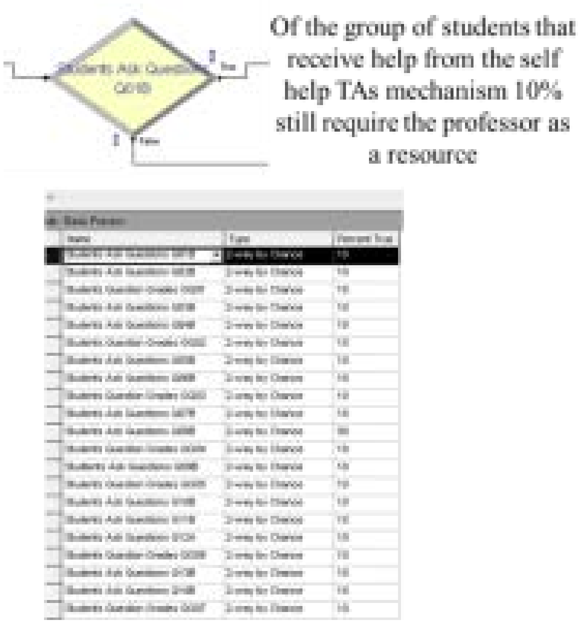
Value-added time is accrued to the student from accessing the self-help mechanism of about an hour per occurrence seen in Figure 56.



The self-help & TAs mechanism adds a minimum 0.5 hour to 1.5 hour value-added time to the student. The most likely value is set to one hour

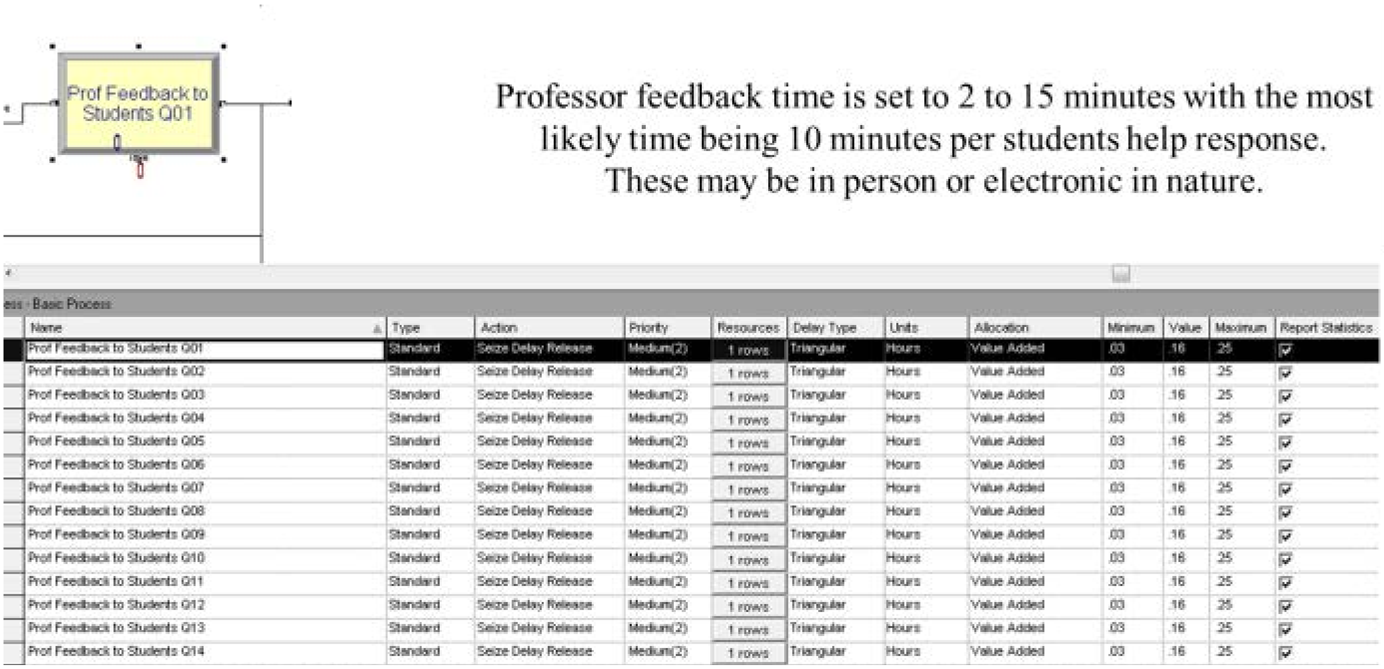
Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Minimum	Value	Maximum	Report Statistics
Self Help Mechanism S01	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Help Mechanism S02	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Help Mechanism S03	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Help Mechanism S04	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Help Mechanism S05	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Help Mechanism S06	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Help Mechanism S07	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Help Mechanism S08	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Help Mechanism S09	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Help Mechanism S10	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Help Mechanism S11	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Help Mechanism S12	Standard	Seize Delay Release	Medium(2)	0 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Help Mechanism S13	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑

Figure 56 - Setting for value-added time accrues to the student from use of the self-help mechanism



Of the group of students that receive help from the self help TAs mechanism 10% still require the professor as a resource

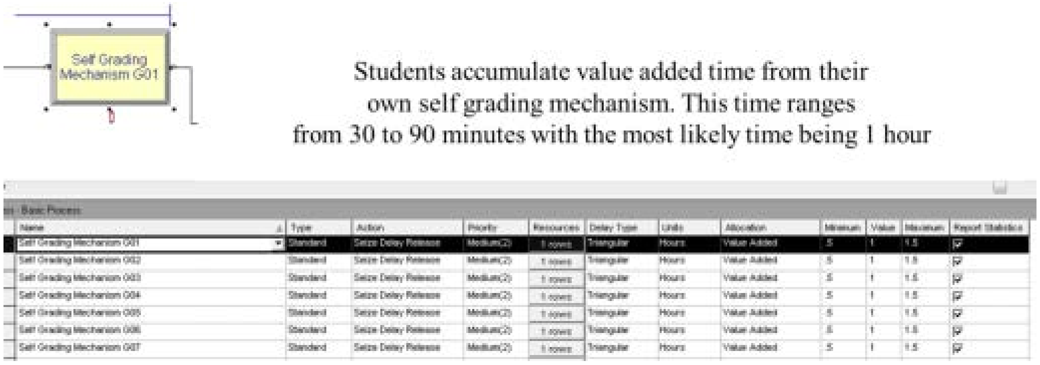
Figure 57 - Setting for decesion point for students that reqauire professor support after self-help



Professor feedback time is set to 2 to 15 minutes with the most likely time being 10 minutes per students help response. These may be in person or electronic in nature.

Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Minimum	Value	Maximum	Report Statistics
Prof Feedback to Students Q01	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.03	.16	.25	☑
Prof Feedback to Students Q02	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.03	.16	.25	☑
Prof Feedback to Students Q03	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.03	.16	.25	☑
Prof Feedback to Students Q04	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.03	.16	.25	☑
Prof Feedback to Students Q05	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.03	.16	.25	☑
Prof Feedback to Students Q06	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.03	.16	.25	☑
Prof Feedback to Students Q07	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.03	.16	.25	☑
Prof Feedback to Students Q08	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.03	.16	.25	☑
Prof Feedback to Students Q09	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.03	.16	.25	☑
Prof Feedback to Students Q10	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.03	.16	.25	☑
Prof Feedback to Students Q11	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.03	.16	.25	☑
Prof Feedback to Students Q12	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.03	.16	.25	☑
Prof Feedback to Students Q13	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.03	.16	.25	☑
Prof Feedback to Students Q14	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.03	.16	.25	☑

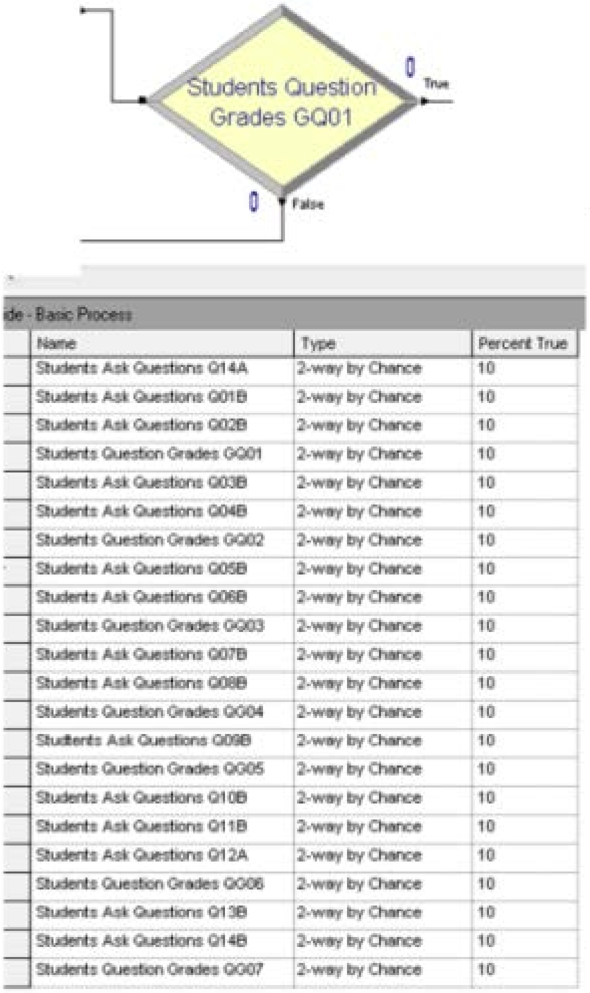
Figure 58 - Setting for professor feedback time setting



Students accumulate value added time from their own self grading mechanism. This time ranges from 30 to 90 minutes with the most likely time being 1 hour

Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Minimum	Value	Maximum	Report Statistics
Self Grading Mechanism G01	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Grading Mechanism G02	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Grading Mechanism G03	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Grading Mechanism G04	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Grading Mechanism G05	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Grading Mechanism G06	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑
Self Grading Mechanism G07	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Value Added	.5	1	1.5	☑

Figure 59 - Setting for student self-help grading mechanism

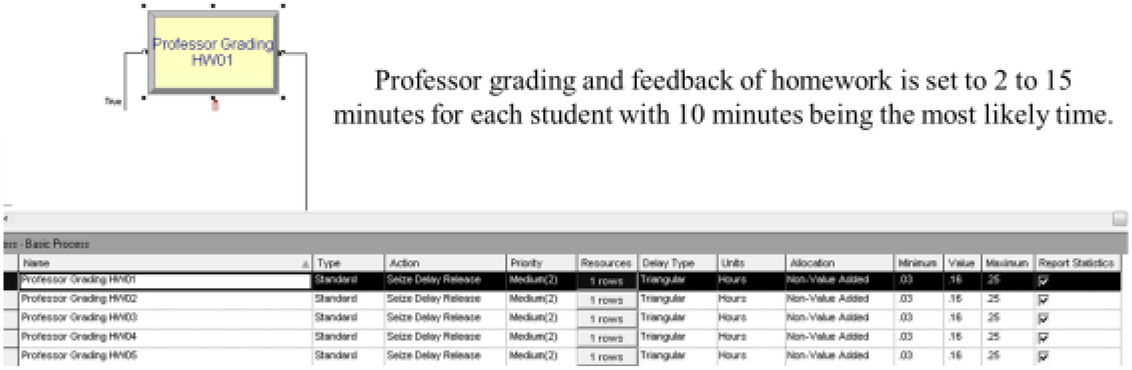


ide - Basic Process

Name	Type	Percent True
Students Ask Questions Q14A	2-way by Chance	10
Students Ask Questions Q01B	2-way by Chance	10
Students Ask Questions Q02B	2-way by Chance	10
Students Question Grades GQ01	2-way by Chance	10
Students Ask Questions Q03B	2-way by Chance	10
Students Ask Questions Q04B	2-way by Chance	10
Students Question Grades GQ02	2-way by Chance	10
Students Ask Questions Q05B	2-way by Chance	10
Students Ask Questions Q06B	2-way by Chance	10
Students Question Grades GQ03	2-way by Chance	10
Students Ask Questions Q07B	2-way by Chance	10
Students Ask Questions Q08B	2-way by Chance	10
Students Question Grades GQ04	2-way by Chance	10
Students Ask Questions Q09B	2-way by Chance	10
Students Question Grades GQ05	2-way by Chance	10
Students Ask Questions Q10B	2-way by Chance	10
Students Ask Questions Q11B	2-way by Chance	10
Students Ask Questions Q12A	2-way by Chance	10
Students Question Grades GQ06	2-way by Chance	10
Students Ask Questions Q13B	2-way by Chance	10
Students Ask Questions Q14B	2-way by Chance	10
Students Question Grades GQ07	2-way by Chance	10

The percentage of students that require further support after an exam is scored is set at 10%.

Figure 60 - Setting for students requiring support after grade scoring

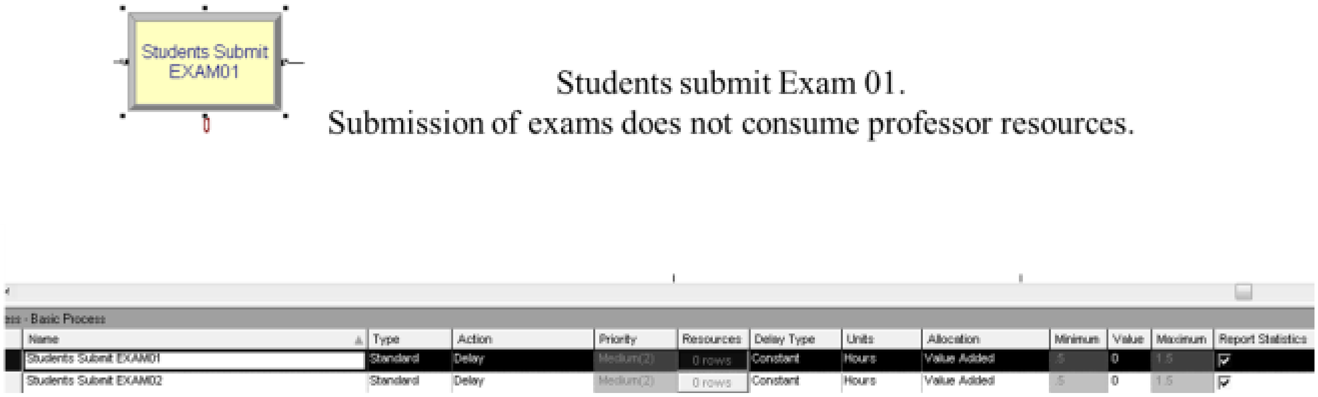


Professor grading and feedback of homework is set to 2 to 15 minutes for each student with 10 minutes being the most likely time.

ss - Basic Process

Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Minimum	Value	Maximum	Report Statistics
Professor Grading HW01	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Non-Value Added	.03	.16	.25	☑
Professor Grading HW02	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Non-Value Added	.03	.16	.25	☑
Professor Grading HW03	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Non-Value Added	.03	.16	.25	☑
Professor Grading HW04	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Non-Value Added	.03	.16	.25	☑
Professor Grading HW05	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Non-Value Added	.03	.16	.25	☑

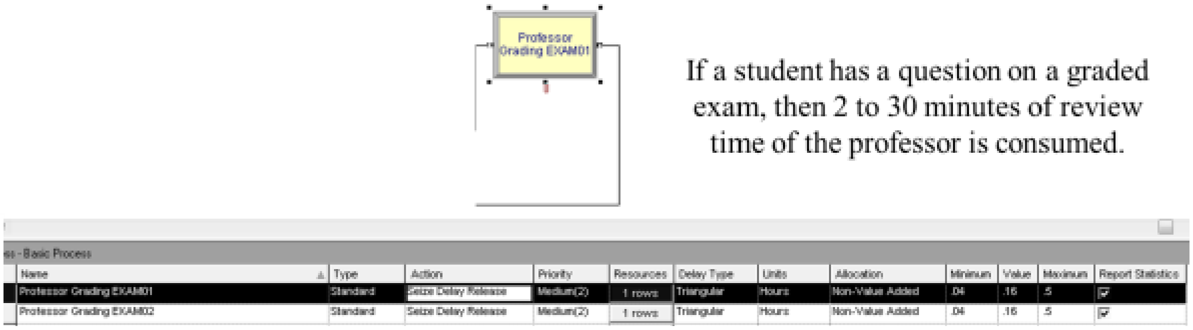
Figure 61 - Setting for professor time consumed in grading or scoring



Students submit Exam 01.
Submission of exams does not consume professor resources.

Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Minimum	Value	Maximum	Report Statistics
Students Submit EXAM01	Standard	Delay	Medium(2)	0 rows	Constant	Hours	Value Added	.5	0	1.5	☑
Students Submit EXAM02	Standard	Delay	Medium(2)	0 rows	Constant	Hours	Value Added	.5	0	1.5	☑

Figure 62 - Setting for self grading or scoring not consuming professor resources

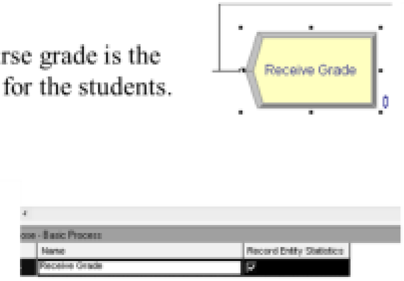


If a student has a question on a graded exam, then 2 to 30 minutes of review time of the professor is consumed.

Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Minimum	Value	Maximum	Report Statistics
Professor Grading EXAM01	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Non-Value Added	.04	.16	.5	☑
Professor Grading EXAM02	Standard	Seize Delay Release	Medium(2)	1 rows	Triangular	Hours	Non-Value Added	.04	.16	.5	☑

Figure 63 - Setting for professor response time on grading or scoring

Receiving a course grade is the course exit point for the students.



Name	Record Entity Statistics
Receive Grade	☑

Figure 64 - Student receipt of score or grade is exit point for the course

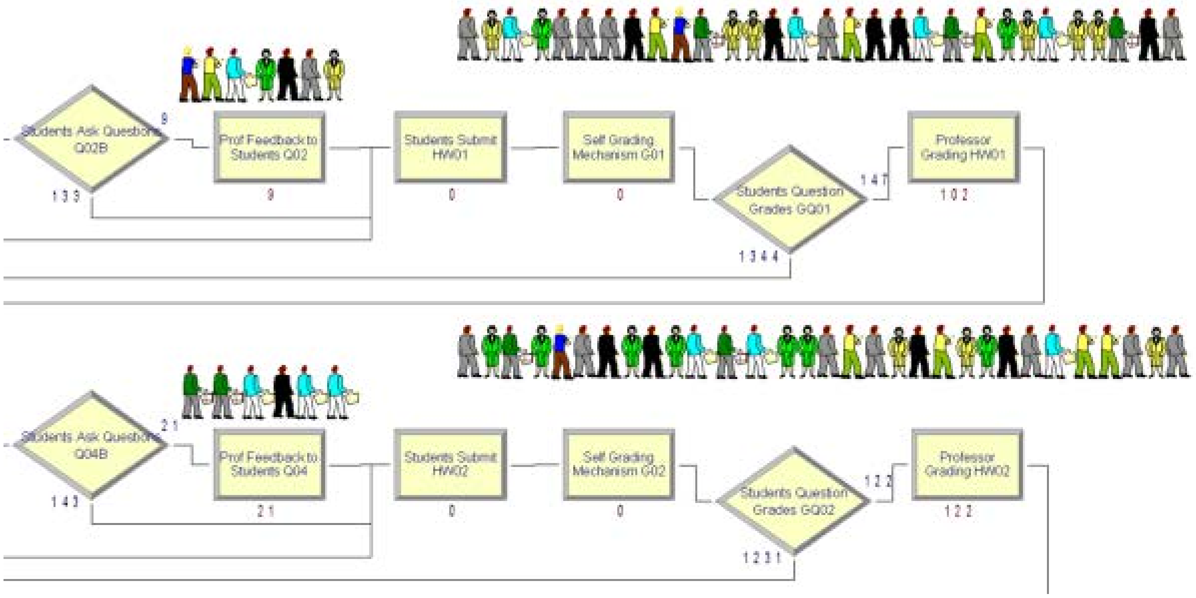


Figure 65 - Detailed graphic showing queues in the course

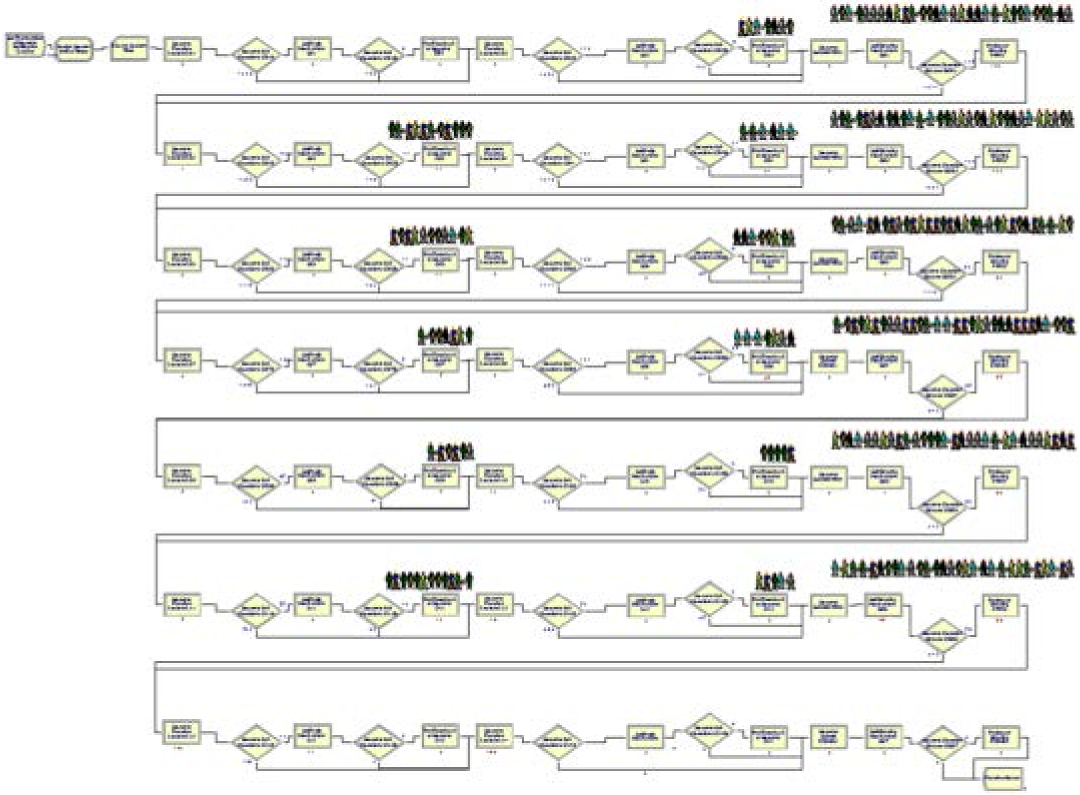
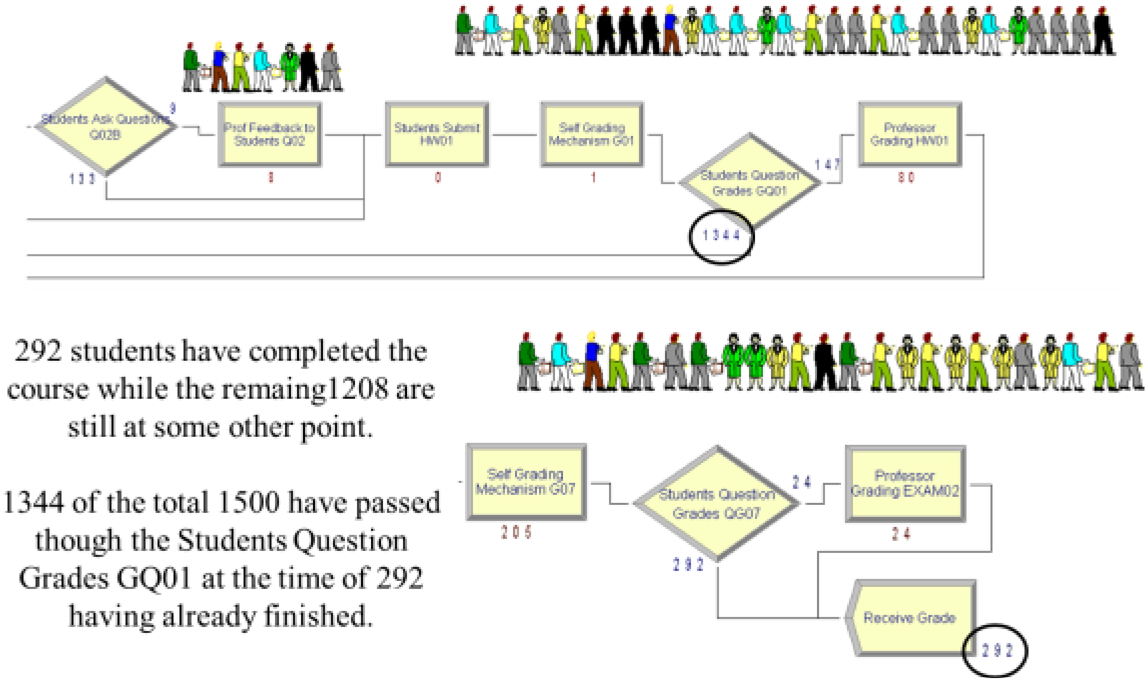


Figure 66 - Graphic showing students dispersed throughout the course

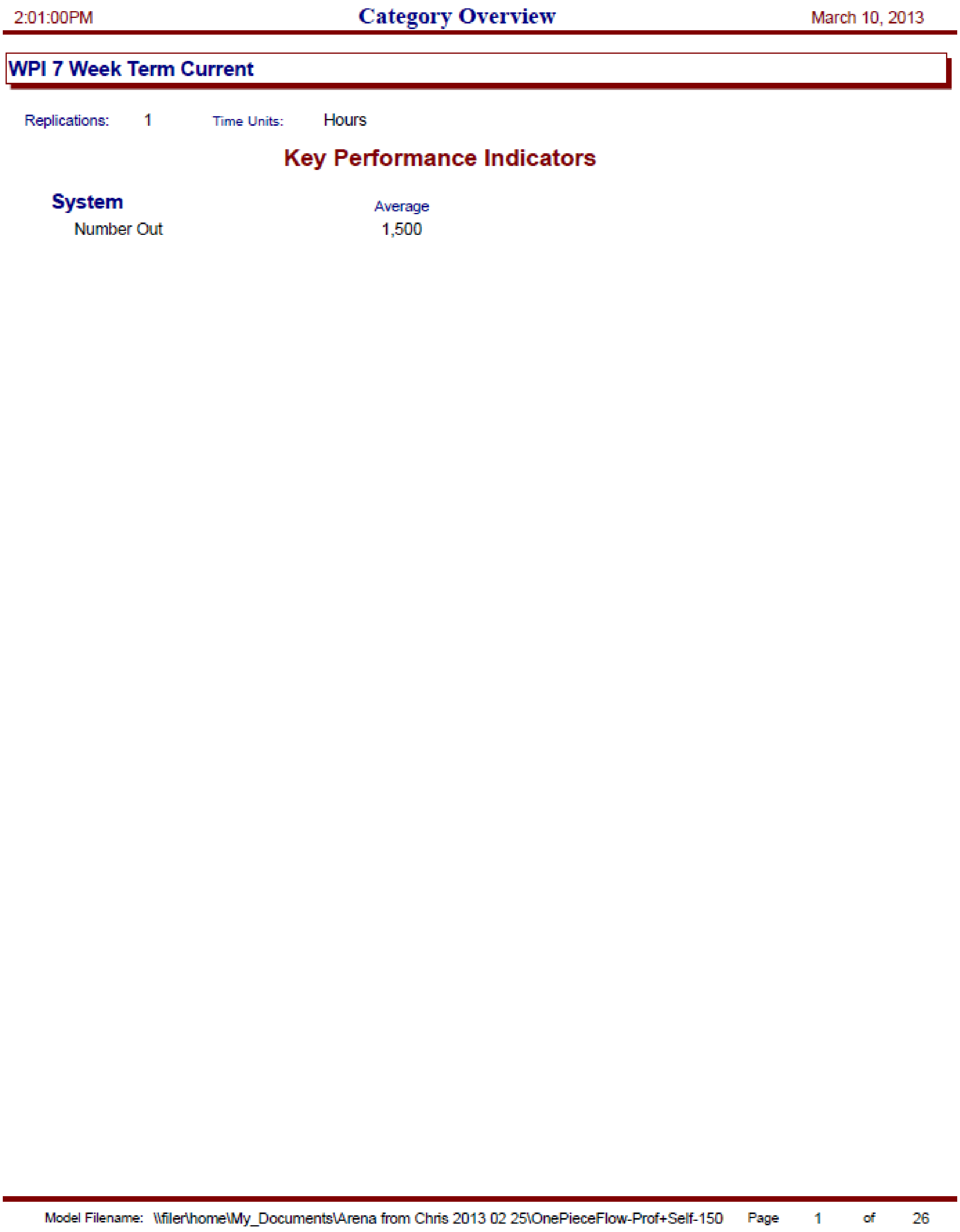
The above graphic shows the general seven week model of lectures, homework submissions and subsequent feedback from the professor to that student. Each process will have different time distributions as some questions are handled easily and quickly and some take more time.



292 students have completed the course while the remaing1208 are still at some other point.

1344 of the total 1500 have passed though the Students Question Grades GQ01 at the time of 292 having already finished.

Figure 67 - Results showing 292 students completing the course & 1208 still progressing



2:01:00PM **Category Overview** March 10, 2013

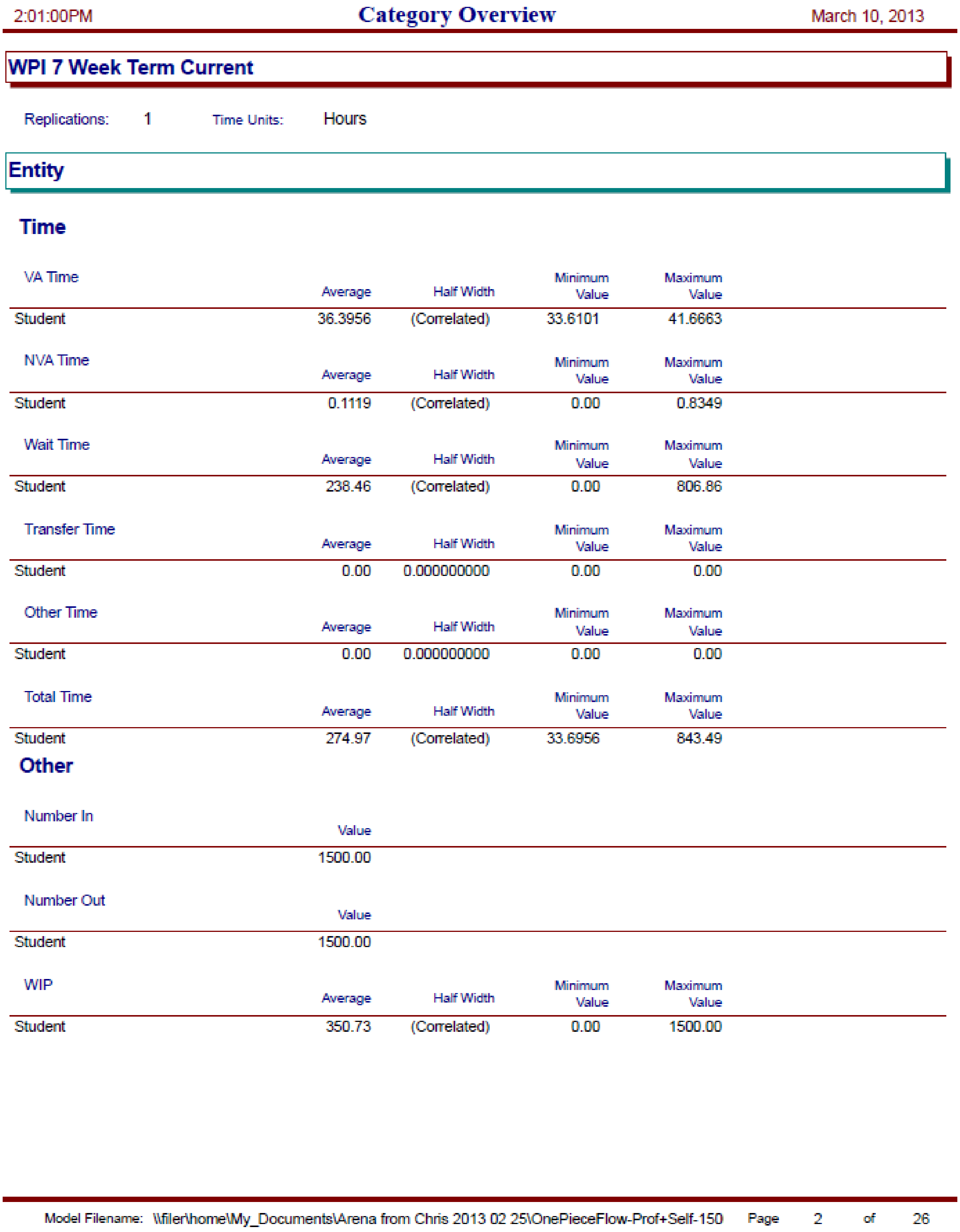
WPI 7 Week Term Current

Replications: 1 Time Units: Hours

Key Performance Indicators

System	Average
Number Out	1,500

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 1 of 26



2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

Replications: 1 Time Units: Hours

Entity

Time

VA Time

	Average	Half Width	Minimum Value	Maximum Value
Student	36.3956	(Correlated)	33.6101	41.6663

NVA Time

	Average	Half Width	Minimum Value	Maximum Value
Student	0.1119	(Correlated)	0.00	0.8349

Wait Time

	Average	Half Width	Minimum Value	Maximum Value
Student	238.46	(Correlated)	0.00	806.86

Transfer Time

	Average	Half Width	Minimum Value	Maximum Value
Student	0.00	0.000000000	0.00	0.00

Other Time

	Average	Half Width	Minimum Value	Maximum Value
Student	0.00	0.000000000	0.00	0.00

Total Time

	Average	Half Width	Minimum Value	Maximum Value
Student	274.97	(Correlated)	33.6956	843.49

Other

Number In

	Value
Student	1500.00

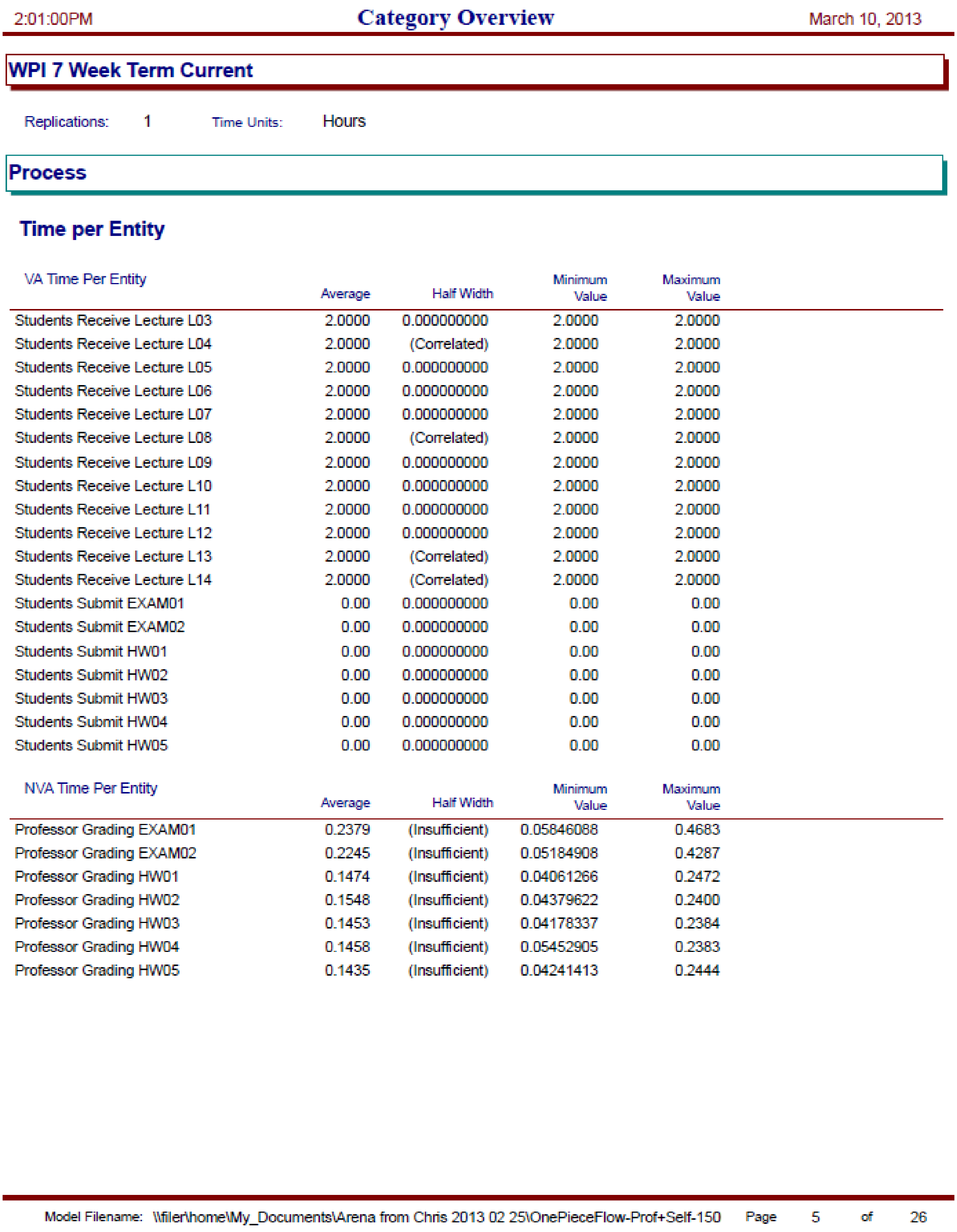
Number Out

	Value
Student	1500.00

WIP

	Average	Half Width	Minimum Value	Maximum Value
Student	350.73	(Correlated)	0.00	1500.00

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 2 of 26



2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

Replications: 1 Time Units: Hours

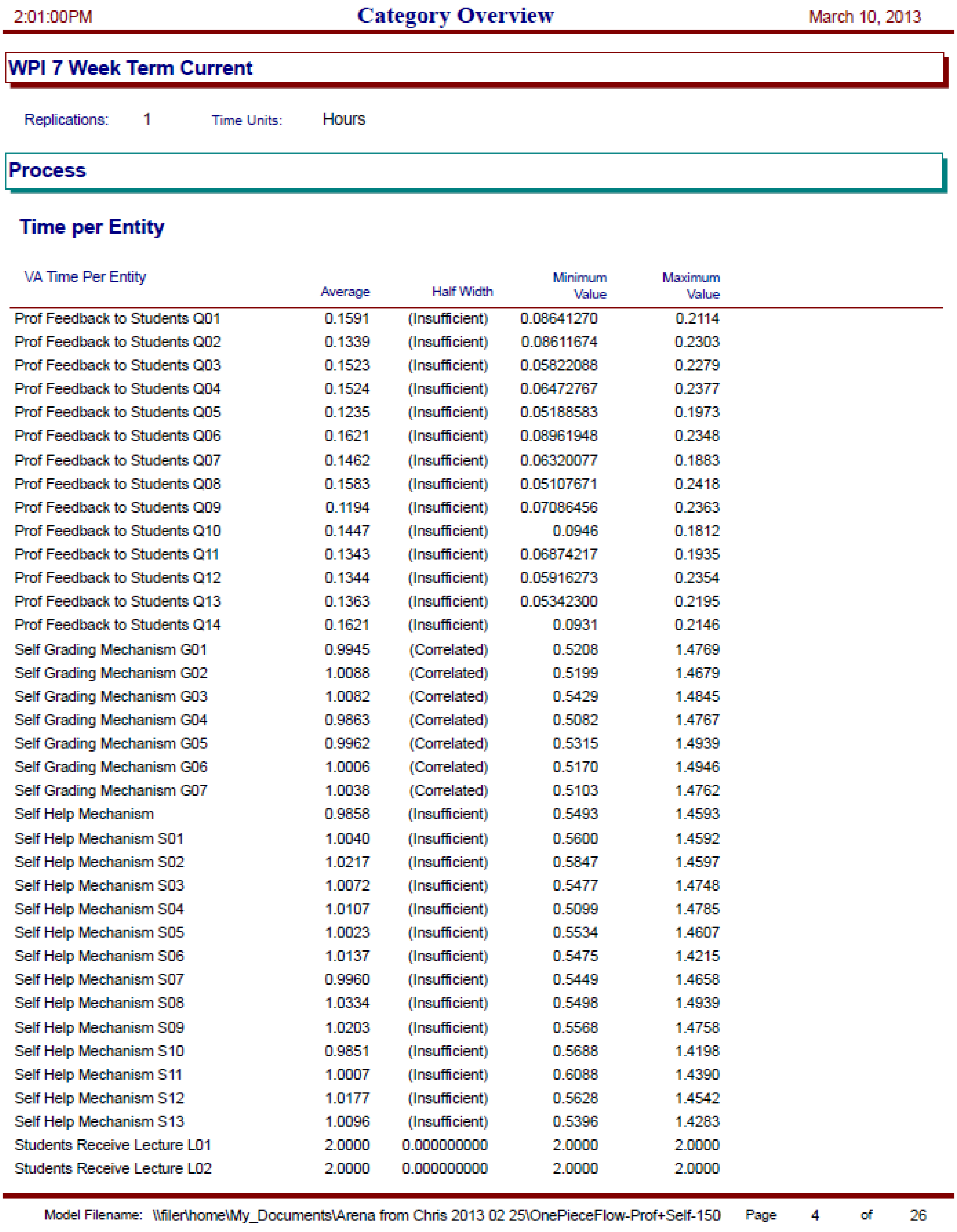
Process

Time per Entity

VA Time Per Entity	Average	Half Width	Minimum Value	Maximum Value
Students Receive Lecture L03	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L04	2.0000	(Correlated)	2.0000	2.0000
Students Receive Lecture L05	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L06	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L07	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L08	2.0000	(Correlated)	2.0000	2.0000
Students Receive Lecture L09	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L10	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L11	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L12	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L13	2.0000	(Correlated)	2.0000	2.0000
Students Receive Lecture L14	2.0000	(Correlated)	2.0000	2.0000
Students Submit EXAM01	0.00	0.000000000	0.00	0.00
Students Submit EXAM02	0.00	0.000000000	0.00	0.00
Students Submit HW01	0.00	0.000000000	0.00	0.00
Students Submit HW02	0.00	0.000000000	0.00	0.00
Students Submit HW03	0.00	0.000000000	0.00	0.00
Students Submit HW04	0.00	0.000000000	0.00	0.00
Students Submit HW05	0.00	0.000000000	0.00	0.00

NVA Time Per Entity	Average	Half Width	Minimum Value	Maximum Value
Professor Grading EXAM01	0.2379	(Insufficient)	0.05846088	0.4683
Professor Grading EXAM02	0.2245	(Insufficient)	0.05184908	0.4287
Professor Grading HW01	0.1474	(Insufficient)	0.04061266	0.2472
Professor Grading HW02	0.1548	(Insufficient)	0.04379622	0.2400
Professor Grading HW03	0.1453	(Insufficient)	0.04178337	0.2384
Professor Grading HW04	0.1458	(Insufficient)	0.05452905	0.2383
Professor Grading HW05	0.1435	(Insufficient)	0.04241413	0.2444

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 5 of 26



2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

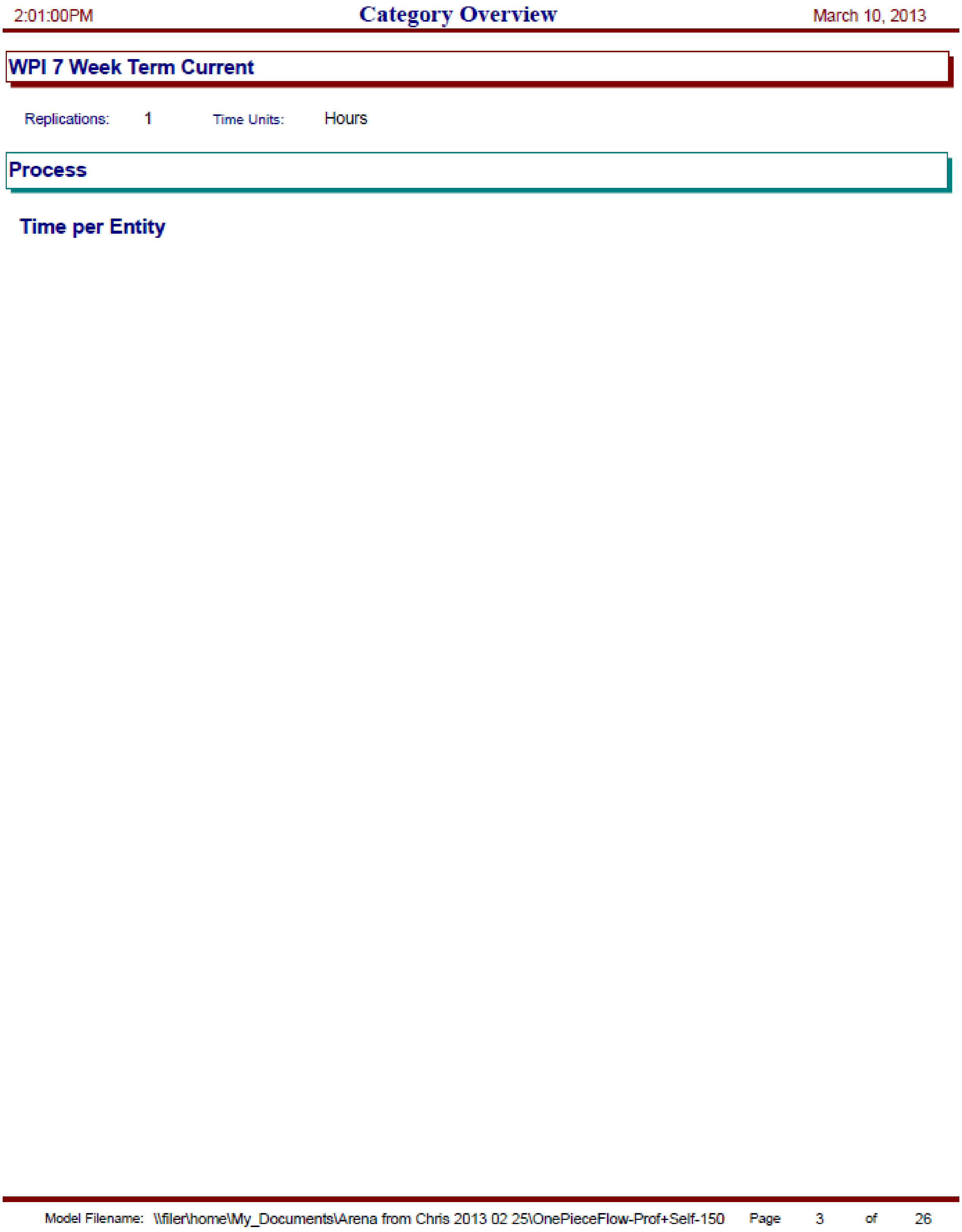
Replications: 1 Time Units: Hours

Process

Time per Entity

VA Time Per Entity	Average	Half Width	Minimum Value	Maximum Value
Prof Feedback to Students Q01	0.1591	(Insufficient)	0.08641270	0.2114
Prof Feedback to Students Q02	0.1339	(Insufficient)	0.08611674	0.2303
Prof Feedback to Students Q03	0.1523	(Insufficient)	0.05822088	0.2279
Prof Feedback to Students Q04	0.1524	(Insufficient)	0.06472767	0.2377
Prof Feedback to Students Q05	0.1235	(Insufficient)	0.05188583	0.1973
Prof Feedback to Students Q06	0.1621	(Insufficient)	0.08961948	0.2348
Prof Feedback to Students Q07	0.1462	(Insufficient)	0.06320077	0.1883
Prof Feedback to Students Q08	0.1583	(Insufficient)	0.05107671	0.2418
Prof Feedback to Students Q09	0.1194	(Insufficient)	0.07086456	0.2363
Prof Feedback to Students Q10	0.1447	(Insufficient)	0.0946	0.1812
Prof Feedback to Students Q11	0.1343	(Insufficient)	0.06874217	0.1935
Prof Feedback to Students Q12	0.1344	(Insufficient)	0.05916273	0.2354
Prof Feedback to Students Q13	0.1363	(Insufficient)	0.05342300	0.2195
Prof Feedback to Students Q14	0.1621	(Insufficient)	0.0931	0.2146
Self Grading Mechanism G01	0.9945	(Correlated)	0.5208	1.4769
Self Grading Mechanism G02	1.0088	(Correlated)	0.5199	1.4679
Self Grading Mechanism G03	1.0082	(Correlated)	0.5429	1.4845
Self Grading Mechanism G04	0.9863	(Correlated)	0.5082	1.4767
Self Grading Mechanism G05	0.9962	(Correlated)	0.5315	1.4939
Self Grading Mechanism G06	1.0006	(Correlated)	0.5170	1.4946
Self Grading Mechanism G07	1.0038	(Correlated)	0.5103	1.4762
Self Help Mechanism	0.9858	(Insufficient)	0.5493	1.4593
Self Help Mechanism S01	1.0040	(Insufficient)	0.5600	1.4592
Self Help Mechanism S02	1.0217	(Insufficient)	0.5847	1.4597
Self Help Mechanism S03	1.0072	(Insufficient)	0.5477	1.4748
Self Help Mechanism S04	1.0107	(Insufficient)	0.5099	1.4785
Self Help Mechanism S05	1.0023	(Insufficient)	0.5534	1.4607
Self Help Mechanism S06	1.0137	(Insufficient)	0.5475	1.4215
Self Help Mechanism S07	0.9960	(Insufficient)	0.5449	1.4658
Self Help Mechanism S08	1.0334	(Insufficient)	0.5498	1.4939
Self Help Mechanism S09	1.0203	(Insufficient)	0.5568	1.4758
Self Help Mechanism S10	0.9851	(Insufficient)	0.5688	1.4198
Self Help Mechanism S11	1.0007	(Insufficient)	0.6088	1.4390
Self Help Mechanism S12	1.0177	(Insufficient)	0.5628	1.4542
Self Help Mechanism S13	1.0096	(Insufficient)	0.5396	1.4283
Students Receive Lecture L01	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L02	2.0000	0.000000000	2.0000	2.0000

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 4 of 26



2:01:00PM **Category Overview** March 10, 2013

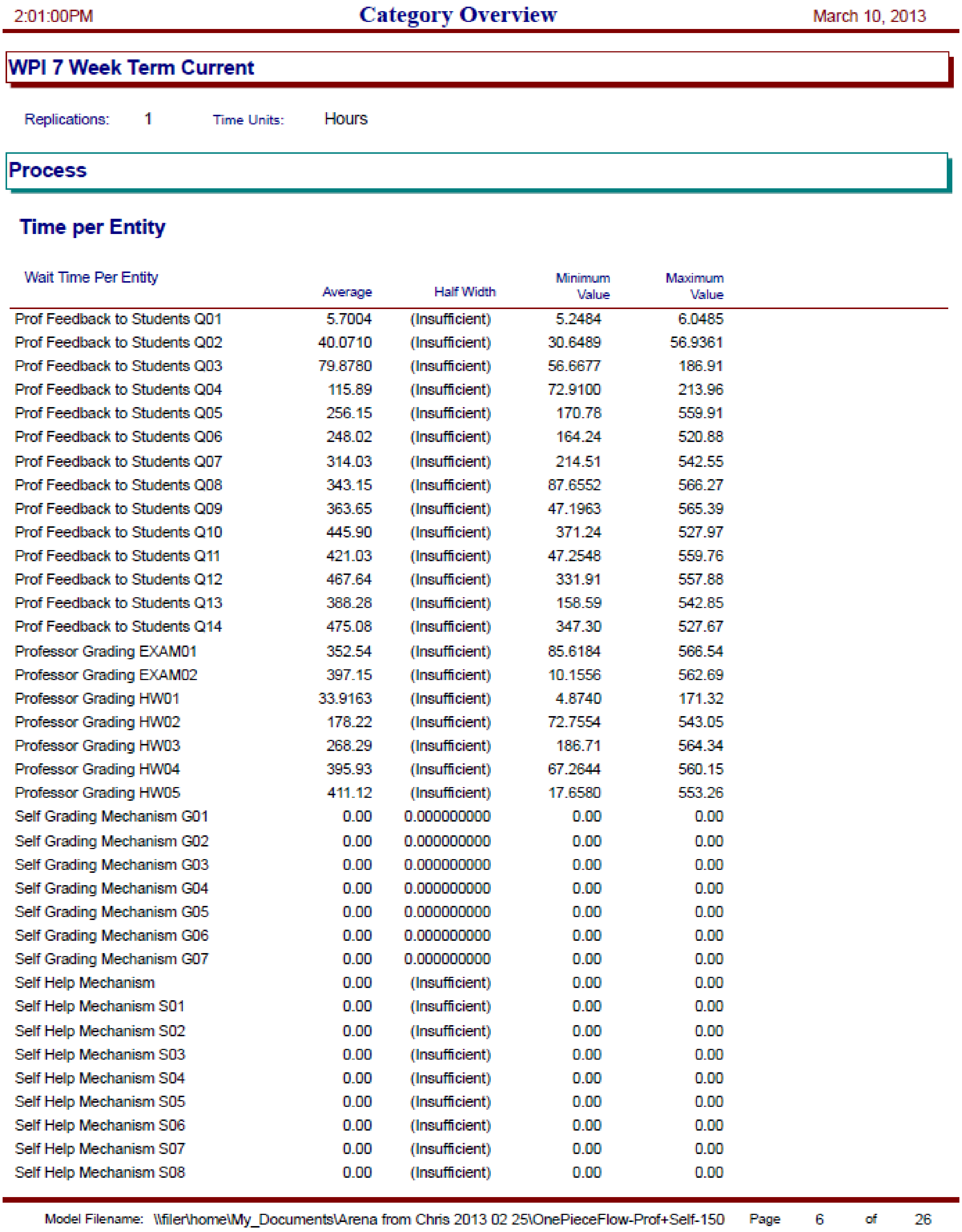
WPI 7 Week Term Current

Replications: 1 Time Units: Hours

Process

Time per Entity

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 3 of 26



2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

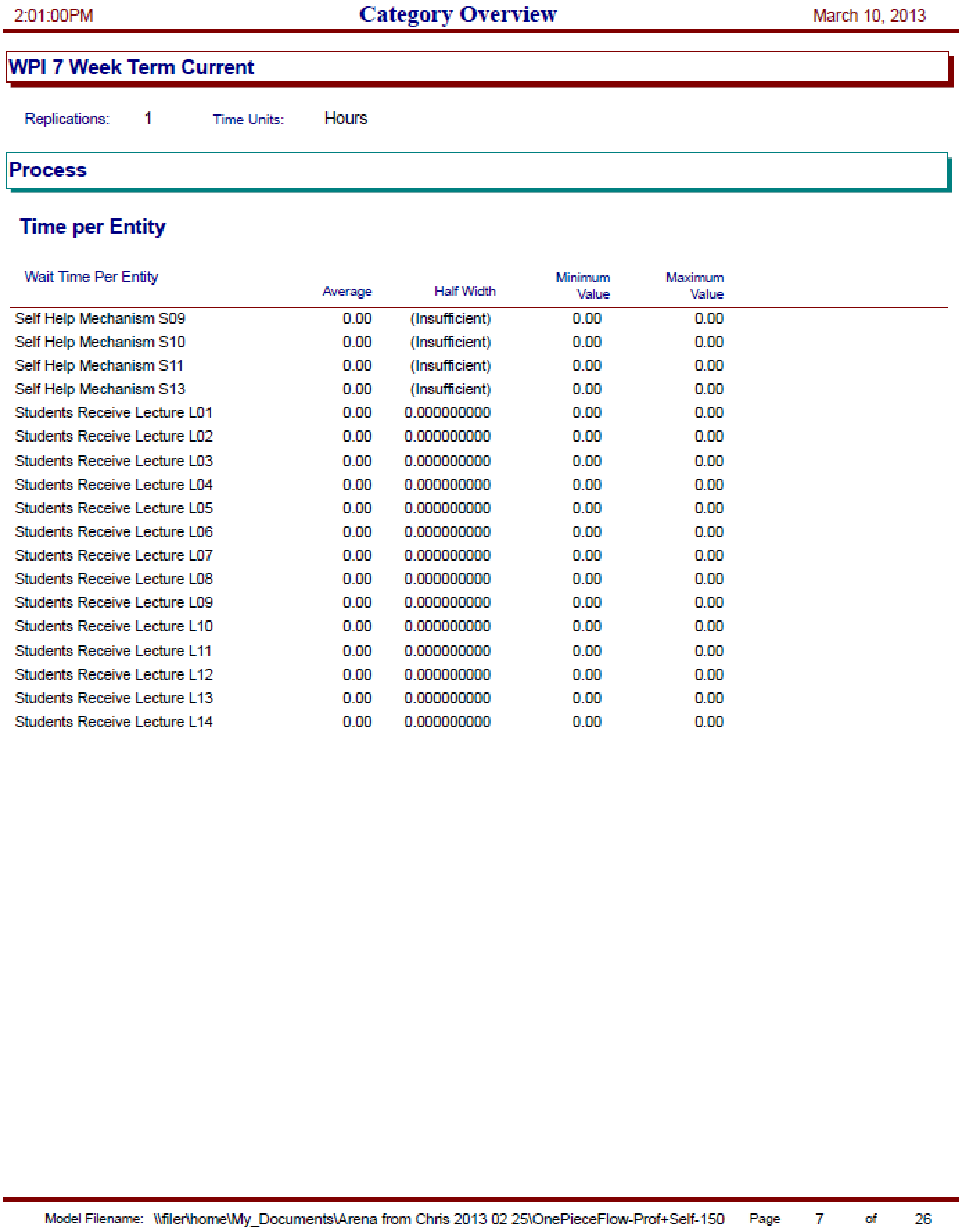
Replications: 1 Time Units: Hours

Process

Time per Entity

Wait Time Per Entity	Average	Half Width	Minimum Value	Maximum Value
Prof Feedback to Students Q01	5.7004	(Insufficient)	5.2484	6.0485
Prof Feedback to Students Q02	40.0710	(Insufficient)	30.6489	56.9361
Prof Feedback to Students Q03	79.8780	(Insufficient)	56.6677	186.91
Prof Feedback to Students Q04	115.89	(Insufficient)	72.9100	213.96
Prof Feedback to Students Q05	256.15	(Insufficient)	170.78	559.91
Prof Feedback to Students Q06	248.02	(Insufficient)	164.24	520.88
Prof Feedback to Students Q07	314.03	(Insufficient)	214.51	542.55
Prof Feedback to Students Q08	343.15	(Insufficient)	87.6552	566.27
Prof Feedback to Students Q09	363.65	(Insufficient)	47.1963	565.39
Prof Feedback to Students Q10	445.90	(Insufficient)	371.24	527.97
Prof Feedback to Students Q11	421.03	(Insufficient)	47.2548	559.76
Prof Feedback to Students Q12	467.64	(Insufficient)	331.91	557.88
Prof Feedback to Students Q13	388.28	(Insufficient)	158.59	542.85
Prof Feedback to Students Q14	475.08	(Insufficient)	347.30	527.67
Professor Grading EXAM01	352.54	(Insufficient)	85.6184	566.54
Professor Grading EXAM02	397.15	(Insufficient)	10.1556	562.69
Professor Grading HW01	33.9163	(Insufficient)	4.8740	171.32
Professor Grading HW02	178.22	(Insufficient)	72.7554	543.05
Professor Grading HW03	268.29	(Insufficient)	186.71	564.34
Professor Grading HW04	395.93	(Insufficient)	67.2644	560.15
Professor Grading HW05	411.12	(Insufficient)	17.6580	553.26
Self Grading Mechanism G01	0.00	0.000000000	0.00	0.00
Self Grading Mechanism G02	0.00	0.000000000	0.00	0.00
Self Grading Mechanism G03	0.00	0.000000000	0.00	0.00
Self Grading Mechanism G04	0.00	0.000000000	0.00	0.00
Self Grading Mechanism G05	0.00	0.000000000	0.00	0.00
Self Grading Mechanism G06	0.00	0.000000000	0.00	0.00
Self Grading Mechanism G07	0.00	0.000000000	0.00	0.00
Self Help Mechanism	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S01	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S02	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S03	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S04	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S05	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S06	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S07	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S08	0.00	(Insufficient)	0.00	0.00

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 6 of 26



2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

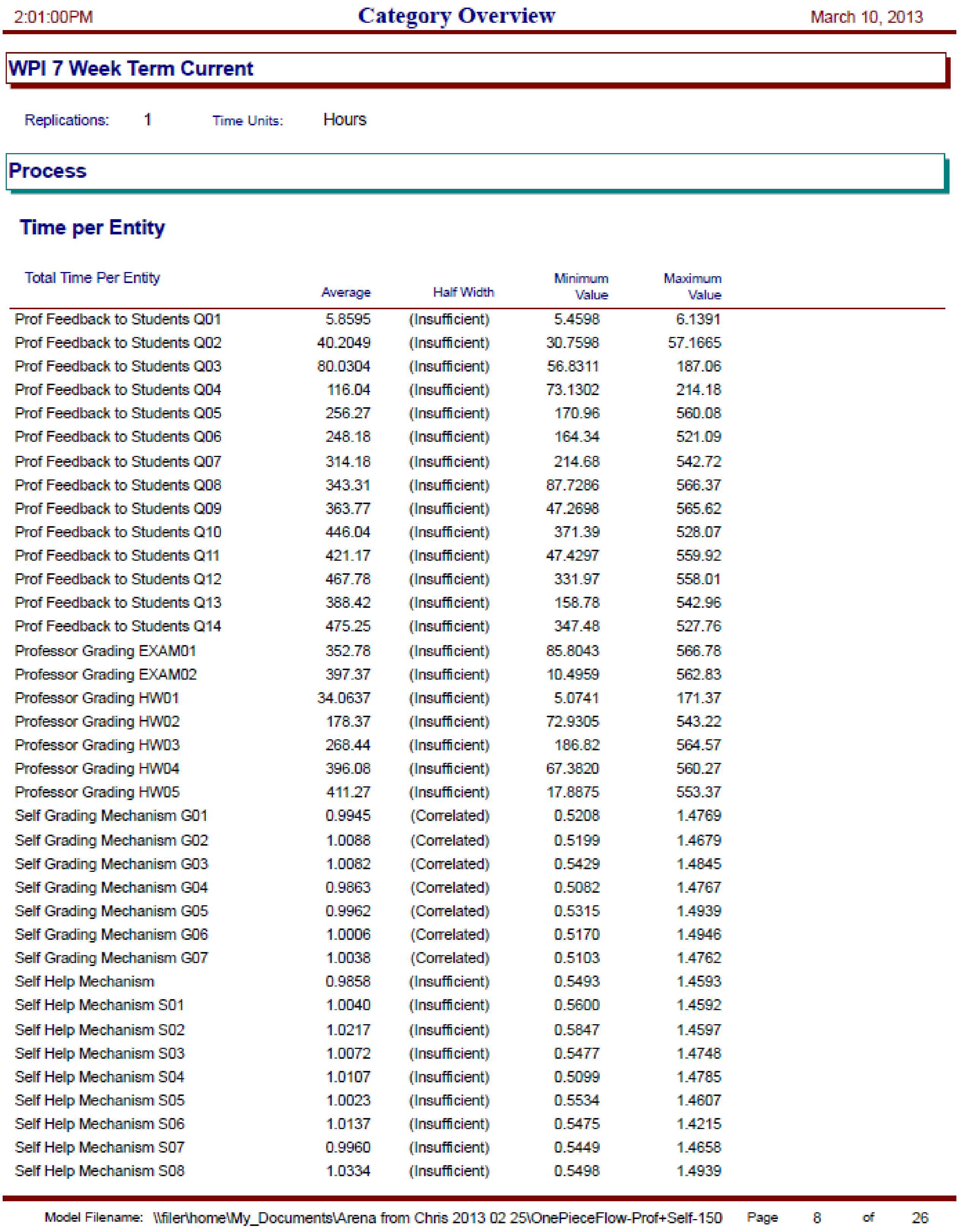
Replications: 1 Time Units: Hours

Process

Time per Entity

Wait Time Per Entity	Average	Half Width	Minimum Value	Maximum Value
Self Help Mechanism S09	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S10	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S11	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S13	0.00	(Insufficient)	0.00	0.00
Students Receive Lecture L01	0.00	0.000000000	0.00	0.00
Students Receive Lecture L02	0.00	0.000000000	0.00	0.00
Students Receive Lecture L03	0.00	0.000000000	0.00	0.00
Students Receive Lecture L04	0.00	0.000000000	0.00	0.00
Students Receive Lecture L05	0.00	0.000000000	0.00	0.00
Students Receive Lecture L06	0.00	0.000000000	0.00	0.00
Students Receive Lecture L07	0.00	0.000000000	0.00	0.00
Students Receive Lecture L08	0.00	0.000000000	0.00	0.00
Students Receive Lecture L09	0.00	0.000000000	0.00	0.00
Students Receive Lecture L10	0.00	0.000000000	0.00	0.00
Students Receive Lecture L11	0.00	0.000000000	0.00	0.00
Students Receive Lecture L12	0.00	0.000000000	0.00	0.00
Students Receive Lecture L13	0.00	0.000000000	0.00	0.00
Students Receive Lecture L14	0.00	0.000000000	0.00	0.00

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 7 of 26



2:01:00PM

Category Overview

March 10, 2013

WPI 7 Week Term Current

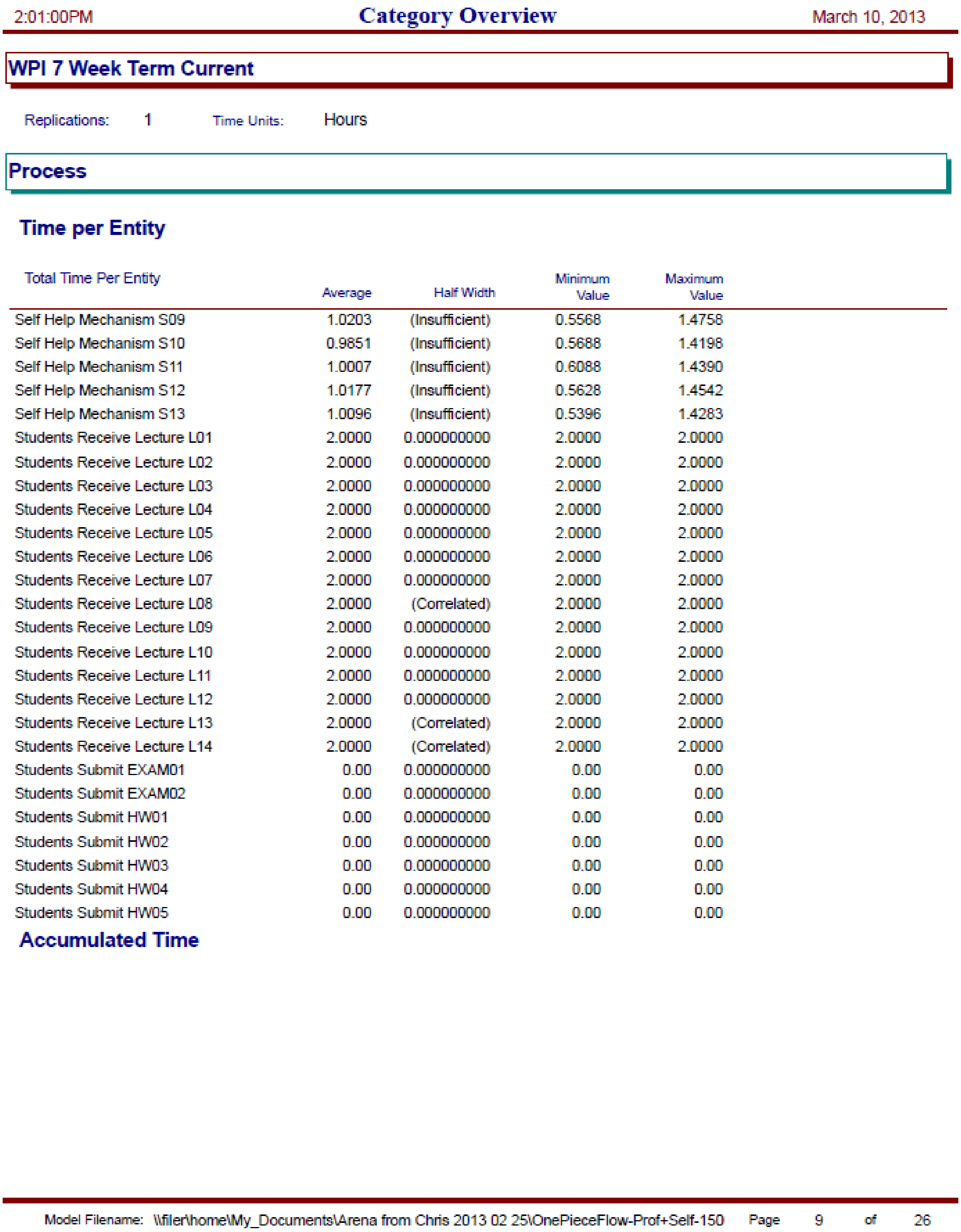
Replications: 1   Time Units: Hours

Process

Time per Entity

Total Time Per Entity	Average	Half Width	Minimum Value	Maximum Value
Prof Feedback to Students Q01	5.8595	(Insufficient)	5.4598	6.1391
Prof Feedback to Students Q02	40.2049	(Insufficient)	30.7598	57.1665
Prof Feedback to Students Q03	80.0304	(Insufficient)	56.8311	187.06
Prof Feedback to Students Q04	116.04	(Insufficient)	73.1302	214.18
Prof Feedback to Students Q05	256.27	(Insufficient)	170.96	560.08
Prof Feedback to Students Q06	248.18	(Insufficient)	164.34	521.09
Prof Feedback to Students Q07	314.18	(Insufficient)	214.68	542.72
Prof Feedback to Students Q08	343.31	(Insufficient)	87.7286	566.37
Prof Feedback to Students Q09	363.77	(Insufficient)	47.2698	565.62
Prof Feedback to Students Q10	446.04	(Insufficient)	371.39	528.07
Prof Feedback to Students Q11	421.17	(Insufficient)	47.4297	559.92
Prof Feedback to Students Q12	467.78	(Insufficient)	331.97	558.01
Prof Feedback to Students Q13	388.42	(Insufficient)	158.78	542.96
Prof Feedback to Students Q14	475.25	(Insufficient)	347.48	527.76
Professor Grading EXAM01	352.78	(Insufficient)	85.8043	566.78
Professor Grading EXAM02	397.37	(Insufficient)	10.4959	562.83
Professor Grading HW01	34.0637	(Insufficient)	5.0741	171.37
Professor Grading HW02	178.37	(Insufficient)	72.9305	543.22
Professor Grading HW03	268.44	(Insufficient)	186.82	564.57
Professor Grading HW04	396.08	(Insufficient)	67.3820	560.27
Professor Grading HW05	411.27	(Insufficient)	17.8875	553.37
Self Grading Mechanism G01	0.9945	(Correlated)	0.5208	1.4769
Self Grading Mechanism G02	1.0088	(Correlated)	0.5199	1.4679
Self Grading Mechanism G03	1.0082	(Correlated)	0.5429	1.4845
Self Grading Mechanism G04	0.9863	(Correlated)	0.5082	1.4767
Self Grading Mechanism G05	0.9962	(Correlated)	0.5315	1.4939
Self Grading Mechanism G06	1.0006	(Correlated)	0.5170	1.4946
Self Grading Mechanism G07	1.0038	(Correlated)	0.5103	1.4762
Self Help Mechanism	0.9858	(Insufficient)	0.5493	1.4593
Self Help Mechanism S01	1.0040	(Insufficient)	0.5600	1.4592
Self Help Mechanism S02	1.0217	(Insufficient)	0.5847	1.4597
Self Help Mechanism S03	1.0072	(Insufficient)	0.5477	1.4748
Self Help Mechanism S04	1.0107	(Insufficient)	0.5099	1.4785
Self Help Mechanism S05	1.0023	(Insufficient)	0.5534	1.4607
Self Help Mechanism S06	1.0137	(Insufficient)	0.5475	1.4215
Self Help Mechanism S07	0.9960	(Insufficient)	0.5449	1.4658
Self Help Mechanism S08	1.0334	(Insufficient)	0.5498	1.4939

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150   Page 8 of 26



2:01:00PM

Category Overview

March 10, 2013

WPI 7 Week Term Current

Replications: 1 Time Units: Hours

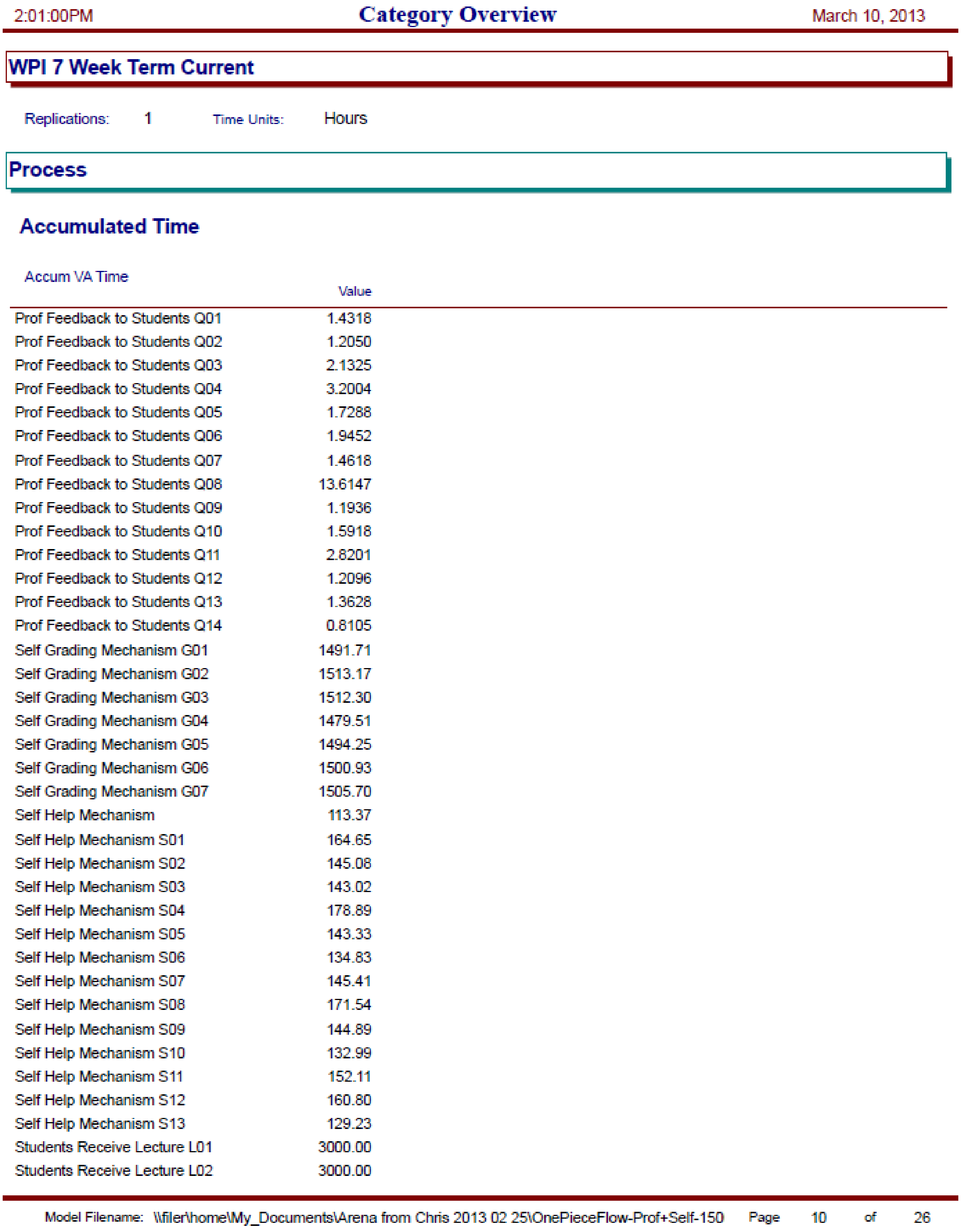
Process

Time per Entity

Total Time Per Entity	Average	Half Width	Minimum Value	Maximum Value
Self Help Mechanism S09	1.0203	(Insufficient)	0.5568	1.4758
Self Help Mechanism S10	0.9851	(Insufficient)	0.5688	1.4198
Self Help Mechanism S11	1.0007	(Insufficient)	0.6088	1.4390
Self Help Mechanism S12	1.0177	(Insufficient)	0.5628	1.4542
Self Help Mechanism S13	1.0096	(Insufficient)	0.5396	1.4283
Students Receive Lecture L01	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L02	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L03	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L04	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L05	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L06	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L07	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L08	2.0000	(Correlated)	2.0000	2.0000
Students Receive Lecture L09	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L10	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L11	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L12	2.0000	0.000000000	2.0000	2.0000
Students Receive Lecture L13	2.0000	(Correlated)	2.0000	2.0000
Students Receive Lecture L14	2.0000	(Correlated)	2.0000	2.0000
Students Submit EXAM01	0.00	0.000000000	0.00	0.00
Students Submit EXAM02	0.00	0.000000000	0.00	0.00
Students Submit HW01	0.00	0.000000000	0.00	0.00
Students Submit HW02	0.00	0.000000000	0.00	0.00
Students Submit HW03	0.00	0.000000000	0.00	0.00
Students Submit HW04	0.00	0.000000000	0.00	0.00
Students Submit HW05	0.00	0.000000000	0.00	0.00

Accumulated Time

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 9 of 26



2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

Replications: 1 Time Units: Hours

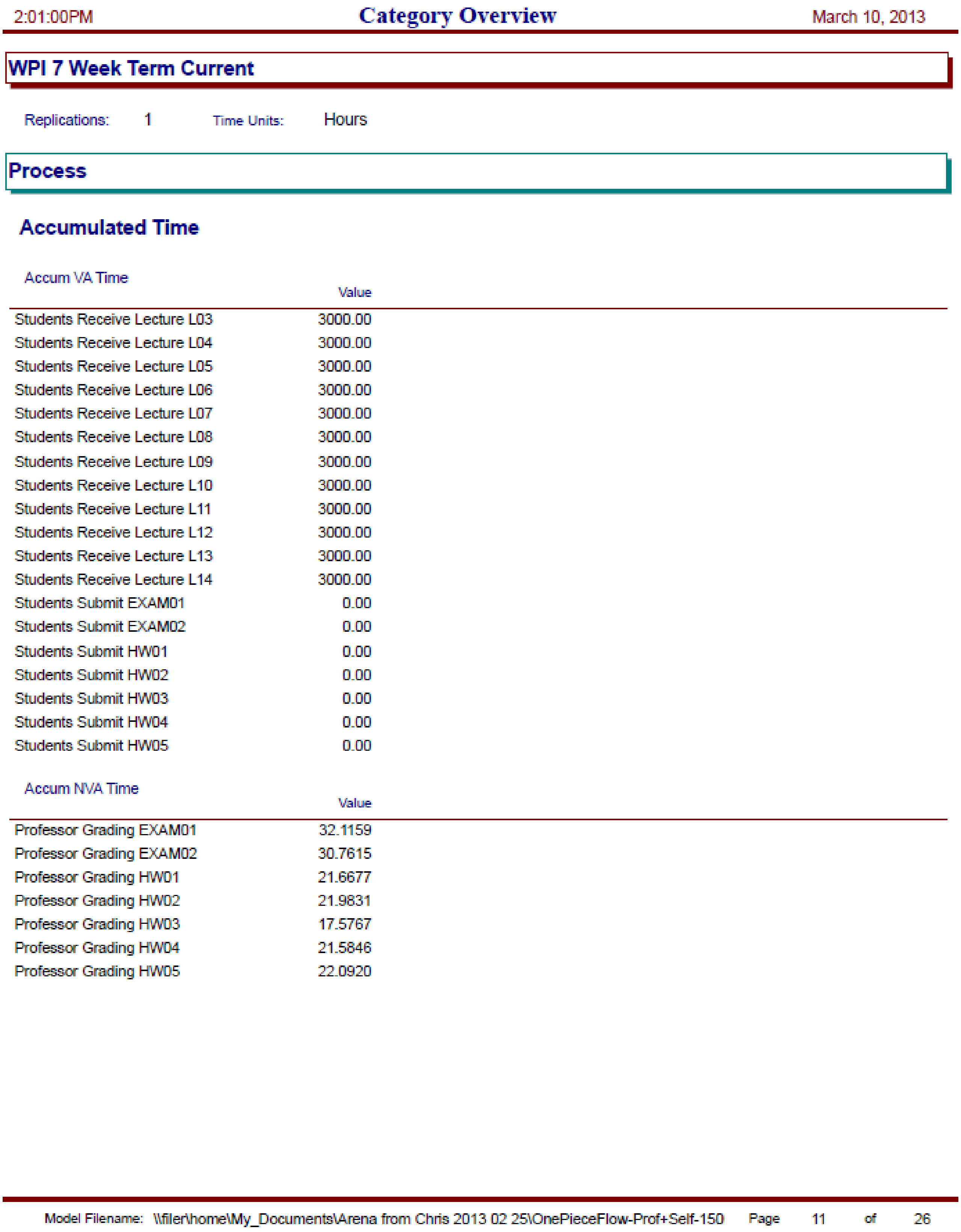
Process

Accumulated Time

Accum VA Time

	Value
Prof Feedback to Students Q01	1.4318
Prof Feedback to Students Q02	1.2050
Prof Feedback to Students Q03	2.1325
Prof Feedback to Students Q04	3.2004
Prof Feedback to Students Q05	1.7288
Prof Feedback to Students Q06	1.9452
Prof Feedback to Students Q07	1.4618
Prof Feedback to Students Q08	13.6147
Prof Feedback to Students Q09	1.1936
Prof Feedback to Students Q10	1.5918
Prof Feedback to Students Q11	2.8201
Prof Feedback to Students Q12	1.2096
Prof Feedback to Students Q13	1.3628
Prof Feedback to Students Q14	0.8105
Self Grading Mechanism G01	1491.71
Self Grading Mechanism G02	1513.17
Self Grading Mechanism G03	1512.30
Self Grading Mechanism G04	1479.51
Self Grading Mechanism G05	1494.25
Self Grading Mechanism G06	1500.93
Self Grading Mechanism G07	1505.70
Self Help Mechanism	113.37
Self Help Mechanism S01	164.65
Self Help Mechanism S02	145.08
Self Help Mechanism S03	143.02
Self Help Mechanism S04	178.89
Self Help Mechanism S05	143.33
Self Help Mechanism S06	134.83
Self Help Mechanism S07	145.41
Self Help Mechanism S08	171.54
Self Help Mechanism S09	144.89
Self Help Mechanism S10	132.99
Self Help Mechanism S11	152.11
Self Help Mechanism S12	160.80
Self Help Mechanism S13	129.23
Students Receive Lecture L01	3000.00
Students Receive Lecture L02	3000.00

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 10 of 26



2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

Replications: 1 Time Units: Hours

Process

Accumulated Time

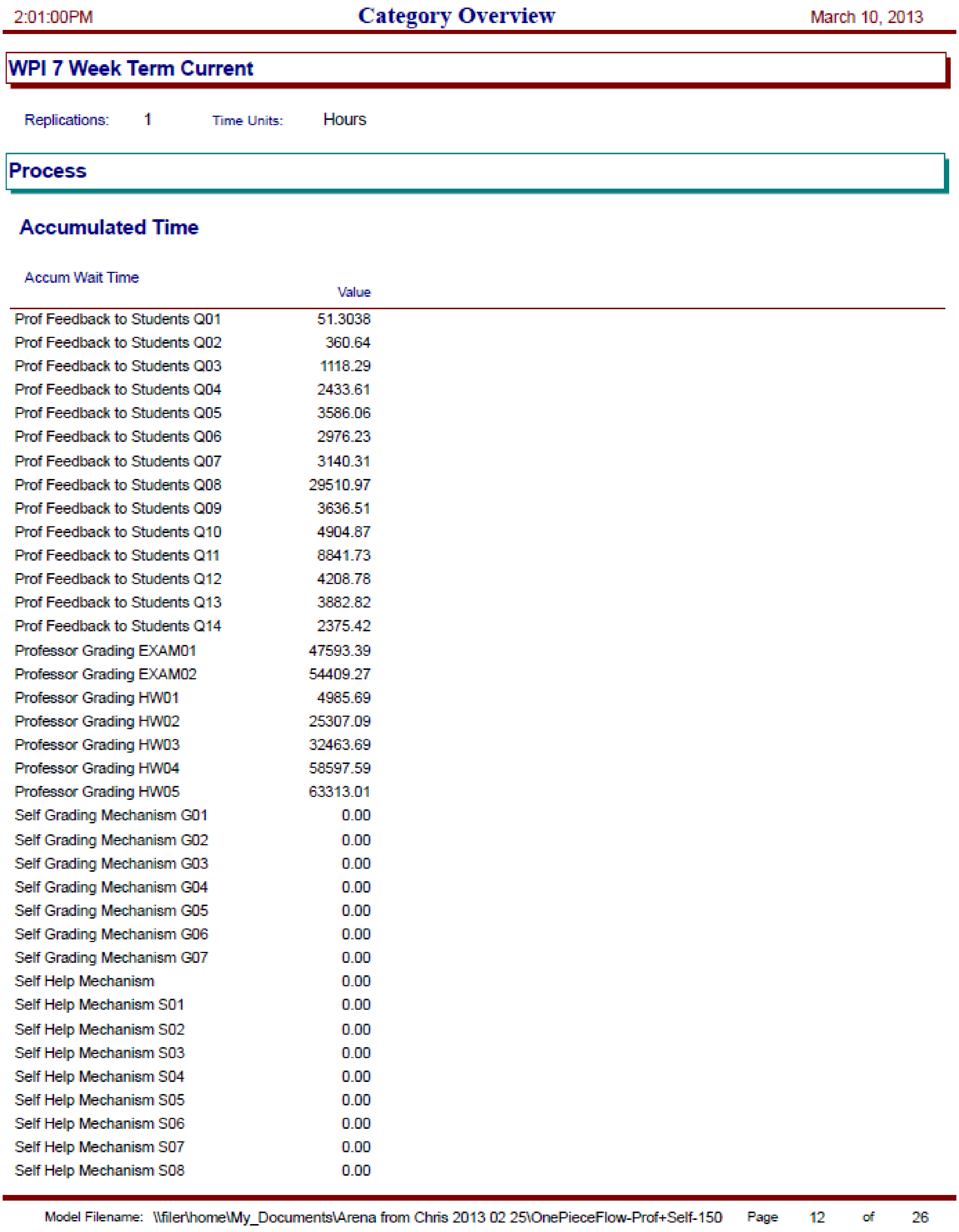
Accum VA Time

	Value
Students Receive Lecture L03	3000.00
Students Receive Lecture L04	3000.00
Students Receive Lecture L05	3000.00
Students Receive Lecture L06	3000.00
Students Receive Lecture L07	3000.00
Students Receive Lecture L08	3000.00
Students Receive Lecture L09	3000.00
Students Receive Lecture L10	3000.00
Students Receive Lecture L11	3000.00
Students Receive Lecture L12	3000.00
Students Receive Lecture L13	3000.00
Students Receive Lecture L14	3000.00
Students Submit EXAM01	0.00
Students Submit EXAM02	0.00
Students Submit HW01	0.00
Students Submit HW02	0.00
Students Submit HW03	0.00
Students Submit HW04	0.00
Students Submit HW05	0.00

Accum NVA Time

	Value
Professor Grading EXAM01	32.1159
Professor Grading EXAM02	30.7615
Professor Grading HW01	21.6677
Professor Grading HW02	21.9831
Professor Grading HW03	17.5767
Professor Grading HW04	21.5846
Professor Grading HW05	22.0920

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 11 of 26



2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

Replications: 1 Time Units: Hours

Process

Accumulated Time

Accum Wait Time

	Value
Prof Feedback to Students Q01	51.3038
Prof Feedback to Students Q02	360.64
Prof Feedback to Students Q03	1118.29
Prof Feedback to Students Q04	2433.61
Prof Feedback to Students Q05	3586.06
Prof Feedback to Students Q06	2976.23
Prof Feedback to Students Q07	3140.31
Prof Feedback to Students Q08	29510.97
Prof Feedback to Students Q09	3636.51
Prof Feedback to Students Q10	4904.87
Prof Feedback to Students Q11	8841.73
Prof Feedback to Students Q12	4208.78
Prof Feedback to Students Q13	3882.82
Prof Feedback to Students Q14	2375.42
Professor Grading EXAM01	47593.39
Professor Grading EXAM02	54409.27
Professor Grading HW01	4985.69
Professor Grading HW02	25307.09
Professor Grading HW03	32463.69
Professor Grading HW04	58597.59
Professor Grading HW05	63313.01
Self Grading Mechanism G01	0.00
Self Grading Mechanism G02	0.00
Self Grading Mechanism G03	0.00
Self Grading Mechanism G04	0.00
Self Grading Mechanism G05	0.00
Self Grading Mechanism G06	0.00
Self Grading Mechanism G07	0.00
Self Help Mechanism	0.00
Self Help Mechanism S01	0.00
Self Help Mechanism S02	0.00
Self Help Mechanism S03	0.00
Self Help Mechanism S04	0.00
Self Help Mechanism S05	0.00
Self Help Mechanism S06	0.00
Self Help Mechanism S07	0.00
Self Help Mechanism S08	0.00

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 12 of 26

WPI 7 Week Term Current

Replications: 1 Time Units: Hours

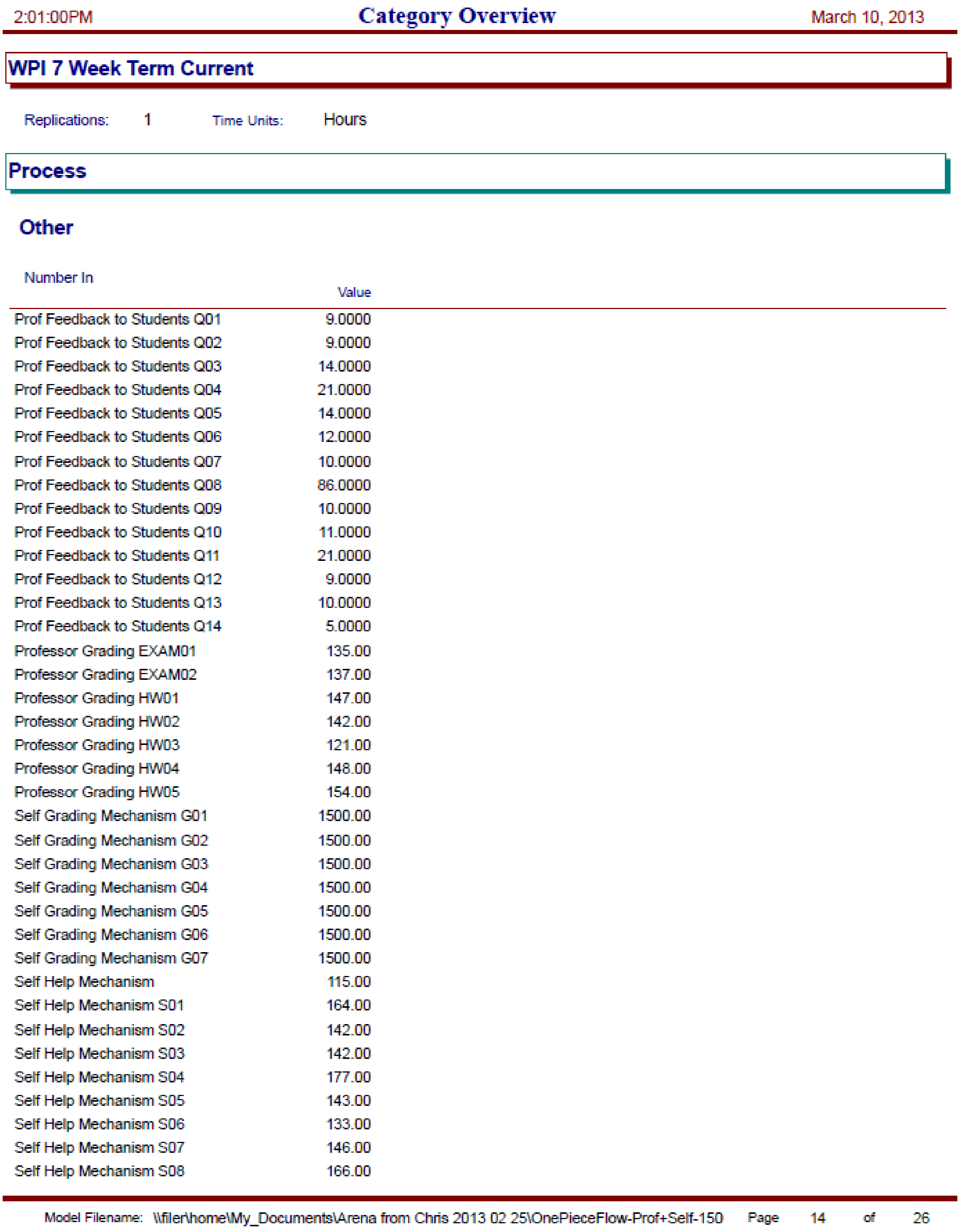
Process

Accumulated Time

Accum Wait Time

	Value
Self Help Mechanism S09	0.00
Self Help Mechanism S10	0.00
Self Help Mechanism S11	0.00
Self Help Mechanism S13	0.00
Students Receive Lecture L01	0.00
Students Receive Lecture L02	0.00
Students Receive Lecture L03	0.00
Students Receive Lecture L04	0.00
Students Receive Lecture L05	0.00
Students Receive Lecture L06	0.00
Students Receive Lecture L07	0.00
Students Receive Lecture L08	0.00
Students Receive Lecture L09	0.00
Students Receive Lecture L10	0.00
Students Receive Lecture L11	0.00
Students Receive Lecture L12	0.00
Students Receive Lecture L13	0.00
Students Receive Lecture L14	0.00

Other



2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

Replications: 1 Time Units: Hours

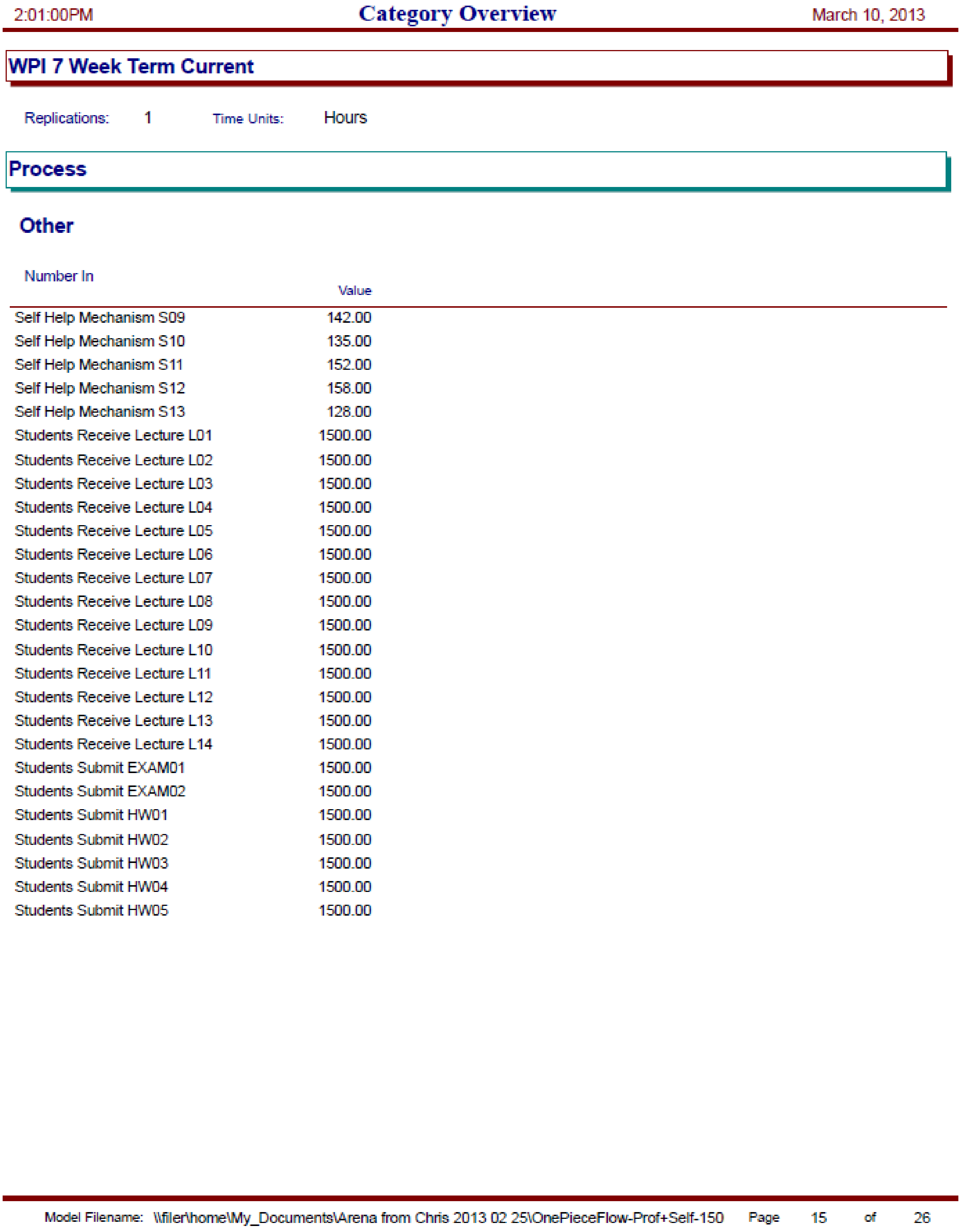
Process

Other

Number In

	Value
Prof Feedback to Students Q01	9.0000
Prof Feedback to Students Q02	9.0000
Prof Feedback to Students Q03	14.0000
Prof Feedback to Students Q04	21.0000
Prof Feedback to Students Q05	14.0000
Prof Feedback to Students Q06	12.0000
Prof Feedback to Students Q07	10.0000
Prof Feedback to Students Q08	86.0000
Prof Feedback to Students Q09	10.0000
Prof Feedback to Students Q10	11.0000
Prof Feedback to Students Q11	21.0000
Prof Feedback to Students Q12	9.0000
Prof Feedback to Students Q13	10.0000
Prof Feedback to Students Q14	5.0000
Professor Grading EXAM01	135.00
Professor Grading EXAM02	137.00
Professor Grading HW01	147.00
Professor Grading HW02	142.00
Professor Grading HW03	121.00
Professor Grading HW04	148.00
Professor Grading HW05	154.00
Self Grading Mechanism G01	1500.00
Self Grading Mechanism G02	1500.00
Self Grading Mechanism G03	1500.00
Self Grading Mechanism G04	1500.00
Self Grading Mechanism G05	1500.00
Self Grading Mechanism G06	1500.00
Self Grading Mechanism G07	1500.00
Self Help Mechanism	115.00
Self Help Mechanism S01	164.00
Self Help Mechanism S02	142.00
Self Help Mechanism S03	142.00
Self Help Mechanism S04	177.00
Self Help Mechanism S05	143.00
Self Help Mechanism S06	133.00
Self Help Mechanism S07	146.00
Self Help Mechanism S08	166.00

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 14 of 26



2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

Replications: 1 Time Units: Hours

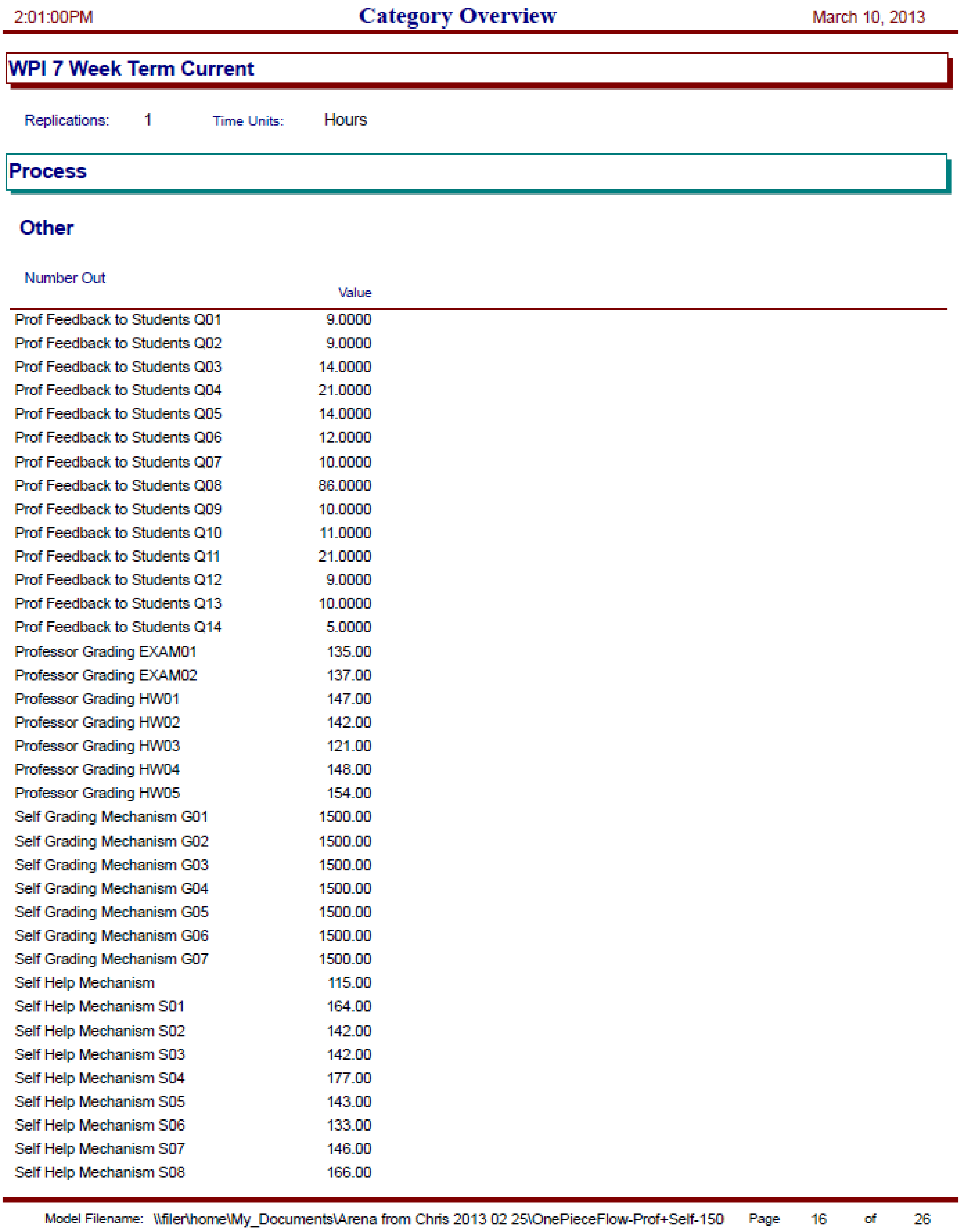
Process

Other

Number In

	Value
Self Help Mechanism S09	142.00
Self Help Mechanism S10	135.00
Self Help Mechanism S11	152.00
Self Help Mechanism S12	158.00
Self Help Mechanism S13	128.00
Students Receive Lecture L01	1500.00
Students Receive Lecture L02	1500.00
Students Receive Lecture L03	1500.00
Students Receive Lecture L04	1500.00
Students Receive Lecture L05	1500.00
Students Receive Lecture L06	1500.00
Students Receive Lecture L07	1500.00
Students Receive Lecture L08	1500.00
Students Receive Lecture L09	1500.00
Students Receive Lecture L10	1500.00
Students Receive Lecture L11	1500.00
Students Receive Lecture L12	1500.00
Students Receive Lecture L13	1500.00
Students Receive Lecture L14	1500.00
Students Submit EXAM01	1500.00
Students Submit EXAM02	1500.00
Students Submit HW01	1500.00
Students Submit HW02	1500.00
Students Submit HW03	1500.00
Students Submit HW04	1500.00
Students Submit HW05	1500.00

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 15 of 26



2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

Replications: 1 Time Units: Hours

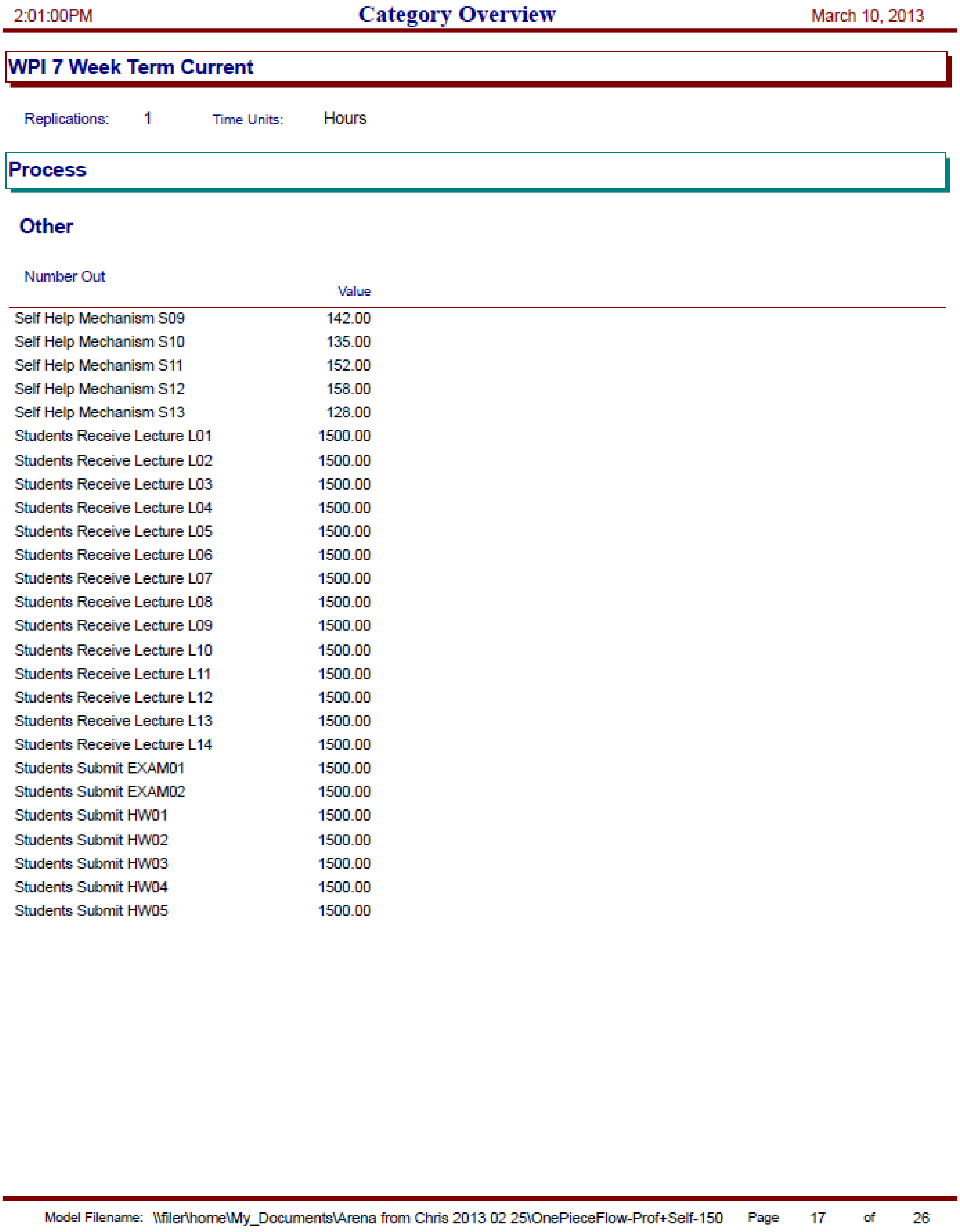
Process

Other

Number Out

	Value
Prof Feedback to Students Q01	9.0000
Prof Feedback to Students Q02	9.0000
Prof Feedback to Students Q03	14.0000
Prof Feedback to Students Q04	21.0000
Prof Feedback to Students Q05	14.0000
Prof Feedback to Students Q06	12.0000
Prof Feedback to Students Q07	10.0000
Prof Feedback to Students Q08	86.0000
Prof Feedback to Students Q09	10.0000
Prof Feedback to Students Q10	11.0000
Prof Feedback to Students Q11	21.0000
Prof Feedback to Students Q12	9.0000
Prof Feedback to Students Q13	10.0000
Prof Feedback to Students Q14	5.0000
Professor Grading EXAM01	135.00
Professor Grading EXAM02	137.00
Professor Grading HW01	147.00
Professor Grading HW02	142.00
Professor Grading HW03	121.00
Professor Grading HW04	148.00
Professor Grading HW05	154.00
Self Grading Mechanism G01	1500.00
Self Grading Mechanism G02	1500.00
Self Grading Mechanism G03	1500.00
Self Grading Mechanism G04	1500.00
Self Grading Mechanism G05	1500.00
Self Grading Mechanism G06	1500.00
Self Grading Mechanism G07	1500.00
Self Help Mechanism	115.00
Self Help Mechanism S01	164.00
Self Help Mechanism S02	142.00
Self Help Mechanism S03	142.00
Self Help Mechanism S04	177.00
Self Help Mechanism S05	143.00
Self Help Mechanism S06	133.00
Self Help Mechanism S07	146.00
Self Help Mechanism S08	166.00

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 16 of 26



2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

Replications: 1 Time Units: Hours

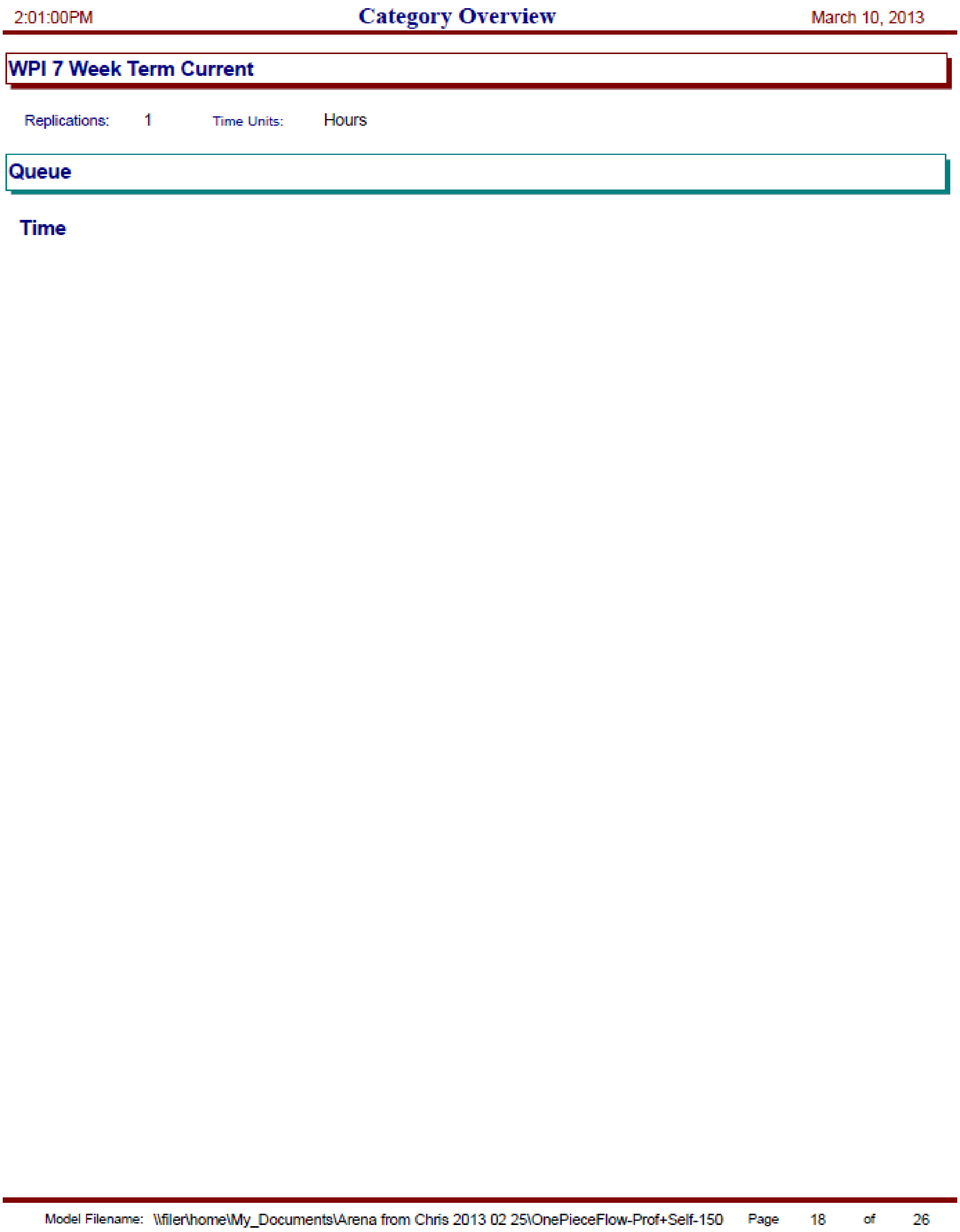
Process

Other

Number Out

	Value
Self Help Mechanism S09	142.00
Self Help Mechanism S10	135.00
Self Help Mechanism S11	152.00
Self Help Mechanism S12	158.00
Self Help Mechanism S13	128.00
Students Receive Lecture L01	1500.00
Students Receive Lecture L02	1500.00
Students Receive Lecture L03	1500.00
Students Receive Lecture L04	1500.00
Students Receive Lecture L05	1500.00
Students Receive Lecture L06	1500.00
Students Receive Lecture L07	1500.00
Students Receive Lecture L08	1500.00
Students Receive Lecture L09	1500.00
Students Receive Lecture L10	1500.00
Students Receive Lecture L11	1500.00
Students Receive Lecture L12	1500.00
Students Receive Lecture L13	1500.00
Students Receive Lecture L14	1500.00
Students Submit EXAM01	1500.00
Students Submit EXAM02	1500.00
Students Submit HW01	1500.00
Students Submit HW02	1500.00
Students Submit HW03	1500.00
Students Submit HW04	1500.00
Students Submit HW05	1500.00

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 17 of 26



2:01:00PM **Category Overview** March 10, 2013

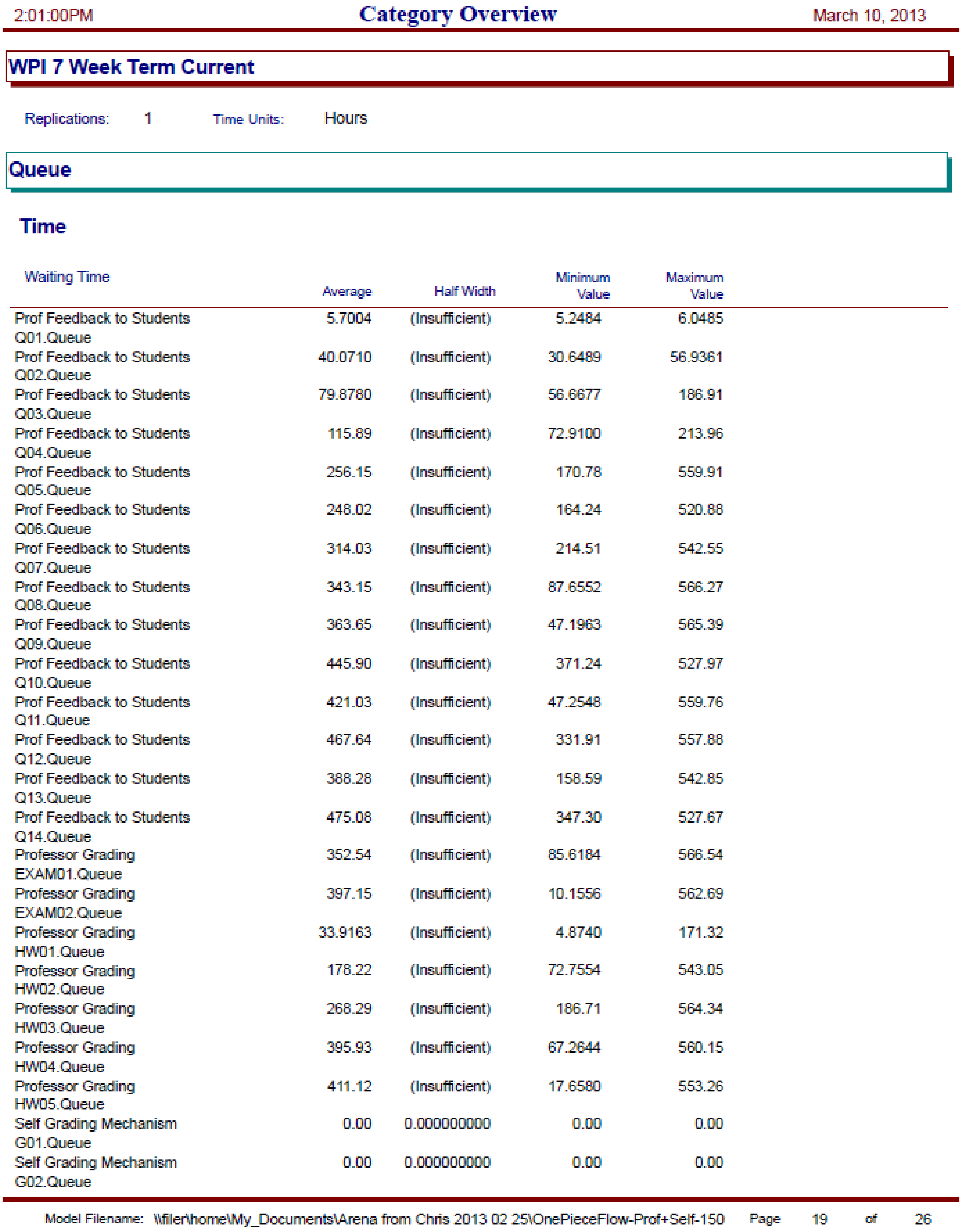
WPI 7 Week Term Current

Replications: 1 Time Units: Hours

Queue

Time

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 18 of 26



2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

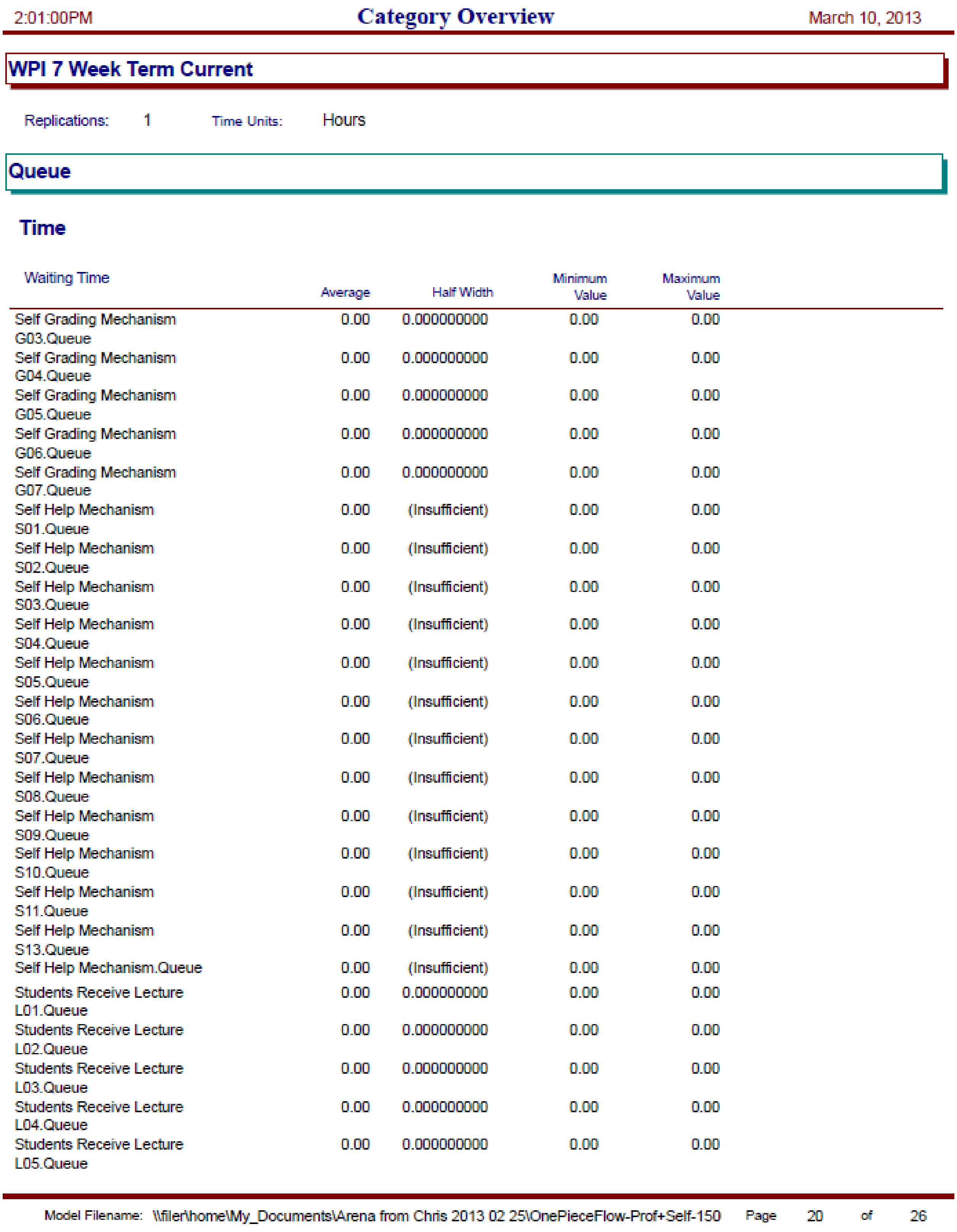
Replications: 1 Time Units: Hours

Queue

Time

Waiting Time	Average	Half Width	Minimum Value	Maximum Value
Prof Feedback to Students Q01.Queue	5.7004	(Insufficient)	5.2484	6.0485
Prof Feedback to Students Q02.Queue	40.0710	(Insufficient)	30.6489	56.9361
Prof Feedback to Students Q03.Queue	79.8780	(Insufficient)	56.6677	186.91
Prof Feedback to Students Q04.Queue	115.89	(Insufficient)	72.9100	213.96
Prof Feedback to Students Q05.Queue	256.15	(Insufficient)	170.78	559.91
Prof Feedback to Students Q06.Queue	248.02	(Insufficient)	164.24	520.88
Prof Feedback to Students Q07.Queue	314.03	(Insufficient)	214.51	542.55
Prof Feedback to Students Q08.Queue	343.15	(Insufficient)	87.6552	566.27
Prof Feedback to Students Q09.Queue	363.65	(Insufficient)	47.1963	565.39
Prof Feedback to Students Q10.Queue	445.90	(Insufficient)	371.24	527.97
Prof Feedback to Students Q11.Queue	421.03	(Insufficient)	47.2548	559.76
Prof Feedback to Students Q12.Queue	467.64	(Insufficient)	331.91	557.88
Prof Feedback to Students Q13.Queue	388.28	(Insufficient)	158.59	542.85
Prof Feedback to Students Q14.Queue	475.08	(Insufficient)	347.30	527.67
Professor Grading EXAM01.Queue	352.54	(Insufficient)	85.6184	566.54
Professor Grading EXAM02.Queue	397.15	(Insufficient)	10.1556	562.69
Professor Grading HW01.Queue	33.9163	(Insufficient)	4.8740	171.32
Professor Grading HW02.Queue	178.22	(Insufficient)	72.7554	543.05
Professor Grading HW03.Queue	268.29	(Insufficient)	186.71	564.34
Professor Grading HW04.Queue	395.93	(Insufficient)	67.2644	560.15
Professor Grading HW05.Queue	411.12	(Insufficient)	17.6580	553.26
Self Grading Mechanism G01.Queue	0.00	0.000000000	0.00	0.00
Self Grading Mechanism G02.Queue	0.00	0.000000000	0.00	0.00

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 19 of 26



2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

Replications: 1 Time Units: Hours

Queue

Time

Waiting Time	Average	Half Width	Minimum Value	Maximum Value
Self Grading Mechanism G03.Queue	0.00	0.000000000	0.00	0.00
Self Grading Mechanism G04.Queue	0.00	0.000000000	0.00	0.00
Self Grading Mechanism G05.Queue	0.00	0.000000000	0.00	0.00
Self Grading Mechanism G06.Queue	0.00	0.000000000	0.00	0.00
Self Grading Mechanism G07.Queue	0.00	0.000000000	0.00	0.00
Self Help Mechanism S01.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S02.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S03.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S04.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S05.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S06.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S07.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S08.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S09.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S10.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S11.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S13.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism.Queue	0.00	(Insufficient)	0.00	0.00
Students Receive Lecture L01.Queue	0.00	0.000000000	0.00	0.00
Students Receive Lecture L02.Queue	0.00	0.000000000	0.00	0.00
Students Receive Lecture L03.Queue	0.00	0.000000000	0.00	0.00
Students Receive Lecture L04.Queue	0.00	0.000000000	0.00	0.00
Students Receive Lecture L05.Queue	0.00	0.000000000	0.00	0.00

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 20 of 26

2:01:00PM

Category Overview

March 10, 2013

WPI 7 Week Term Current

Replications: 1 Time Units: Hours

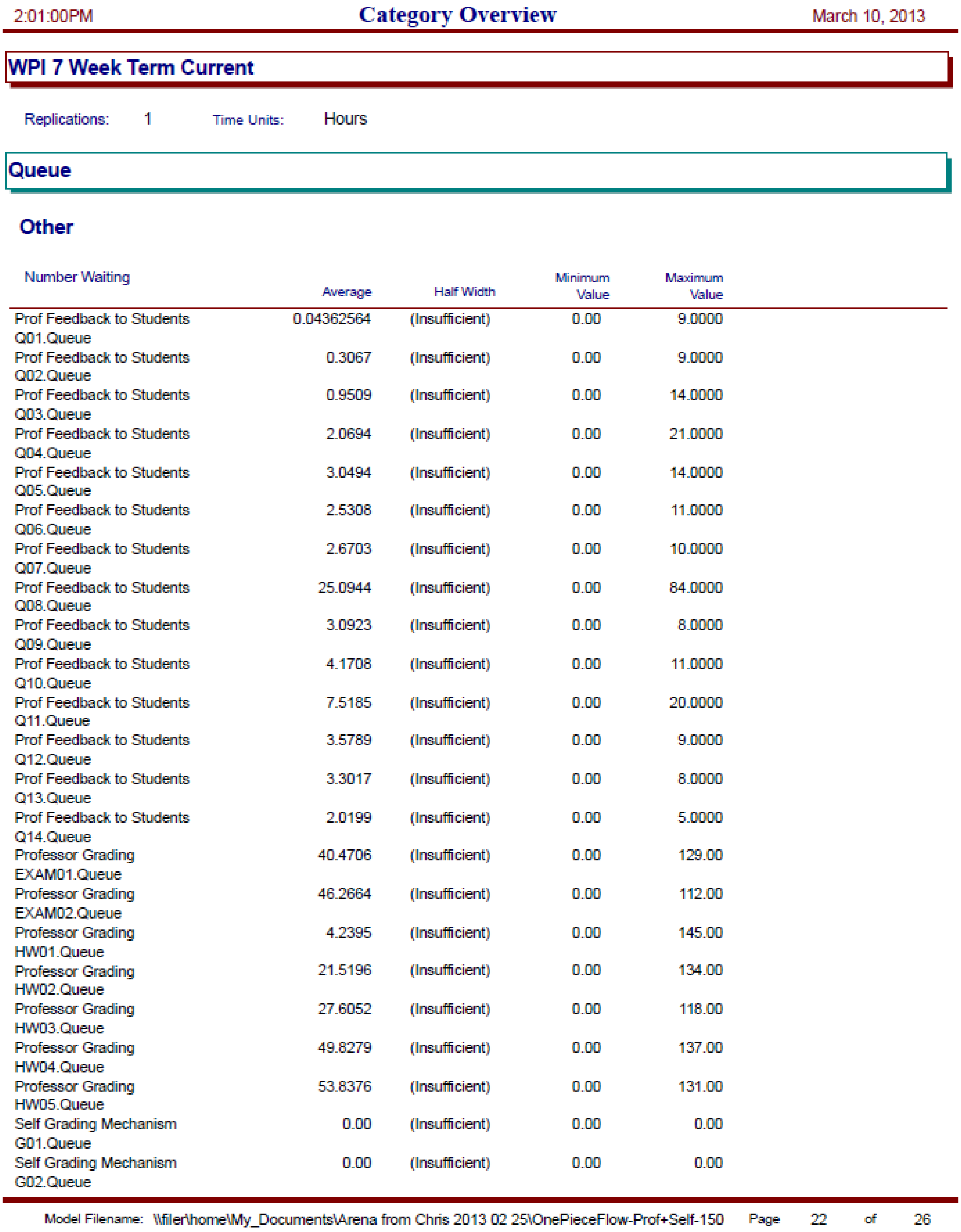
Queue

Time

Waiting Time	Average	Half Width	Minimum Value	Maximum Value
Students Receive Lecture L06.Queue	0.00	0.000000000	0.00	0.00
Students Receive Lecture L07.Queue	0.00	0.000000000	0.00	0.00
Students Receive Lecture L08.Queue	0.00	0.000000000	0.00	0.00
Students Receive Lecture L09.Queue	0.00	0.000000000	0.00	0.00
Students Receive Lecture L10.Queue	0.00	0.000000000	0.00	0.00
Students Receive Lecture L11.Queue	0.00	0.000000000	0.00	0.00
Students Receive Lecture L12.Queue	0.00	0.000000000	0.00	0.00
Students Receive Lecture L13.Queue	0.00	0.000000000	0.00	0.00
Students Receive Lecture L14.Queue	0.00	0.000000000	0.00	0.00

Other

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 21 of 26



2:01:00PM

Category Overview

March 10, 2013

WPI 7 Week Term Current

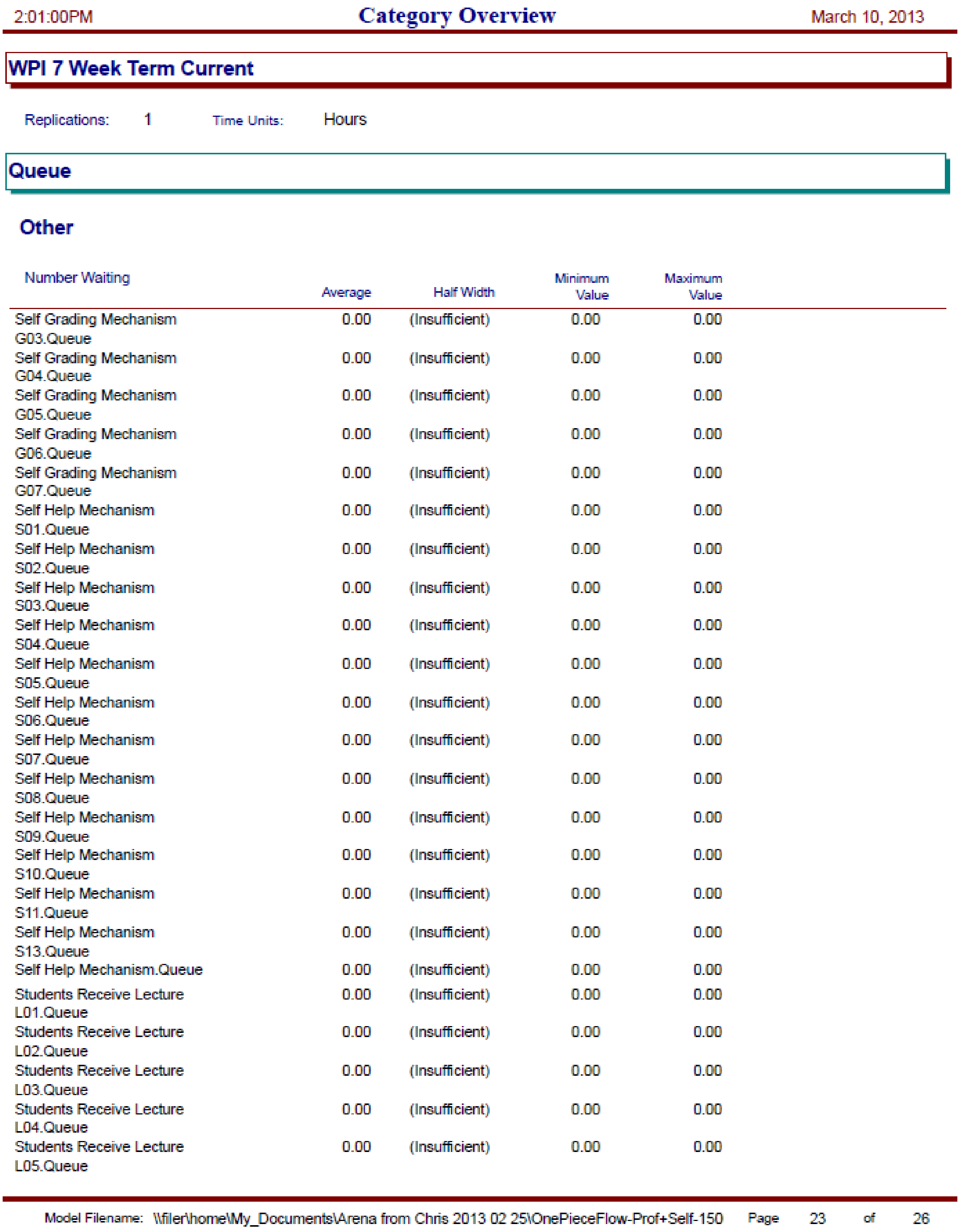
Replications: 1 Time Units: Hours

Queue

Other

Number Waiting	Average	Half Width	Minimum Value	Maximum Value
Prof Feedback to Students Q01.Queue	0.04362564	(Insufficient)	0.00	9.0000
Prof Feedback to Students Q02.Queue	0.3067	(Insufficient)	0.00	9.0000
Prof Feedback to Students Q03.Queue	0.9509	(Insufficient)	0.00	14.0000
Prof Feedback to Students Q04.Queue	2.0694	(Insufficient)	0.00	21.0000
Prof Feedback to Students Q05.Queue	3.0494	(Insufficient)	0.00	14.0000
Prof Feedback to Students Q06.Queue	2.5308	(Insufficient)	0.00	11.0000
Prof Feedback to Students Q07.Queue	2.6703	(Insufficient)	0.00	10.0000
Prof Feedback to Students Q08.Queue	25.0944	(Insufficient)	0.00	84.0000
Prof Feedback to Students Q09.Queue	3.0923	(Insufficient)	0.00	8.0000
Prof Feedback to Students Q10.Queue	4.1708	(Insufficient)	0.00	11.0000
Prof Feedback to Students Q11.Queue	7.5185	(Insufficient)	0.00	20.0000
Prof Feedback to Students Q12.Queue	3.5789	(Insufficient)	0.00	9.0000
Prof Feedback to Students Q13.Queue	3.3017	(Insufficient)	0.00	8.0000
Prof Feedback to Students Q14.Queue	2.0199	(Insufficient)	0.00	5.0000
Professor Grading EXAM01.Queue	40.4706	(Insufficient)	0.00	129.00
Professor Grading EXAM02.Queue	46.2664	(Insufficient)	0.00	112.00
Professor Grading HW01.Queue	4.2395	(Insufficient)	0.00	145.00
Professor Grading HW02.Queue	21.5196	(Insufficient)	0.00	134.00
Professor Grading HW03.Queue	27.6052	(Insufficient)	0.00	118.00
Professor Grading HW04.Queue	49.8279	(Insufficient)	0.00	137.00
Professor Grading HW05.Queue	53.8376	(Insufficient)	0.00	131.00
Self Grading Mechanism G01.Queue	0.00	(Insufficient)	0.00	0.00
Self Grading Mechanism G02.Queue	0.00	(Insufficient)	0.00	0.00

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 22 of 26



2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

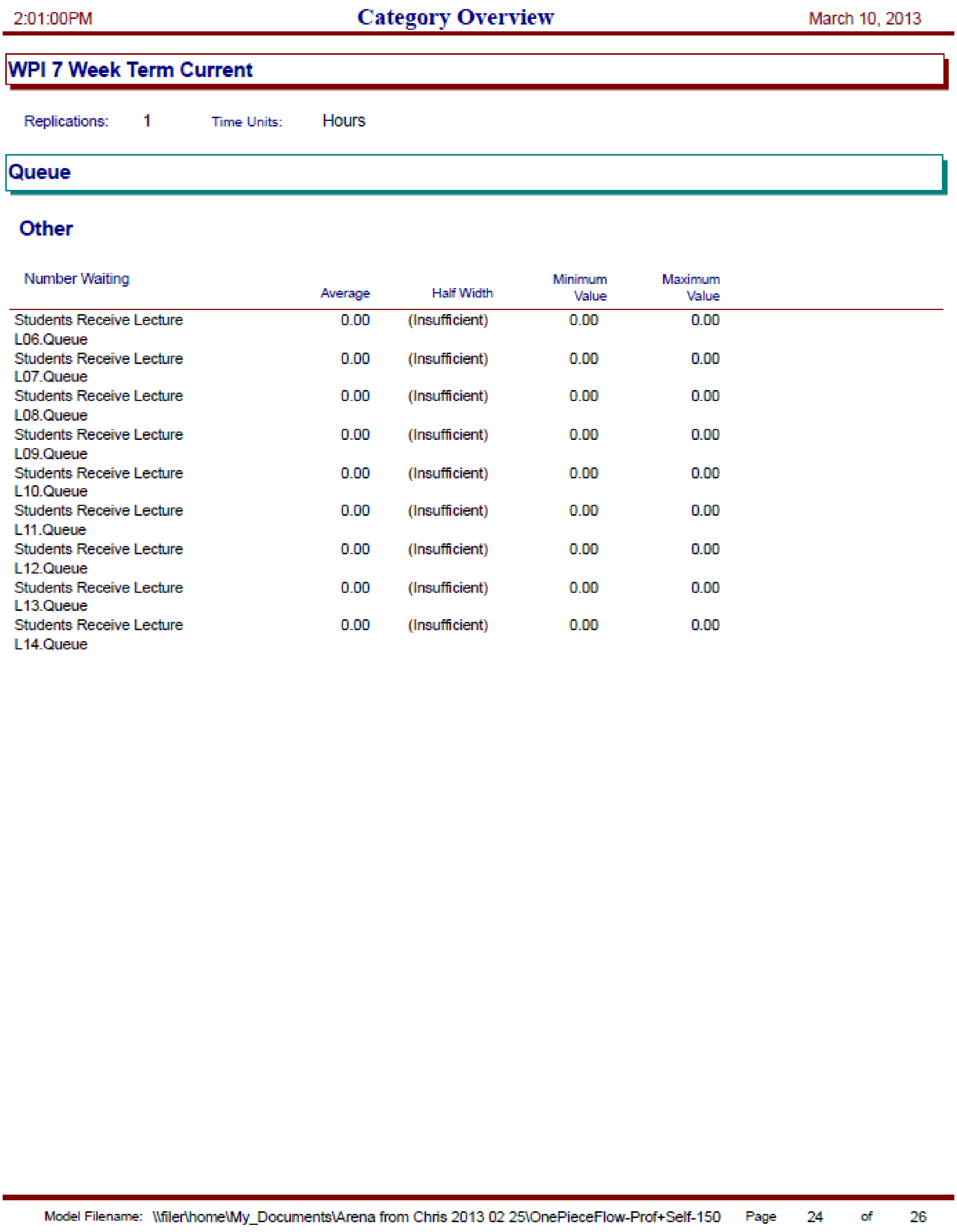
Replications: 1 Time Units: Hours

Queue

Other

Number Waiting	Average	Half Width	Minimum Value	Maximum Value
Self Grading Mechanism G03.Queue	0.00	(Insufficient)	0.00	0.00
Self Grading Mechanism G04.Queue	0.00	(Insufficient)	0.00	0.00
Self Grading Mechanism G05.Queue	0.00	(Insufficient)	0.00	0.00
Self Grading Mechanism G06.Queue	0.00	(Insufficient)	0.00	0.00
Self Grading Mechanism G07.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S01.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S02.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S03.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S04.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S05.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S06.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S07.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S08.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S09.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S10.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S11.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism S13.Queue	0.00	(Insufficient)	0.00	0.00
Self Help Mechanism.Queue	0.00	(Insufficient)	0.00	0.00
Students Receive Lecture L01.Queue	0.00	(Insufficient)	0.00	0.00
Students Receive Lecture L02.Queue	0.00	(Insufficient)	0.00	0.00
Students Receive Lecture L03.Queue	0.00	(Insufficient)	0.00	0.00
Students Receive Lecture L04.Queue	0.00	(Insufficient)	0.00	0.00
Students Receive Lecture L05.Queue	0.00	(Insufficient)	0.00	0.00

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 23 of 26



2:01:00PM

Category Overview

March 10, 2013

WPI 7 Week Term Current

Replications: 1 Time Units: Hours

Queue

Other

Number Waiting	Average	Half Width	Minimum Value	Maximum Value
Students Receive Lecture L06.Queue	0.00	(Insufficient)	0.00	0.00
Students Receive Lecture L07.Queue	0.00	(Insufficient)	0.00	0.00
Students Receive Lecture L08.Queue	0.00	(Insufficient)	0.00	0.00
Students Receive Lecture L09.Queue	0.00	(Insufficient)	0.00	0.00
Students Receive Lecture L10.Queue	0.00	(Insufficient)	0.00	0.00
Students Receive Lecture L11.Queue	0.00	(Insufficient)	0.00	0.00
Students Receive Lecture L12.Queue	0.00	(Insufficient)	0.00	0.00
Students Receive Lecture L13.Queue	0.00	(Insufficient)	0.00	0.00
Students Receive Lecture L14.Queue	0.00	(Insufficient)	0.00	0.00

Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 24 of 26

2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

Replications: 1 Time Units: Hours

Resource

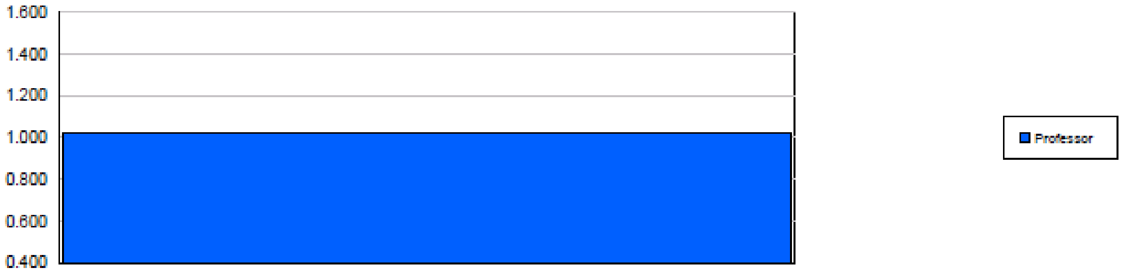
Usage

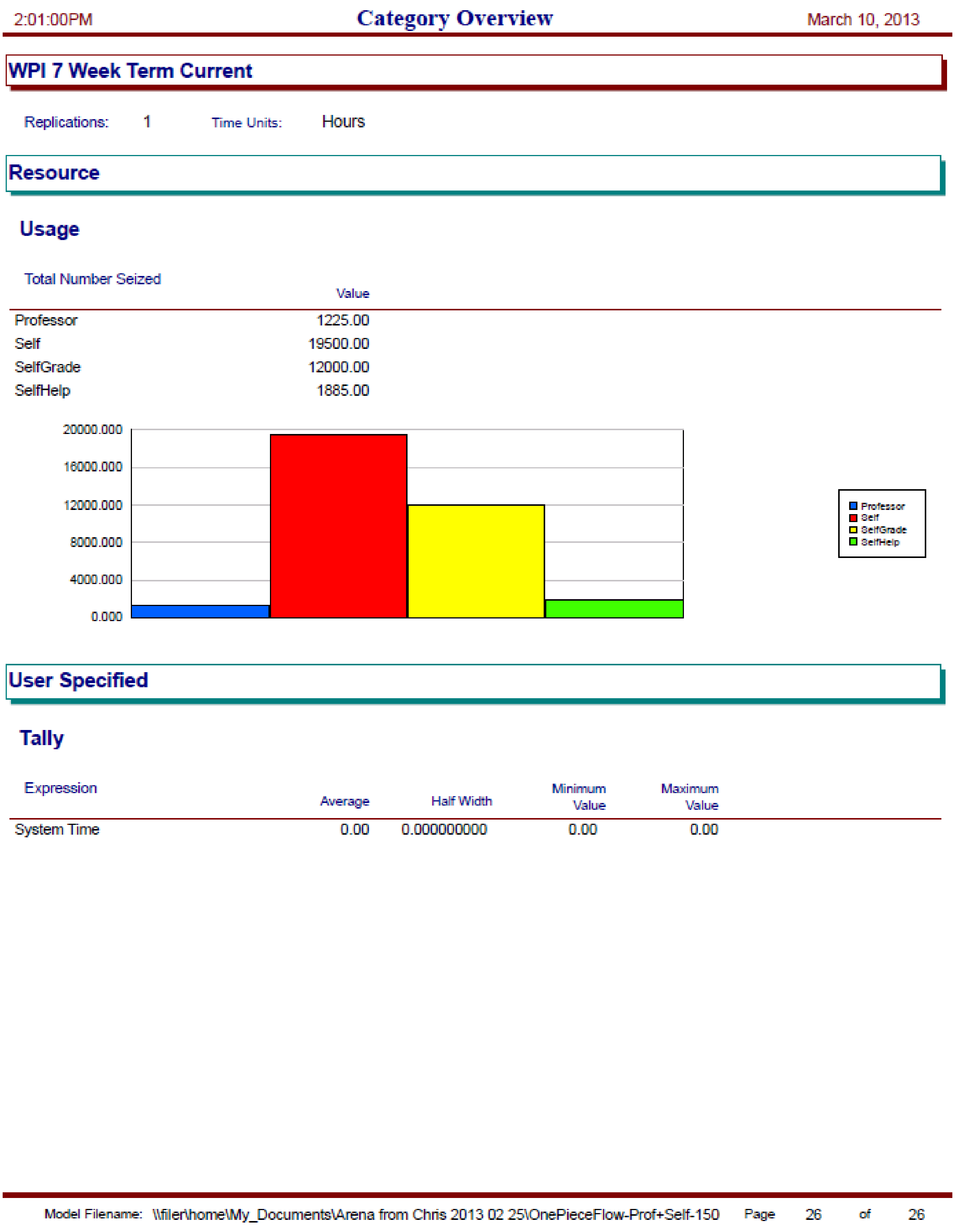
Instantaneous Utilization	Average	Half Width	Minimum Value	Maximum Value
Professor	0.1730	(Insufficient)	0.00	1.0000

Number Busy	Average	Half Width	Minimum Value	Maximum Value
Professor	0.1730	(Insufficient)	0.00	1.0000
Self	33.1633	(Correlated)	0.00	1500.00
SelfGrade	11.4775	(Correlated)	0.00	1211.00
SelfHelp	1.6151	(Correlated)	0.00	164.00

Number Scheduled	Average	Half Width	Minimum Value	Maximum Value
Professor	0.1701	(Insufficient)	0.00	1.0000

Scheduled Utilization	Value
Professor	1.0175





2:01:00PM **Category Overview** March 10, 2013

WPI 7 Week Term Current

Replications: 1 Time Units: Hours

Resource

Usage

Total Number Seized

	Value
Professor	1225.00
Self	19500.00
SelfGrade	12000.00
SelfHelp	1885.00

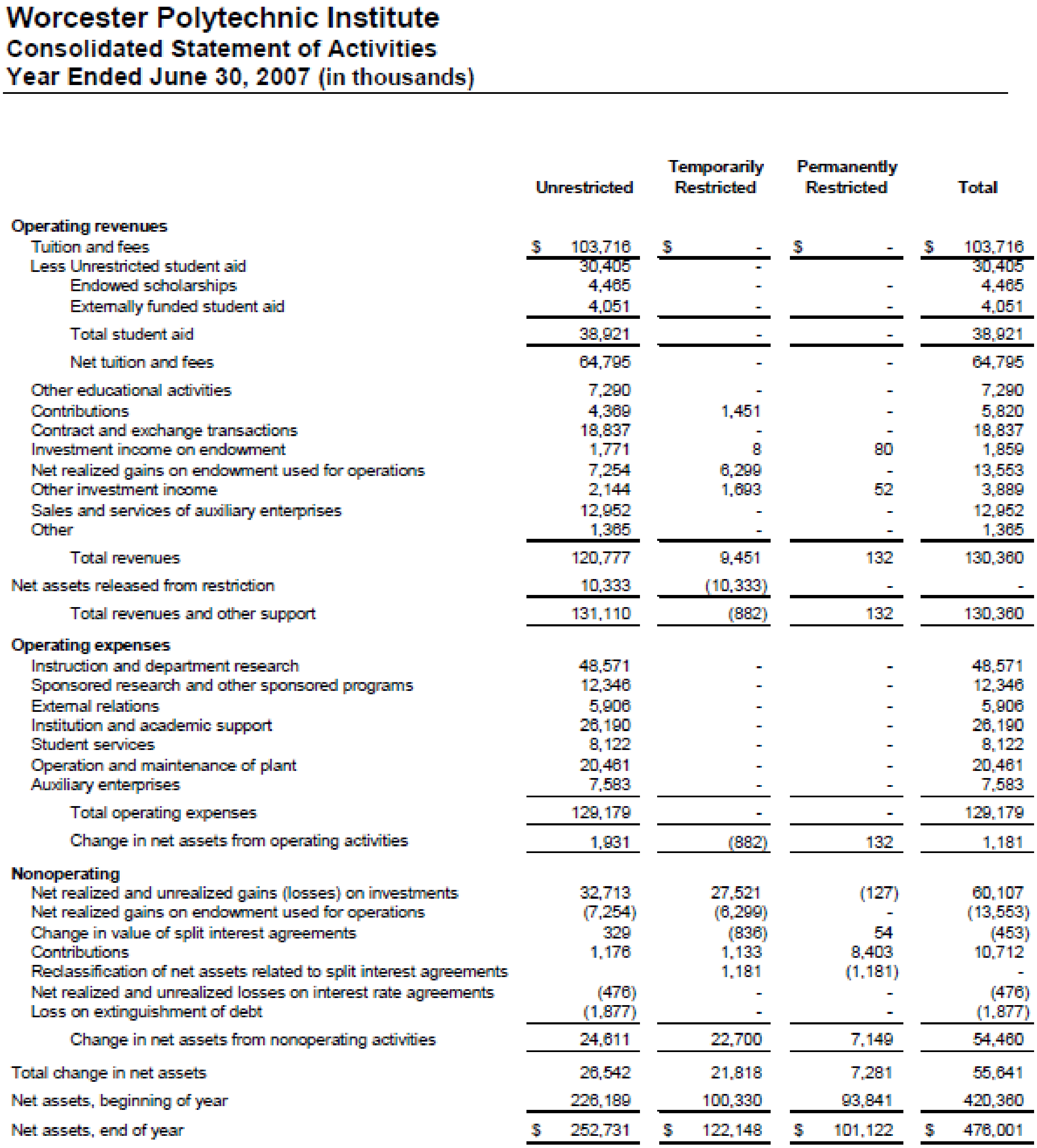
User Specified

Tally

Expression	Average	Half Width	Minimum Value	Maximum Value
System Time	0.00	0.000000000	0.00	0.00

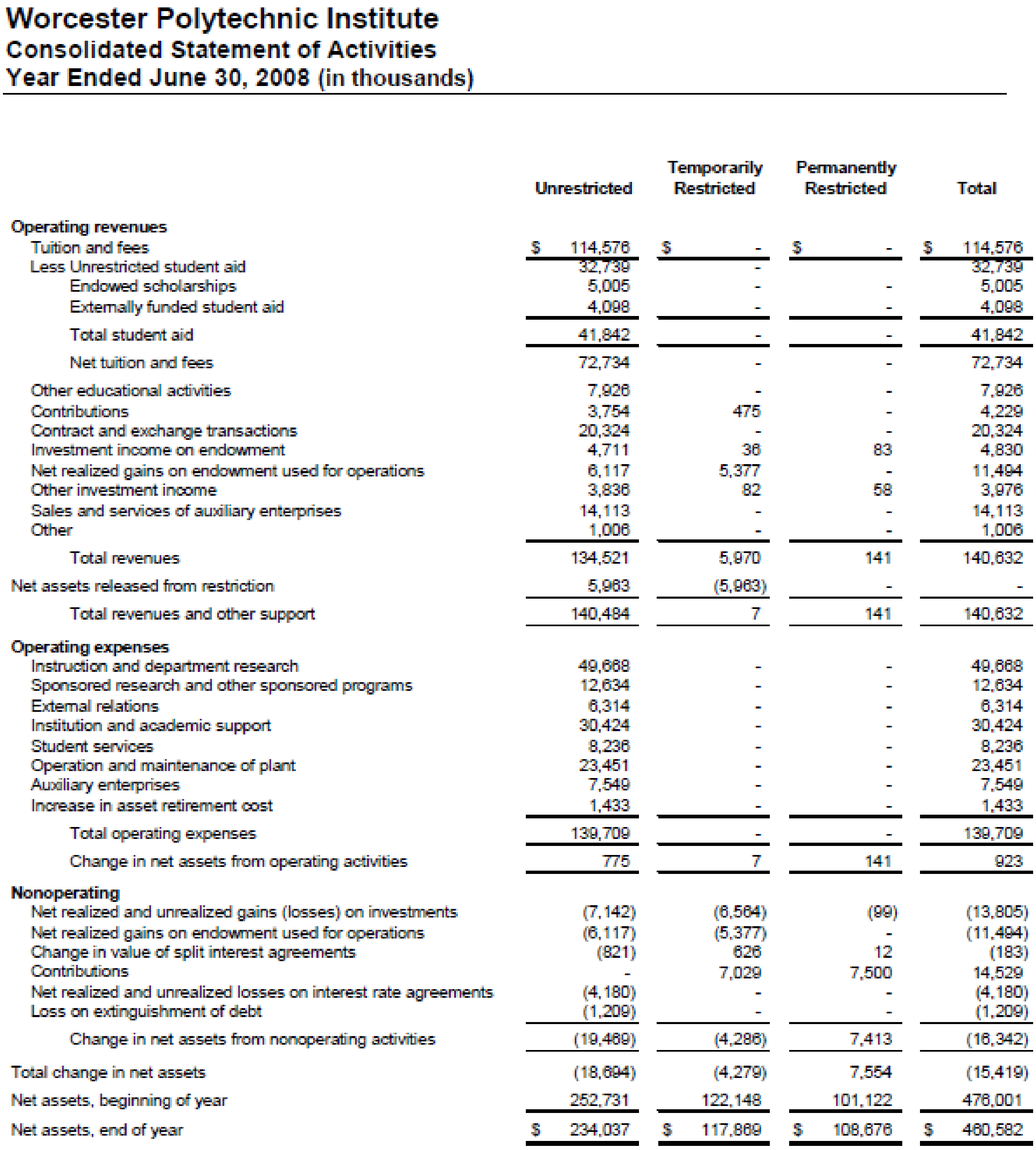
Model Filename: \\filer\home\My_Documents\Arena from Chris 2013 02 25\OnePieceFlow-Prof+Self-150 Page 26 of 26

Appendix G - Financial Statements for Worcester Polytechnic Institute 2007-2012



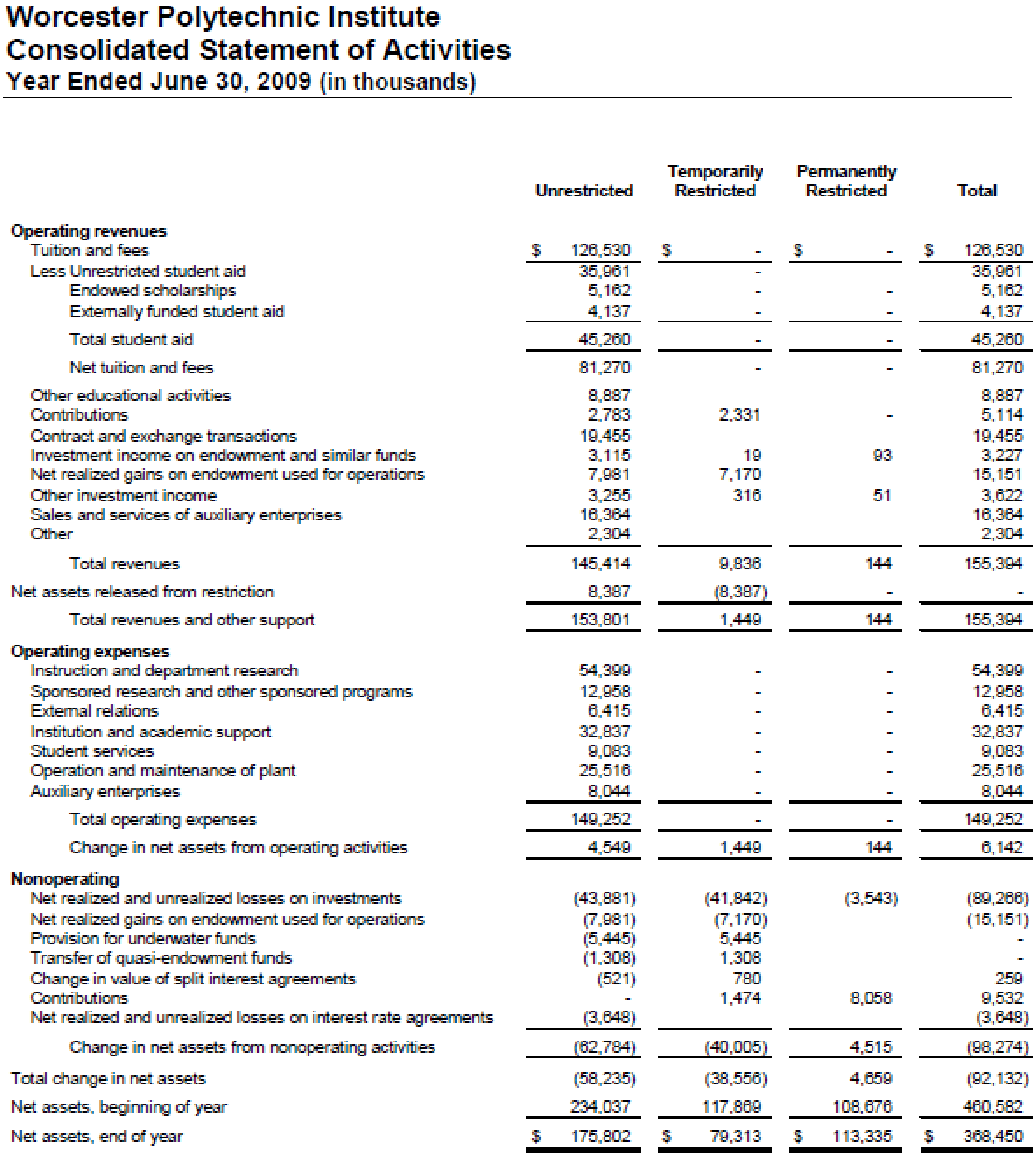
Worcester Polytechnic Institute
Consolidated Statement of Activities
Year Ended June 30, 2007 (in thousands)

	Unrestricted	Temporarily Restricted	Permanently Restricted	Total
Operating revenues				
Tuition and fees	$ 103,716	$ -	$ -	$ 103,716
Less Unrestricted student aid	30,405	-		30,405
Endowed scholarships	4,465	-	-	4,465
Externally funded student aid	4,051	-	-	4,051
Total student aid	38,921	-	-	38,921
Net tuition and fees	64,795	-	-	64,795
Other educational activities	7,290	-	-	7,290
Contributions	4,369	1,451	-	5,820
Contract and exchange transactions	18,837	-	-	18,837
Investment income on endowment	1,771	8	80	1,859
Net realized gains on endowment used for operations	7,254	6,299	-	13,553
Other investment income	2,144	1,693	52	3,889
Sales and services of auxiliary enterprises	12,952	-	-	12,952
Other	1,365	-	-	1,365
Total revenues	120,777	9,451	132	130,360
Net assets released from restriction	10,333	(10,333)	-	-
Total revenues and other support	131,110	(882)	132	130,360
Operating expenses				
Instruction and department research	48,571	-	-	48,571
Sponsored research and other sponsored programs	12,346	-	-	12,346
External relations	5,906	-	-	5,906
Institution and academic support	26,190	-	-	26,190
Student services	8,122	-	-	8,122
Operation and maintenance of plant	20,461	-	-	20,461
Auxiliary enterprises	7,583	-	-	7,583
Total operating expenses	129,179	-	-	129,179
Change in net assets from operating activities	1,931	(882)	132	1,181
Nonoperating				
Net realized and unrealized gains (losses) on investments	32,713	27,521	(127)	60,107
Net realized gains on endowment used for operations	(7,254)	(6,299)	-	(13,553)
Change in value of split interest agreements	329	(836)	54	(453)
Contributions	1,176	1,133	8,403	10,712
Reclassification of net assets related to split interest agreements		1,181	(1,181)	-
Net realized and unrealized losses on interest rate agreements	(476)	-	-	(476)
Loss on extinguishment of debt	(1,877)	-	-	(1,877)
Change in net assets from nonoperating activities	24,611	22,700	7,149	54,460
Total change in net assets	26,542	21,818	7,281	55,641
Net assets, beginning of year	226,189	100,330	93,841	420,360
Net assets, end of year	$ 252,731	$ 122,148	$ 101,122	$ 476,001



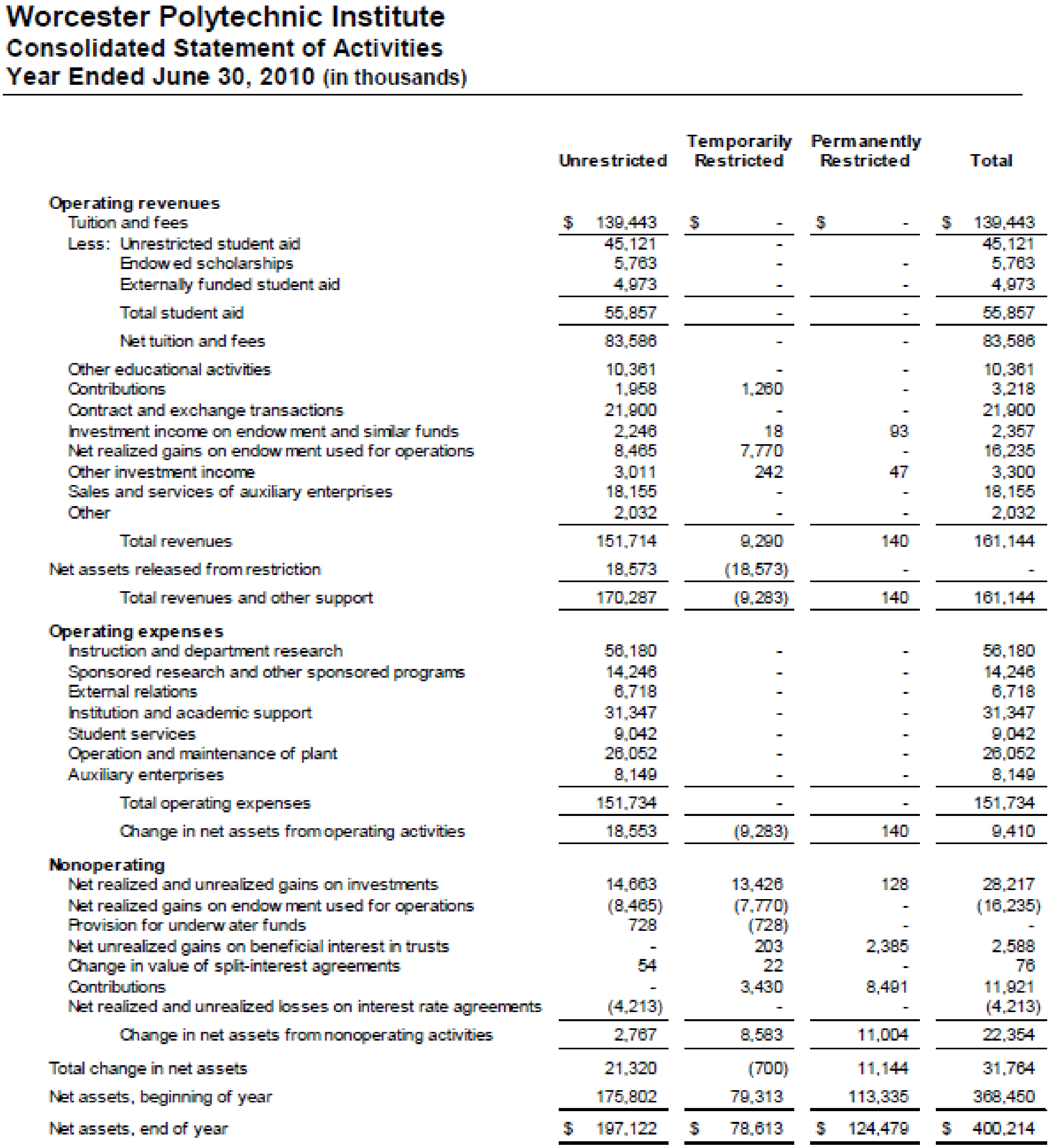
Worcester Polytechnic Institute
Consolidated Statement of Activities
Year Ended June 30, 2008 (in thousands)

	Unrestricted	Temporarily Restricted	Permanently Restricted	Total
Operating revenues				
Tuition and fees	$ 114,576	$ -	$ -	$ 114,576
Less Unrestricted student aid	32,739	-		32,739
Endowed scholarships	5,005	-	-	5,005
Externally funded student aid	4,098	-	-	4,098
Total student aid	41,842	-	-	41,842
Net tuition and fees	72,734	-	-	72,734
Other educational activities	7,926	-	-	7,926
Contributions	3,754	475	-	4,229
Contract and exchange transactions	20,324	-	-	20,324
Investment income on endowment	4,711	36	83	4,830
Net realized gains on endowment used for operations	6,117	5,377	-	11,494
Other investment income	3,836	82	58	3,976
Sales and services of auxiliary enterprises	14,113	-	-	14,113
Other	1,006	-	-	1,006
Total revenues	134,521	5,970	141	140,632
Net assets released from restriction	5,963	(5,963)	-	-
Total revenues and other support	140,484	7	141	140,632
Operating expenses				
Instruction and department research	49,668	-	-	49,668
Sponsored research and other sponsored programs	12,634	-	-	12,634
External relations	6,314	-	-	6,314
Institution and academic support	30,424	-	-	30,424
Student services	8,236	-	-	8,236
Operation and maintenance of plant	23,451	-	-	23,451
Auxiliary enterprises	7,549	-	-	7,549
Increase in asset retirement cost	1,433	-	-	1,433
Total operating expenses	139,709	-	-	139,709
Change in net assets from operating activities	775	7	141	923
Nonoperating				
Net realized and unrealized gains (losses) on investments	(7,142)	(6,564)	(99)	(13,805)
Net realized gains on endowment used for operations	(6,117)	(5,377)	-	(11,494)
Change in value of split interest agreements	(821)	626	12	(183)
Contributions	-	7,029	7,500	14,529
Net realized and unrealized losses on interest rate agreements	(4,180)	-	-	(4,180)
Loss on extinguishment of debt	(1,209)	-	-	(1,209)
Change in net assets from nonoperating activities	(19,469)	(4,286)	7,413	(16,342)
Total change in net assets	(18,694)	(4,279)	7,554	(15,419)
Net assets, beginning of year	252,731	122,148	101,122	476,001
Net assets, end of year	$ 234,037	$ 117,869	$ 108,676	$ 460,582



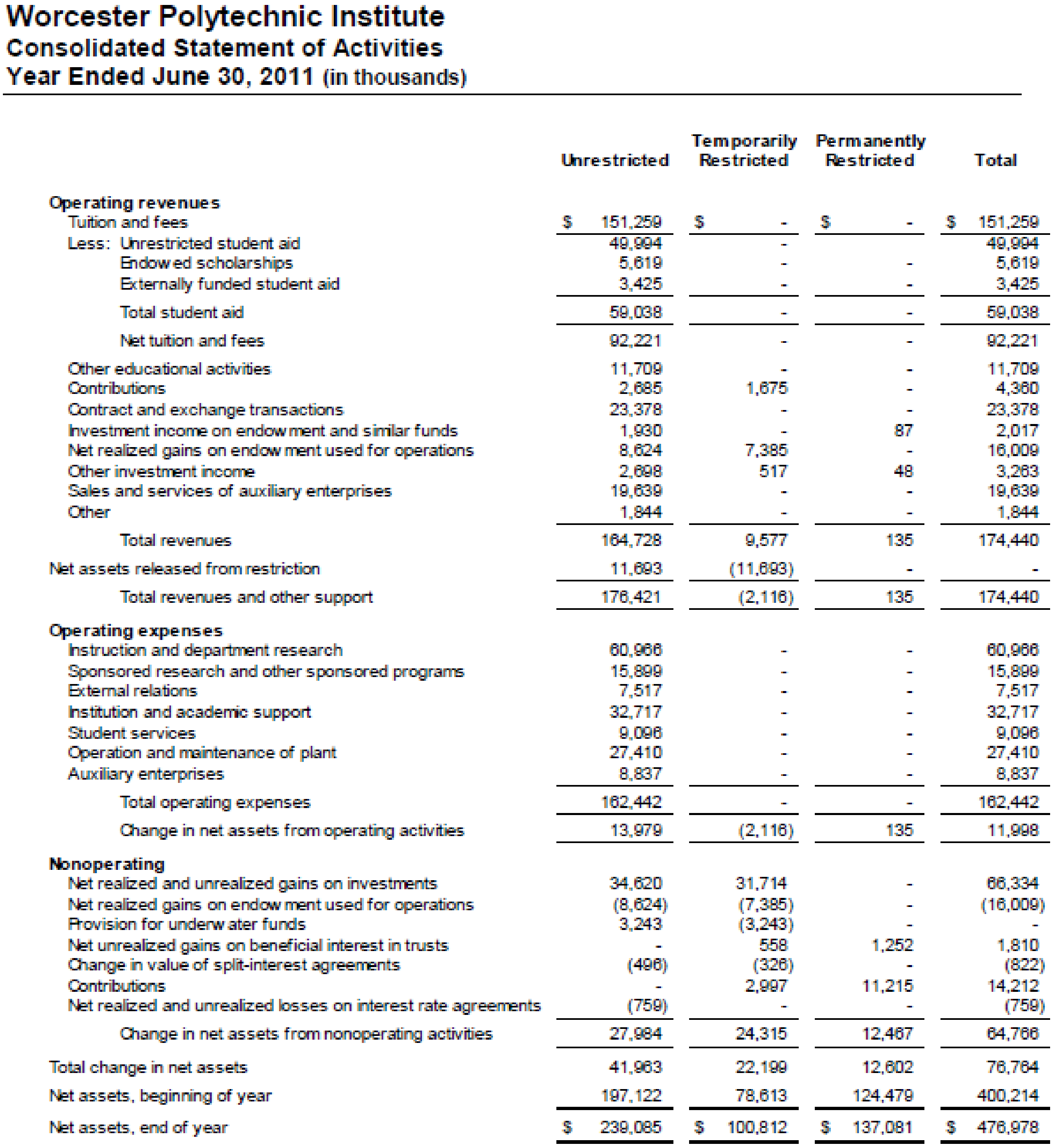
Worcester Polytechnic Institute
Consolidated Statement of Activities
Year Ended June 30, 2009 (in thousands)

	Unrestricted	Temporarily Restricted	Permanently Restricted	Total
Operating revenues				
Tuition and fees	$ 126,530	$ -	$ -	$ 126,530
Less Unrestricted student aid	35,961	-		35,961
Endowed scholarships	5,162	-	-	5,162
Externally funded student aid	4,137	-	-	4,137
Total student aid	45,260	-	-	45,260
Net tuition and fees	81,270	-	-	81,270
Other educational activities	8,887			8,887
Contributions	2,783	2,331	-	5,114
Contract and exchange transactions	19,455			19,455
Investment income on endowment and similar funds	3,115	19	93	3,227
Net realized gains on endowment used for operations	7,981	7,170		15,151
Other investment income	3,255	316	51	3,622
Sales and services of auxiliary enterprises	16,364			16,364
Other	2,304			2,304
Total revenues	145,414	9,836	144	155,394
Net assets released from restriction	8,387	(8,387)	-	-
Total revenues and other support	153,801	1,449	144	155,394
Operating expenses				
Instruction and department research	54,399	-	-	54,399
Sponsored research and other sponsored programs	12,958	-	-	12,958
External relations	6,415	-	-	6,415
Institution and academic support	32,837	-	-	32,837
Student services	9,083	-	-	9,083
Operation and maintenance of plant	25,516	-	-	25,516
Auxiliary enterprises	8,044	-	-	8,044
Total operating expenses	149,252	-	-	149,252
Change in net assets from operating activities	4,549	1,449	144	6,142
Nonoperating				
Net realized and unrealized losses on investments	(43,881)	(41,842)	(3,543)	(89,266)
Net realized gains on endowment used for operations	(7,981)	(7,170)		(15,151)
Provision for underwater funds	(5,445)	5,445		-
Transfer of quasi-endowment funds	(1,308)	1,308		-
Change in value of split interest agreements	(521)	780		259
Contributions	-	1,474	8,058	9,532
Net realized and unrealized losses on interest rate agreements	(3,648)			(3,648)
Change in net assets from nonoperating activities	(62,784)	(40,005)	4,515	(98,274)
Total change in net assets	(58,235)	(38,556)	4,659	(92,132)
Net assets, beginning of year	234,037	117,869	108,676	460,582
Net assets, end of year	$ 175,802	$ 79,313	$ 113,335	$ 368,450



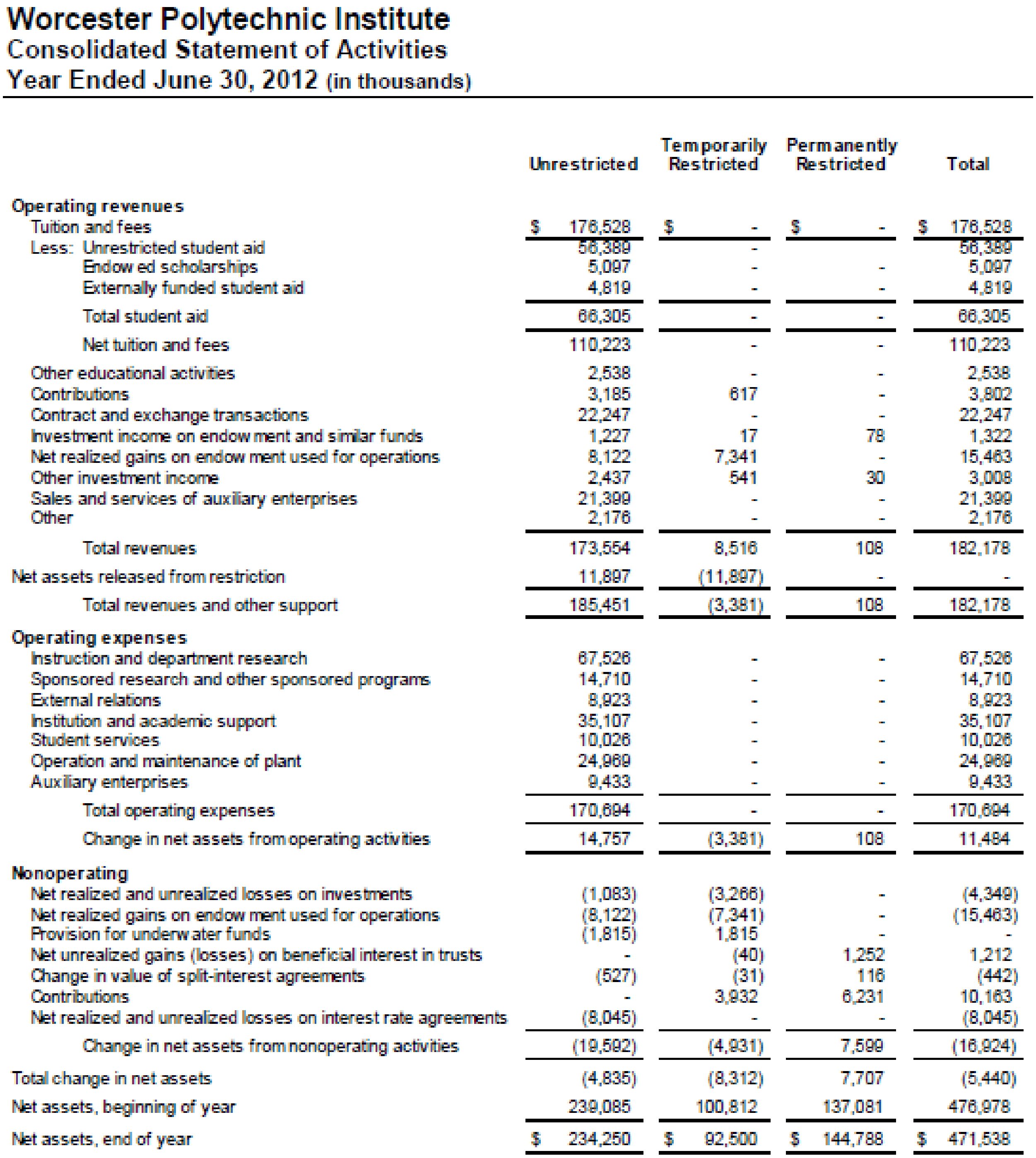
Worcester Polytechnic Institute
Consolidated Statement of Activities
Year Ended June 30, 2010 (in thousands)

	Unrestricted	Temporarily Restricted	Permanently Restricted	Total
Operating revenues				
Tuition and fees	$ 139,443	$ -	$ -	$ 139,443
Less: Unrestricted student aid	45,121	-		45,121
Endowed scholarships	5,763	-	-	5,763
Externally funded student aid	4,973	-	-	4,973
Total student aid	55,857	-	-	55,857
Net tuition and fees	83,586	-	-	83,586
Other educational activities	10,361	-	-	10,361
Contributions	1,958	1,260	-	3,218
Contract and exchange transactions	21,900	-	-	21,900
Investment income on endowment and similar funds	2,246	18	93	2,357
Net realized gains on endowment used for operations	8,465	7,770	-	16,235
Other investment income	3,011	242	47	3,300
Sales and services of auxiliary enterprises	18,155	-	-	18,155
Other	2,032	-	-	2,032
Total revenues	151,714	9,290	140	161,144
Net assets released from restriction	18,573	(18,573)	-	-
Total revenues and other support	170,287	(9,283)	140	161,144
Operating expenses				
Instruction and department research	56,180	-	-	56,180
Sponsored research and other sponsored programs	14,246	-	-	14,246
External relations	6,718	-	-	6,718
Institution and academic support	31,347	-	-	31,347
Student services	9,042	-	-	9,042
Operation and maintenance of plant	26,052	-	-	26,052
Auxiliary enterprises	8,149	-	-	8,149
Total operating expenses	151,734	-	-	151,734
Change in net assets from operating activities	18,553	(9,283)	140	9,410
Nonoperating				
Net realized and unrealized gains on investments	14,663	13,426	128	28,217
Net realized gains on endowment used for operations	(8,465)	(7,770)	-	(16,235)
Provision for underwater funds	728	(728)	-	-
Net unrealized gains on beneficial interest in trusts	-	203	2,385	2,588
Change in value of split-interest agreements	54	22	-	76
Contributions	-	3,430	8,491	11,921
Net realized and unrealized losses on interest rate agreements	(4,213)	-	-	(4,213)
Change in net assets from nonoperating activities	2,767	8,583	11,004	22,354
Total change in net assets	21,320	(700)	11,144	31,764
Net assets, beginning of year	175,802	79,313	113,335	368,450
Net assets, end of year	$ 197,122	$ 78,613	$ 124,479	$ 400,214



Worcester Polytechnic Institute
Consolidated Statement of Activities
Year Ended June 30, 2011 (in thousands)

	Unrestricted	Temporarily Restricted	Permanently Restricted	Total
Operating revenues				
Tuition and fees	$ 151,259	$ -	$ -	$ 151,259
Less: Unrestricted student aid	49,994	-		49,994
Endowed scholarships	5,619	-	-	5,619
Externally funded student aid	3,425	-	-	3,425
Total student aid	59,038	-	-	59,038
Net tuition and fees	92,221	-	-	92,221
Other educational activities	11,709	-	-	11,709
Contributions	2,685	1,675	-	4,360
Contract and exchange transactions	23,378	-	-	23,378
Investment income on endowment and similar funds	1,930	-	87	2,017
Net realized gains on endowment used for operations	8,624	7,385	-	16,009
Other investment income	2,698	517	48	3,263
Sales and services of auxiliary enterprises	19,639	-	-	19,639
Other	1,844	-	-	1,844
Total revenues	164,728	9,577	135	174,440
Net assets released from restriction	11,693	(11,693)	-	-
Total revenues and other support	176,421	(2,116)	135	174,440
Operating expenses				
Instruction and department research	60,966	-	-	60,966
Sponsored research and other sponsored programs	15,899	-	-	15,899
External relations	7,517	-	-	7,517
Institution and academic support	32,717	-	-	32,717
Student services	9,096	-	-	9,096
Operation and maintenance of plant	27,410	-	-	27,410
Auxiliary enterprises	8,837	-	-	8,837
Total operating expenses	162,442	-	-	162,442
Change in net assets from operating activities	13,979	(2,116)	135	11,998
Nonoperating				
Net realized and unrealized gains on investments	34,620	31,714	-	66,334
Net realized gains on endowment used for operations	(8,624)	(7,385)	-	(16,009)
Provision for underwater funds	3,243	(3,243)	-	-
Net unrealized gains on beneficial interest in trusts	-	558	1,252	1,810
Change in value of split-interest agreements	(496)	(326)	-	(822)
Contributions	-	2,997	11,215	14,212
Net realized and unrealized losses on interest rate agreements	(759)	-	-	(759)
Change in net assets from nonoperating activities	27,984	24,315	12,467	64,766
Total change in net assets	41,963	22,199	12,602	76,764
Net assets, beginning of year	197,122	78,613	124,479	400,214
Net assets, end of year	$ 239,085	$ 100,812	$ 137,081	$ 476,978



Worcester Polytechnic Institute

Consolidated Statement of Activities

Year Ended June 30, 2012 (in thousands)

	Unrestricted	Temporarily Restricted	Permanently Restricted	Total
Operating revenues				
Tuition and fees	$ 176,528	$ -	$ -	$ 176,528
Less: Unrestricted student aid	56,389	-		56,389
Endowed scholarships	5,097	-	-	5,097
Externally funded student aid	4,819	-	-	4,819
Total student aid	66,305	-	-	66,305
Net tuition and fees	110,223	-	-	110,223
Other educational activities	2,538	-	-	2,538
Contributions	3,185	617	-	3,802
Contract and exchange transactions	22,247	-	-	22,247
Investment income on endowment and similar funds	1,227	17	78	1,322
Net realized gains on endowment used for operations	8,122	7,341	-	15,463
Other investment income	2,437	541	30	3,008
Sales and services of auxiliary enterprises	21,399	-	-	21,399
Other	2,176	-	-	2,176
Total revenues	173,554	8,516	108	182,178
Net assets released from restriction	11,897	(11,897)	-	-
Total revenues and other support	185,451	(3,381)	108	182,178
Operating expenses				
Instruction and department research	67,526	-	-	67,526
Sponsored research and other sponsored programs	14,710	-	-	14,710
External relations	8,923	-	-	8,923
Institution and academic support	35,107	-	-	35,107
Student services	10,026	-	-	10,026
Operation and maintenance of plant	24,969	-	-	24,969
Auxiliary enterprises	9,433	-	-	9,433
Total operating expenses	170,694	-	-	170,694
Change in net assets from operating activities	14,757	(3,381)	108	11,484
Nonoperating				
Net realized and unrealized losses on investments	(1,083)	(3,266)	-	(4,349)
Net realized gains on endowment used for operations	(8,122)	(7,341)	-	(15,463)
Provision for underwater funds	(1,815)	1,815	-	-
Net unrealized gains (losses) on beneficial interest in trusts	-	(40)	1,252	1,212
Change in value of split-interest agreements	(527)	(31)	116	(442)
Contributions	-	3,932	6,231	10,163
Net realized and unrealized losses on interest rate agreements	(8,045)	-	-	(8,045)
Change in net assets from nonoperating activities	(19,592)	(4,931)	7,599	(16,924)
Total change in net assets	(4,835)	(8,312)	7,707	(5,440)
Net assets, beginning of year	239,085	100,812	137,081	476,978
Net assets, end of year	$ 234,250	$ 92,500	$ 144,788	$ 471,538

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Biographical Information

Walter T. Towner Jr. MBA CFP® was the President of Thorsen Inc.; a laser based metal fabrication company headquartered in Avon, Massachusetts prior to joining WPI. He has been teaching operations management courses for the WPI School of Business as well as manufacturing system design for WPI Corporate and Professional Education. His research interests include the integration of axiomatic design and manufacturing principles into operations management.