EDITORIAL BOARD

TABLE OF CONTENTS

Using Control Charts to Manage Rainfall Variation in California's Central Valley

[1]Nael Aly and [2]Gene Murti
[1]*California Maritime Academy, Vallejo, CA 94590, USA*
[2]*Management, Operations, and Marketing Department, California State University, Stanislaus, Turlock, CA 953852, USA*
naly@csum.edu; gmurti@csustan.edu

Abstract

This paper shows how control charts can be used to manage rainfall variations in California's central San Joaquin Valley. It demonstrates how rainfall and runoff data can be statistically analyzed to address serious and important water management issues such as drought and flood cycles. Modesto Irrigation District's rainfall and runoff data from 1889 until 2011 are analyzed using control charts. The analysis of these data concludes the claim that the weather in this region, particularly the amount of rainfall, is changing or is different from what we had experienced in the past cannot be statistically supported. Furthermore, it proves that the rainfall pattern is cyclical, stable and can even be predicted. By using control charts and understanding variation, the effects of rainfall variations can be managed more effectively during both the flood and drought cycles.

1. Introduction

California's central valley depends on water for its productive agriculture. Natural rainfall averages about 12 inches per year and is restricted to only a few months in the winter. Thus irrigation is the main water source for crop cultivation. The valley is served by several irrigation districts which tap river water by creating reservoirs. Modesto Irrigation District (MID) serves part of Stanislaus County. Modesto is located in the San Joaquin Valley of California and MID manages the power and irrigation in Modesto and parts of the valley. Water is a precious resource in the valley which is sourced via the rainfall, as well as the Tuolumne River basin caused by the runoff of melted mountain snow. In some cases, in addition to irrigation, the runoff is even more important for power generation. MID has been keeping meticulous data on rainfall, as well as runoff from the mountain snow for over one hundred and twenty years.

California's central valley is known as the breadbasket for the nation. Although rainfall averages only about 12 inches of rain annually (technically a desert), the runoff from the Sierra Nevada Mountains effectively irrigates the rich valley soil to produce abundant crops-vegetables, fruit, nuts, dairy products and meat. An historic welcome arch in Modesto has these words enshrined on it: Water, Wealth, Contentment, Health. Water is essential to the well-being of the community. Hence a few years of drought-like conditions raises concerns for continued economic well-being and adequate water supply.

Even though many studies have been published about analyzing rainfall data in many geographical areas of the world, almost all of them utilize the typical statistical techniques such as correlation analysis, and multivariate statistical models. Türkeş [9] examined the annual rainfall in Turkey during the period 1930–1993 using the Mann–Kendall test. He concluded that all regional mean rainfall anomalies have tended to vary in a statistically coherent manner over the rainfall regions. Samba [7] analyzed the annual variability of rainfall amounts and rainy days from synoptic stations located in different climatic zones of Congo-Brazzaville over the period 1932–2007. The annual and seasonal rainfall evolution is analyzed using standardized indices. Trends examined were based on the non-parametric Mann-Kendall test. The test shows that there is stability in the annual rainfall and rainy days over the southern area in the period 1932–2007

Boone, et al. [2] used data from over 100 Oklahoma Mesonet stations in a space-time decomposition of Oklahoma rainfall from 1 March 1994 to 31 December 2003. Spatially coherent patterns of annual, warm-season, and cold-season rainfall events were derived using principal component analysis. They concluded that there was not much difference between the warm-season and cold-season rainfall patterns, both demonstrating coherent regions in the four quadrants of Oklahoma.

One common method for studying spatial coherence of rainfall data is Principal Component Analysis (PCA), a method that determines the important features of a multivariate data set—in this case, a single variable, rainfall data that vary in space and in time. One advantage of PCA is that, as an eigenvector method, it promotes understanding of the time variation among the variables through analysis of the two displays that are mapped in geographical space and time, the 'loadings' and 'scores', respectively. For rainfall data, PCA loadings describe the regions of coherent rainfall in a study area; the scores indicate how much rain fell across the associated spatially coherent region for any given time period. For example, Wickramagamage [10] used PCA to analyze monthly rainfall means from 646 observing stations across Sri Lanka.

Hallack-Alegria[4] investigated seasonal and annual precipitation data from 34 sites in northwest Baja California, Mexico. Along with the analysis of precipitation climatology and inter-annual variability, El Niño/Southern Oscillation (ENSO) and related Pacific Ocean sea surface temperature (SST) patterns are shown to be potential predictors of seasonal precipitation. Analysis of precipitation variability at seasonal and annual time scales is performed using the standardized precipitation index (SPI) methodology and annual, seasonal, and ENSO-conditioned precipitation frequency analyses are executed using the regional L-moment algorithm. This study confirmed the correlation of precipitation in the study area with ENSO, with both MEI values and ENSO-like Pacific Ocean SST patterns clearly linked to seasonal and annual rainfall variability.

Almazroui et al. [1] analyzed the climatological spatiotemporal distributions of rainfall and temperature (and their trends) on an annual basis for the Arabian Peninsula and Saudi Arabia for a 32-year period (1978–2009). They employed commonly used statistical techniques to estimate the linear trends and percentage differences of their data. The observed monthly temperature and rainfall datasets were used to estimate annual trends through regression methods.

It is observed from the discussion of the literature above that hardly any research dealing with rainfall variations attempted to use Statistical Process Control (SPC) techniques, mainly control charts, to determine how stable the historical rainfall pattern was before jumping into the deeper analysis for the causes of pattern change. It seems that using quality control techniques, which are usually used for process control, can provide a promising approach to analyze rainfall data. This process control approach could provide a scientific way to distinguish between when rainfall variation is natural and predictable within statistical limits and when assignable causes are the major force behind changing the weather and rainfall precipitation.

2. Analysis of the Rainfall in the Modesto Irrigation District

The rainfall data in the Modesto area has been monitored and studied for the last twenty years, observing drought and flood cycles along the way using Statistical Process control techniques, mainly control charts. The first analysis of the rainfall was conducted in 1991, then was updated in 1998, then again in 2005 and finally in 2012. This paper will summarize these studies, draw conclusions, and recommend ideas for overall water policy management. These recommendations may help decision makers deal with the uncertainty and variation of the annual rainfall as well as planning for the drought and flood situations.

2.1. Understanding Variation

One of the most powerful tools any manager can develop is knowledge of variation theory. Understanding variation enables managers to react rationally to variations in the figures, performance output, and data they deal with daily. Managers and decision makers need to be able to distinguish between patterns of variation that are indicative of assignable cause and those which are created by random causes. Control charts can be used effectively to determine whether or not the process variation is random, i.e., the process is stable. A stable process is said to be in a state of statistical control. This implies that variations in the outcome are predictable within statistically established limits based on the Normal Distribution characteristics [3].

2.2. Initial Study in 1991

Following several years of drought conditions (five consecutive years with annual rainfall below average yearly amount), there was concern that there might be a permanent shift in the weather pattern causing below average rainfall. In order to check whether the annual rainfall variation exhibited in the previous few years was caused by chance causes or if some statistical shift had taken place by assigned causes, rainfall and runoff data of the past 102 years, obtained from MID was studied and analyzed. Individual X and Moving Range Control Charts were the most appropriate control charts to analyze these data [8]. Therefore, the rainfall and runoff data were plotted on Individual X and Moving Range Control Charts. Control limits were also calculated to see if any out-of-control conditions existed, indicating evidence of special causes of variation. Moving Range charts for both rainfall and runoff data were in control. Therefore, only individual charts are shown in Figures 1 and 2. Notice that in both charts the last five points are below the average, indicating shortage of rainfall and drought conditions. This raised concern among state officials and the public regarding the possibility of dry weather that could adversely affect agriculture in the Central Valley, as well as the future of development in California in general. Calls for conserving water were raised, water usages were limited, and reasons for the dry-up conditions were debated, ranging from global warming to the ozone layer. But were all these reactions scientifically justified or were they typical reactions to the misunderstanding of variations? The irony is that all these measures to conserve water happened when water was not available due to shortage and drought; a classic example of poor water management strategy.

A more scientific and rational approach to water management is to analyze rainfall data using control charts. Control charts clearly show that the rainfall amounts in MID's entire 102 year history (1889-1991) are within statistical control. In 1983, both rainfall and runoff were outside the upper control limit by a small amount, but this is not enough evidence, statistically speaking, to make the control charts out-of-control. The control charts indicated that the rainfall pattern in the long run had remained remarkably stable. In order to check if any cyclical trend might be discernible, different smoothing methods were tried. A moving average of 5 years showed that the trend was indeed cyclical with an average of about fourteen year spans. The cycles showed seven years of increase leading to a peak (flood) followed by seven years of decline, ending with a bottom (drought) as shown in figures 3 and 4. The only time the cycle didn't repeat was during the dustbowl years of 1920's. The cyclicality is even more clearly visible in the runoff data than rainfall data.

By analyzing figures 1 to 4, it can be concluded that variation is a normal part of life, including annual rainfall in the region. Statistically, over the 102 years period, the rainfall exhibited statistical control or stability. The claim that the weather is different from what we had experienced in the past cannot be statistically supported. Furthe rmore, the drought conditions in 1991 were not unusual. It just happened that we were almost reaching the bottom end of another cycle. Therefore, the perceived shortage was a result of a growing State population and higher demands. A moving average of five years showed a clear cyclical trend. Each cycle was about fourteen years long with seven ascending and seven descending halves. A longitudinal study was recommended to see if the cyclical pattern held up in the future. If it did hold up in the futu re, it would be a useful tool in crafting the water resource policy of the region.

A strong correlation (r =.86) between annual rainfall and runoff amounts in the Central Valley was concluded by Murti and Aly [5]. Salstrom and Dean [6] also found that the rainfall pattern in Santa Clara County to be stable but cyclical.

2.3. Analysis Update in 1998

In 1998, the local newspaper in Modesto, The Modesto Bee, ran headlines such as "Wettest Ever" expressing concerns of flooding in the area due to having higher than average rainfall and blaming El Nino for the deluge. The pessimistic tone seven years ago had given way to a feeling of rainfall surplus. The charts were updated using an additional seven years of data (See figures 5 and 6). These charts indicated that the rainfall data continued to be in statistical control and the five year moving average trend had bottomed out seven years prior and was now towards the peak of the ascending trend. Interestingly, the alarmist tone of the policy makers regarding drought had given way to worry about flooding stance because of the heavy rainfall in 1997 which caused major flooding and damages near the Tuolumne River and in Modesto.

2.4. Analysis Update in 2005

Seven years after the 1998 update, there were calls again by policy makers to install water meters in the community, partially in response to growing shortage and water conservation needs. For three consecutive years, the rainfall amount has been below average, renewing fears of another drought. However, the additional seven years of data again shows that both the rainfall and runoff data, even though they always vary from one year to another, remained in statistical control (Figures 7 and 8). In addition, the 5-year moving average for both rainfall and runoff data showed, as expected, a downward trend (Figures 9 and 10). In fact, the cyclical pattern of figures 9 and 10 clearly show that we were reaching the bottom of yet another rainfall cycle. Statistically, the rainfall cycle should have started to move up again in another year or two, which it did.

2.5. Analysis Update in 2012

After updating the control charts through the 2011 season, it seems that the bottom of the last dry cycle stretched till 2007 before turning upward. The rainfall cycle trend is now going slowly toward more wet weather in the next few years as shown in Figures 11 and 12. The peak rainfall of this cycle can be expected to be in about three years from now!

The initial study and subsequent three updates have shown that using Individual X and Moving Range charts can be very effective tools in managing the annual variation of rainfall in the Modesto area. It also proves that the findings of the first study are valid and that the drought and flood cycles can literally be predicted, as long as the control charts are in control. This also shows that control charts can be used by water resource policy planners to manager water resources more effectively.

3. Conclusion

From studying and analyzing MID rainfall and run-off data for over 120 years, it is apparent that there is no significant change in the patterns of variation of these data. Shortage of rainfall for three or four consecutive years is not an uncommon phenomenon in the Modesto area. In general, the weather we are experiencing now is not only usual, but also stable and can be predicted. As the pattern of five-year moving averages of rainfall in figure 12 shows a fourteen year average cycle, it just happens that we are almost reaching the end of another upward cycle. Even though the bottom of the current rainfall cycle looks stretched more than usual, statistically speaking, we cannot support any claim that the weather is changing or it is different from what we have experienced in the past. Although there are cycles that affect water availability, there are no significant downward trends. Perhaps the reason the severity of the extreme weather cycles of flood and drought is being felt more now is the fact that California has experienced major development and population growth over the last twenty years while the water supply has been stable.

Control charts can be very effective and valuable tools in the management of water resources. By understanding variation, and its natural cycles and by using control charts, water resources can be managed more effectively during both the flood and drought cycles. Plans for the drought should be made during the flood time, when water is available in abundance. Excess water, which is available during the up cycle, should be captured and stored so that it can be used during the down cycle when rainfall is scant and it is drought time. Not only will this help ease times of drought and water shortage, but it will also help minimize the impact and severity of floods by channeling its power for positive use instead of destruction and devastation.

4. References

[1] Almazroui, M., Nazrul Islam, M., Athar, H., Jones, P. D. and Rahman, M. A. (2012), "Recent climate change in the Arabian Peninsula: annual rainfall and temperature analysis of Saudi Arabia for 1978–2009," International Journal of Climatology, Vol. 32, 2012, 831–842

[2] Boone, K. M., McPherson, R. A., Richman, M. B. and Karoly, D. J., "Spatial coherence of rainfall variations using the Oklahoma Mesonet,". International Journal of Climatology, Vol. 32, 2012 843–853.
[3] Evans, J. and W. Lindsay, The Management and Control of Quality, South-Western, 2011.
[4] Hallack-Alegria, M., J. Ramirez-Hernandez, and D. W. Watkins, (2012), "ENSO-conditioned rainfall drought frequency analysis in northwest Baja California, Mexico," International Journal of Climatology, Vol. 32, 2012, 831–842
[5] Murti, G. and N. Aly, "Analysis of Rainfall Variations: An Application of SQC," Proceedings of the Third Annual CSU-POM Conference, Turlock, California, March 1991, 20-25.
[6] Salstrom, R. and B. Dean, "Improving Water Resources Management in Santa Clara County," Proceedings of the Fourth Annual CSU-POM Conference, Long Beach, California, February 1992, 29-34.
[7] Samba, G. and D. Nganga, "Rainfall Variability in Congo-Brazzaville,"1932–2007. International Journal of Climatology, Vol. 32, 2012, 854–873.
[8] Summers, D., Quality, Prentice-Hall, 2003.
[9] Türkeş, M, "Spatial and Temporal Analysis of Annual Rainfall Variations in Turkey," International Journal of Climatology, Vol. 16, 1996, 1057–1076.
[10] Wickramagamage P."Seasonality and Spatial Pattern of Rainfall of Sri Lanka," International Journal of Climatology, Vol. 29, 2009, 1002-1012.

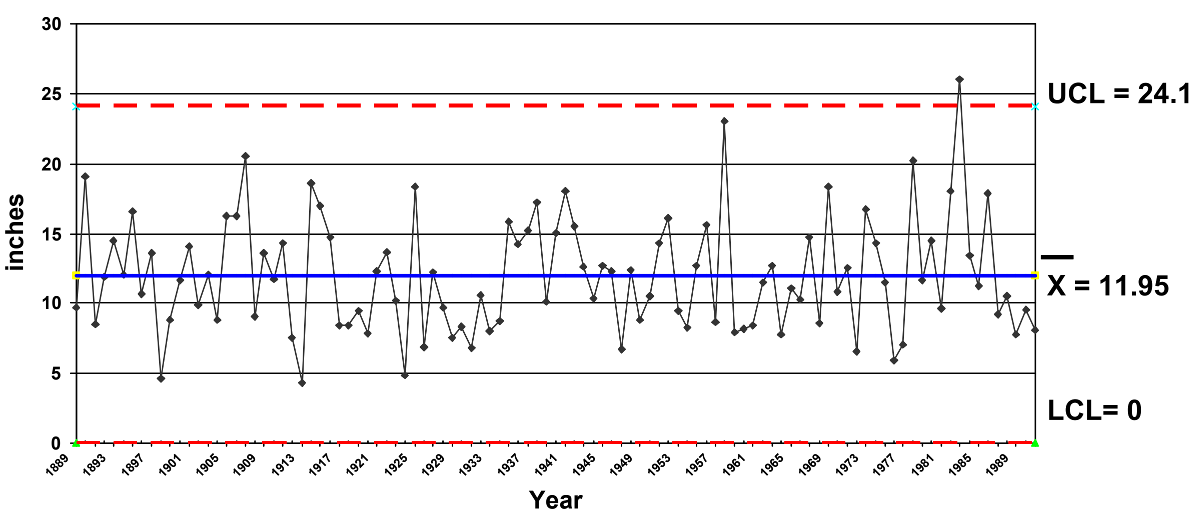


Figure 1. Individual X-Chart for Rainfall (1889-1991)

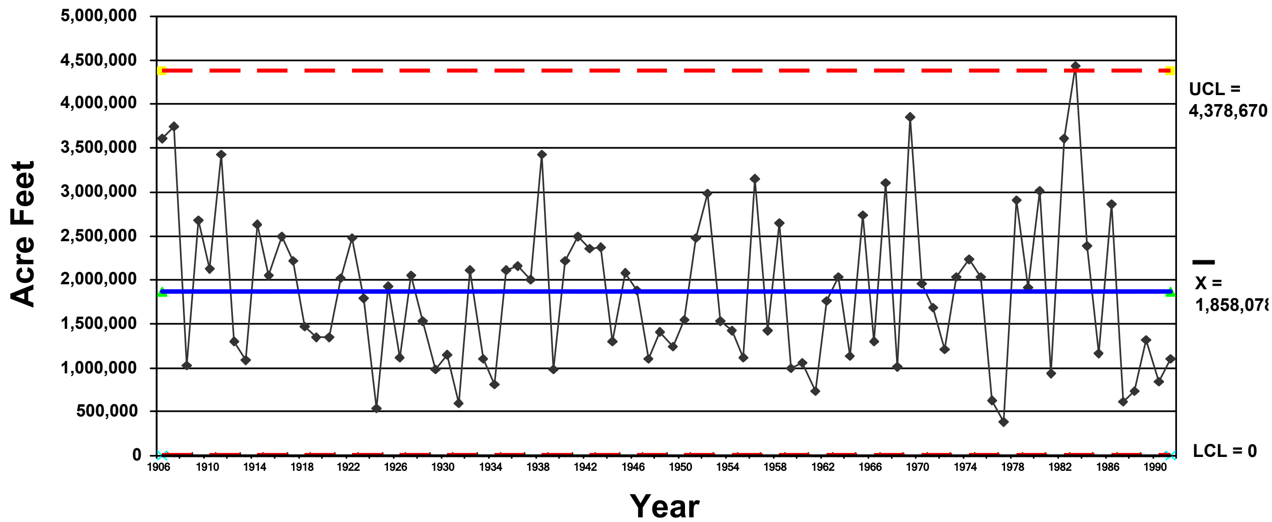


Figure 2. Individual X-Chart for Tuolumne River Water Year Runoff (1906-1991)

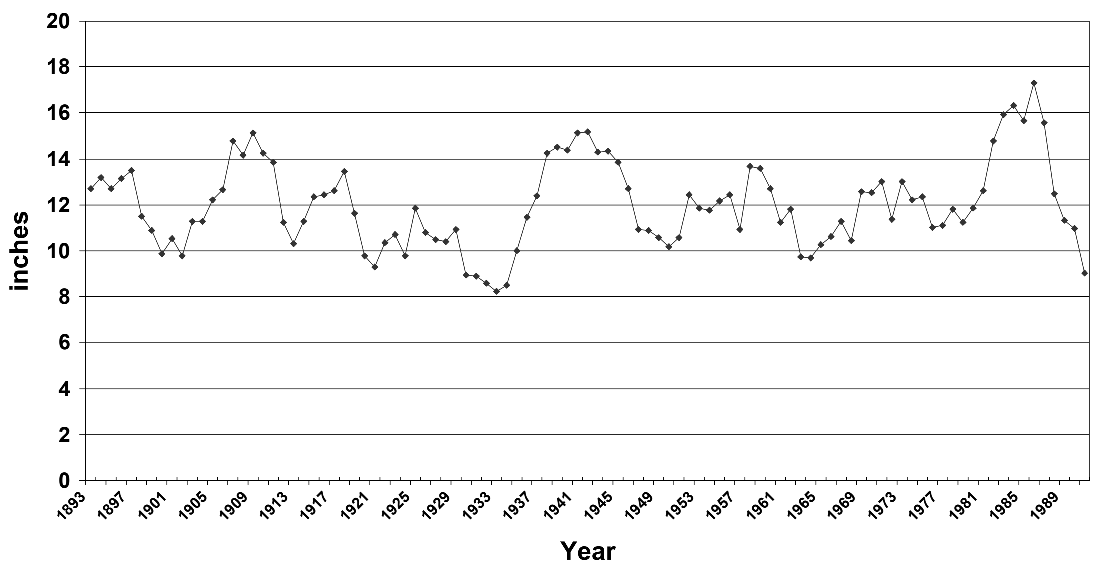


Figure 3. Rainfall 5-year Moving Average(1893-1991)

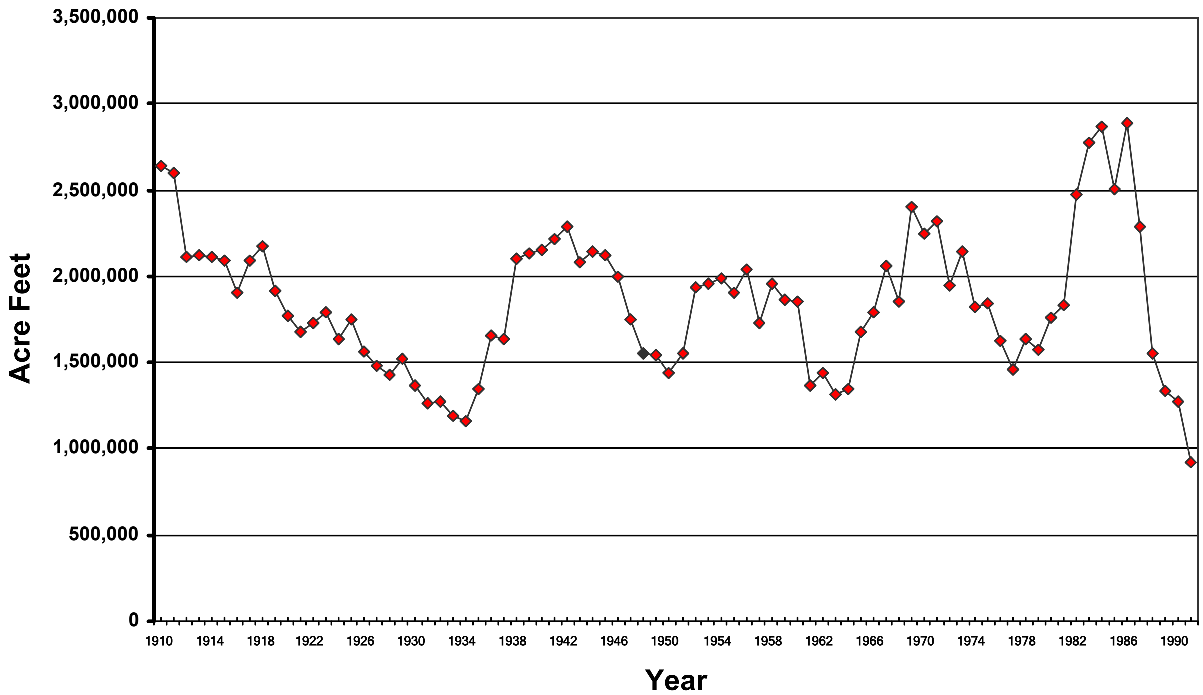


Figure 4. Tuolumne River Water Year Runoff 5-year Moving Average (1910-1991)

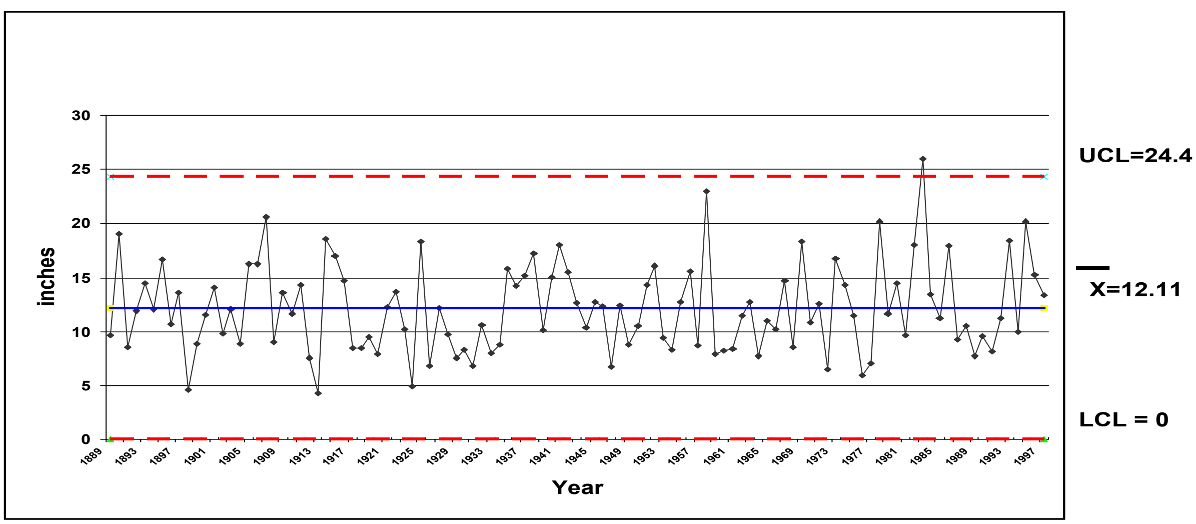


Figure 5. Individual X-Chart for Rainfall (1889-1997)

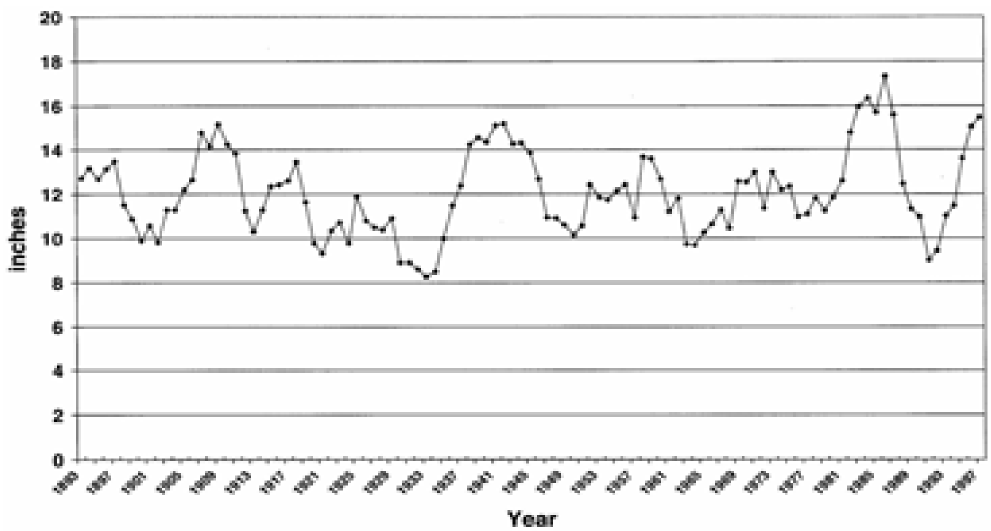


Figure 6. Rainfall 5-year Moving Average(1893-1997)

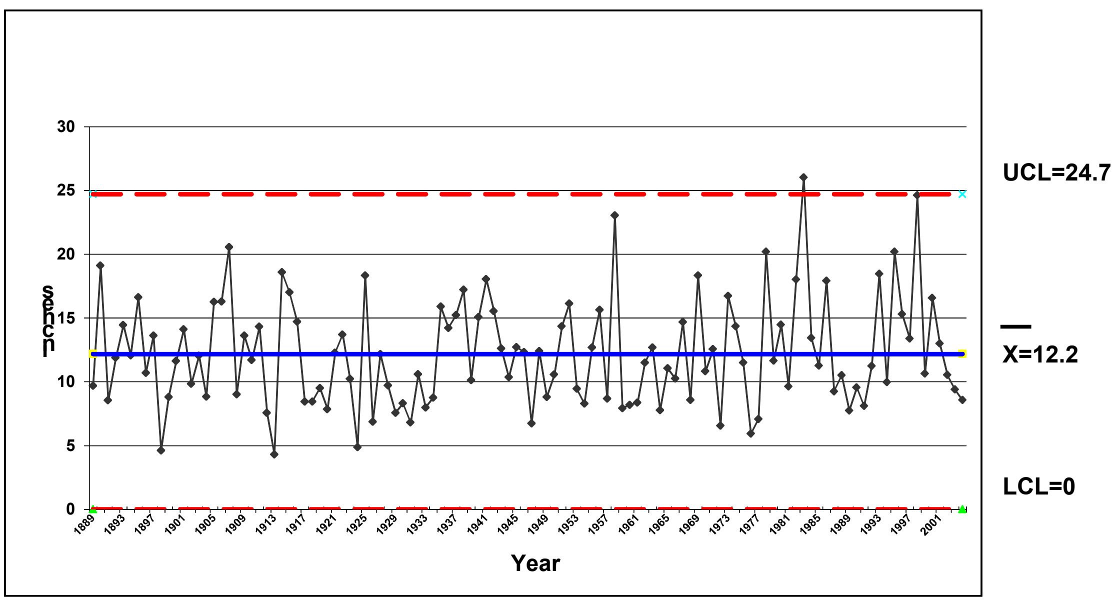


Figure 7. Individual X-Chart for Rainfall (1889-2004)

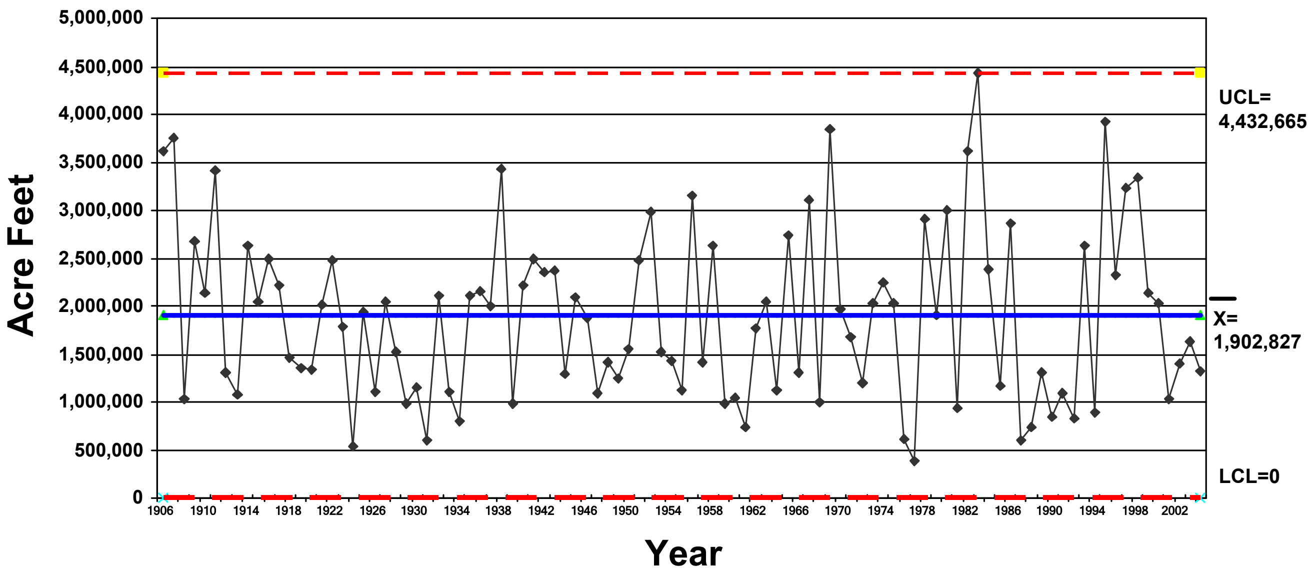


Figure 8. Individual X-Chart for Tuolumne River Water Year Runoff (1906-2004)

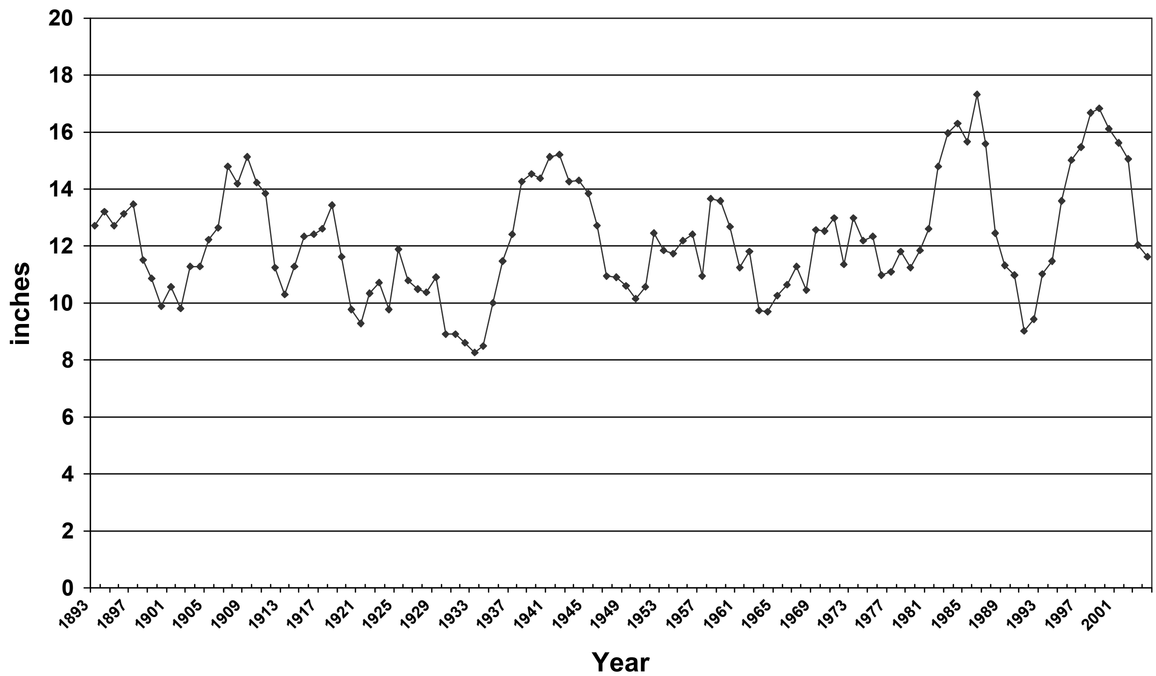


Figure 9. Rainfall 5-year Moving Average(1893-2004)

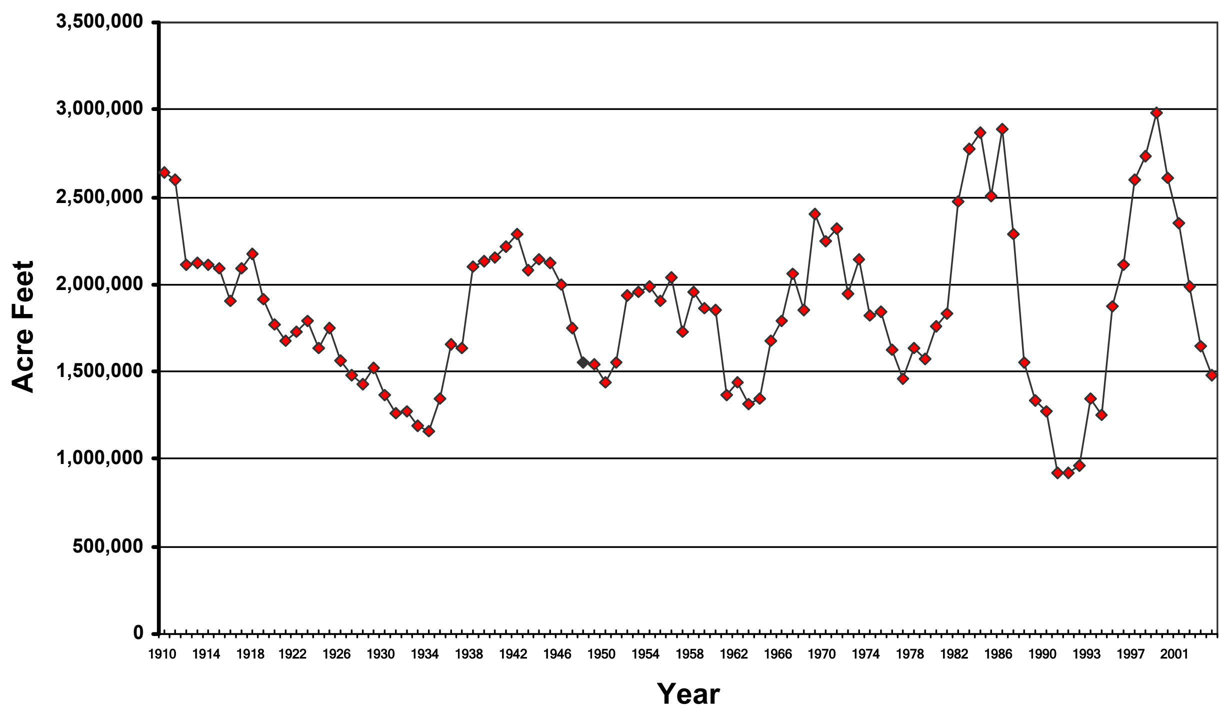


Figure 10. Tuolumne River Water Year Runoff 5-year Moving Average (1910-2004)

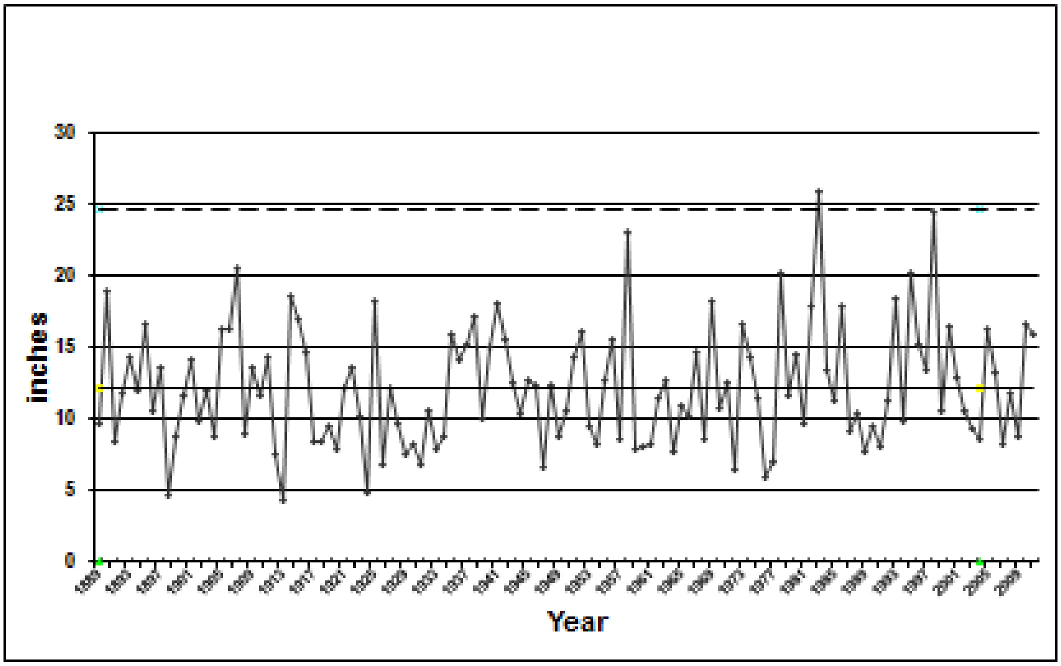


Figure 11. Individual X-Chart for Rainfall (1889-2011)

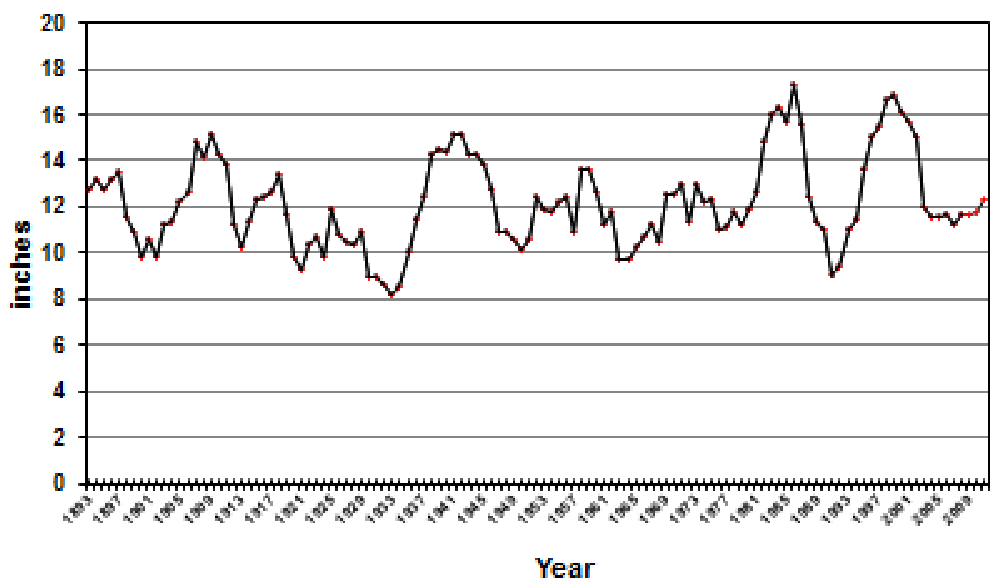


Figure 12. Rainfall 5-year Moving Average(1893-2011)

A Product Development Process in Capstone Courses

Joseph A. Morgan, Wei Zhan, and Jay R. Porter
Department of Engineering Technology & Industrial Distribution, Texas A&M University
College Station, TX 77843, USA
{morganj, zhan, porter}@entc.tamu.edu

Abstract

Based on feedback from industry and faculty members' experiences in product development, the Electronic Engineering Technology (EET) program at Texas A&M University started to follow a rigorous product development process (PDP) in capstone design projects. The process starts with the Voice of Customer, followed by system requirements derivation, feasibility study, creation of test matrix and test plans, preliminary design review, design review, design and testing of components and subsystems, fabrication of working prototypes, and validation of system requirements. Various project management tools are used during the process. Soft skills such as teamwork, presentation skills, writing skills, and ability to deal with ambiguity are emphasized throughout the capstone projects. The objective of the two-semester capstone project experience is to better prepare the students for the real-world challenges they will face after graduation.

1. Introduction

As the business world becomes more and more competitive, many companies rely on the advantage gained through new product development. A rigorous process for product development is essential for companies that develop complex products. An effective product development process can significantly improve the planning of the product development cycle. The process can provide a means to capture all the critical information for sharing among the designers as well as provide a disciplined path for the designers, especially those relatively new to the business. In contrast, without a rigorous process, product development will resemble a random trial-and-error effort. Much critical knowledge will be lost as the designers leave for new jobs and many tasks may be repeated, translating to increased costs. Many researchers have discussed the essential need for a good product development process in order for companies to increase productivity, reduce development cycle time, and stay competitive [4,8,14,28,30].

In the Fall semester of 2008, the EET program at Texas A&M University began a major curriculum revamping effort to shift the focus of the EET program to product development [22]. As is typical with engineering technology programs, most of the faculty members possess significant amount of experience in developing new products, either as practitioners in industry or as entrepreneurs. After several retreats, the faculty of the EET program came to a conclusion that students lacked critical education in the concept of the product development process and that this situation must be changed. The ETT program hosted a product development summit with the participation of all faculty members and many representatives from different companies and organizations. The feedback from these companies and organizations confirmed the faculty members' conclusion: Students graduated from EET possessed strong technical skills, but were unfamiliar with what was involved in a product development process. Virtually all participants of the summit supported the curriculum revamping effort of

EET. As a result, the EET faculty decided to add the concept of product development process in several courses.

Many educators understand that a gap exists between what engineering students learn in college and what they face in the industry. Numerous efforts have been made over the last decade to minimize this gap. One of the solutions promotes the focus on introduction of the product development process (PDP) to students [6,10,17,20,21,29,31]. Rodriguez used PDP in a professional development course [25]. Muci-Küchler *et al*. discussed the importance of a functional requirement in PDP [19]. Early exposure to PDP has proven effective in teaching PDP to students [35]. Barker and Hall developed a freshman engineering student course at Louisiana Tech University that focused on innovative product development tools and processes [1]. There are many tools and processes used in PDP. In many programs system engineering [24] is often taught as a method for developing products [2,27,32]. Project management is another important tool that is widely used in industry [13], but not commonly taught in electronics engineering technology programs, which tend to focus more on the technical design aspects rather than the overall project management and product development process. Other tools such as Failure Mode Effects & Analysis [18] are also left out of most electronics engineering technology programs. Globalization of the world economy has furthermore attracted the interests of researchers in product development in the global environment [15].

Capstone design is one of the key components in electronics engineering technology programs. Capstone design prepares students for a smooth transition from academic learning to industry work [9,16]. It has been extensively studied over the past three decades. Dutson *et al.* conducted an excellent review on the subject of capstone courses [11]. Many capstone projects involve product development; it is typically a course where PDP is introduced and practiced [11]. Sanger *et al.* integrated project management with the product development process in a capstone course to design innovative new product and develop patents [26]. Coms *et al.* used system engineering in capstone to develop new products [7]. Product development is also closely related to entrepreneurship cultivation [3,5]. These PDP-relevant subjects were carefully studied by the faculty of the EET program and subsequently implemented within the curriculum of the program. At the senior level, innovation and entrepreneurship were added in capstone courses. A PDP initially used in the capstone project is now being partially adopted in several of these courses. This article discusses the specific PDP implementation in the capstone series.

The remainder of the article is organized as follows: Section 2 discusses some common practices in product development in industry; Section 3 discusses the product development process being implemented in capstone courses in the EET program at Texas A&M University. Section 4 includes the conclusions and a discussion of future work.

2. Product development processes used in industry

Most companies that develop products follow a unique process. Processes are different for each company. However, there are many common aspects throughout these processes. To educate students, the process used in capstone courses should contain most of these common aspects. Based on the experience of faculty members and input from the industrial advisory board of the EET program, it was determined that system engineering should be the main approach for PDP. Market, budget, risk, and cost analyses are usually conducted before a go/no go decision is made for the product to be developed. If the decision is a go, then the project scope will be established, followed by the creation of the system requirements before the design work begins. The system requirements can be generated through brainstorming, collecting voice of customer (VOC), benchmarking, and using tools such as Quality Function Deployment (QFD). Project management tools such as Work Breakdown

Structure (WBS) and Critical Path Method (CPM) are used for project planning. A test plan is created before designing the product. Tests for validating each system requirement are designed with specific pass or fail criteria. Different options for the product are evaluated and the optimal solution is selected. The system architecture is designed. Subsystems and their requirements are defined, followed by test plans. Feasibility of the product is studied by rapid prototyping and/or simulation. A preliminary review is conducted before a go/no go decision is made. As the product is designed, other aspects such as government regulations, quality, manufacturability, environmental impact, logistics, after market support, and product disposal are considered. Design failure mode effects & analysis (DFMEA), process failure mode effects & analysis (PFMEA), and fault tree analysis (FTA) are conducted. Tests are conducted at the component level, subsystem level, and system level as soon as a prototype is built and ready for testing. The design may go through more than one cycle of requirements/ test plan/design modification/testing before it is finalized. The product needs to go through thorough testing. After the data is analyzed, a design validation plan and report (DVPR) is created. The cost analysis is updated as the design process proceeds. Design reviews are conducted at the end of each major phase. After the product launch, field data or customer feedback are continuously collected for further analysis and improvement. The typical product development process discussed is illustrated in Fig. 1.

3. Process used in capstone design

The capstone design in the EET program consists of two sequential courses. To provide entrepreneurial experience for students, student teams, typically consisting of three to five students, are required to form startup companies. Their goal is develop a new product that can potentially make profit for their startup companies. A faculty member is assigned to each team to provide necessary technical assistance. There are typically four teams each semester. This requires four faculty members to work with the student teams. This has the potential to be a limitation when class sizes are too large. Currently, there are ten faculty members within the EET program. Therefore, this has not yet become an issue. Another challenge is addressing the students' needs for technical assistance in various areas. When students cannot find faculty members with appropriate technical expertise, they must either complete their project with limited help from faculty or choose a different project.

The process depicted in Fig. 1 was thoroughly analyzed, and many parts of the process are now becoming key components of the revamped curriculum. The capstone design adopted a majority of the PDP illustrated in Fig. 1 with a few modifications for educational purpose.

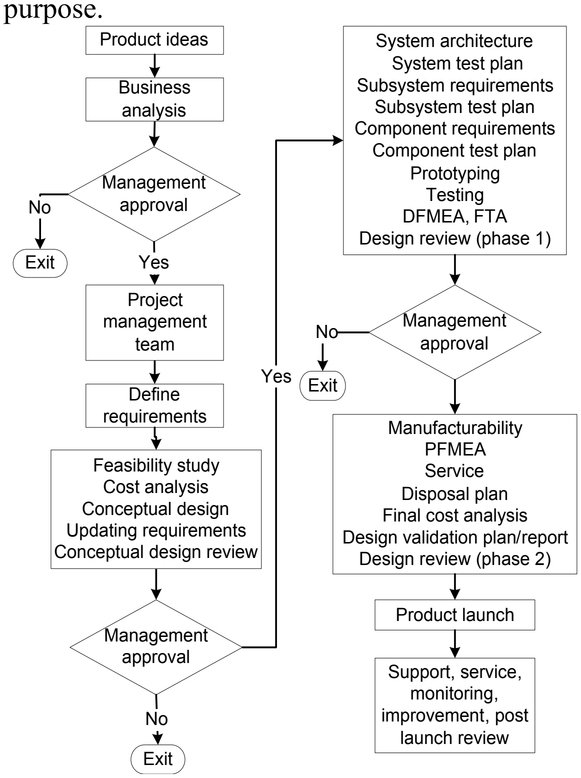


Figure 1. Typical product development process

In the first semester, students learn project management tools and concepts [33], create product ideas, conduct market analysis, identify an industrial sponsor, and define the project scope. The actual design work is carried out in the second semester. A working prototype is required for the completion of the projects. Throughout the entire two-semester capstone design, students first learn the product development process and are then required to follow a system design process (SDP) specifically created for the capstone course. The main components in the SDP are listed as follows:

- Problem Statement
- Functional Requirements
- Conceptual Block Diagram
- Project planning (WBS, NLD, CPM, Deliverables, Milestones, Gantt Chart)
- Preliminary Design Review
- Performance Specifications
- Test Matrix and Test Plan
- Technology Survey
- Detailed Functional Block Diagram
- Sensor Characterization
- Communications Interfaces/Protocols
- Technical Merit
- Critical Design Review
- Demonstration
- Final Documentation

The SDP is a revised version of the PDP. Like a PDP, the SDP provides a single source of information for stakeholders. It is built over time and is an iterative process. All items are maintained in a notebook and are available at all review meetings. The following sections explain the main components of the SDP in more depth.

Problem Statement

The problem statement is a high-level statement of system needs. It includes background information to provide understanding and context. It specifies the project scope agreed to by the industrial sponsor, the faculty advisor, and the student team. The following is an example problem statement:

"Develop and deliver a system that locates and displays the physical position of a mobile device."

Functional Requirements

Functional requirements specify the non-quantitative prototype elements. They are mandatory, organized in subsystems, and must be complete and cover all aspects of prototype. The functional requirements should be developed through interactions with the sponsor/advisor based on the team's expertise and research. Examples of Functional Requirements are given as follows:

- Battery operated and replaceable
- Stand-alone, self-contained intelligent unit
- Attached to anything
- Small Size
- Light Weight
- Simple user interface with Program/diagnostic port
- Locates itself anywhere on earth with lat-long and elevation output
- Weather-proof to work in any existing earth-based condition
- Store and forward operation
- Communicate position via COTS wireless network in pseudo real-time
- Display position information from multiple devices using GIS-based GUI

Conceptual Block Diagram

The conceptual block diagram depicts functional requirements in pictorial diagram format. It supports interaction, discussion, and development of performance specifications while including all elements of the system. A conceptual block diagram created by a student team is illustrated in Fig. 2.

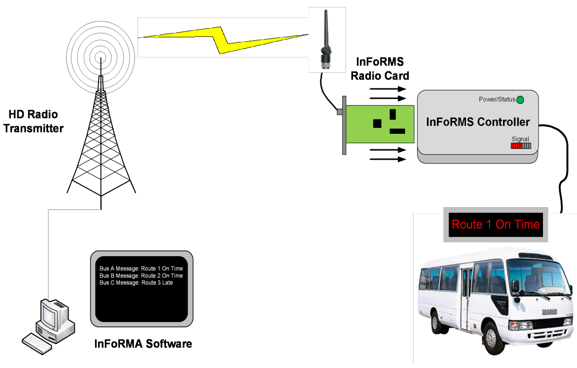


Figure 2. Conceptual block diagram example

Project Planning

Project management tools are required to ensure the project is completed under budget and on time. Students create a work breakdown structure (WBS) and a network logic diagram (NLD) in order to manage resources. Critical path method (CPM) and scheduled performance index (SPI) are used for on time delivery of the project. Cost performance index (CPI) is used to monitor the budget. A Gantt chart is used for project planning. Deliverables and milestone charts are required in the project planning stage. The CPM, SPI, and CPI are updated during weekly review meetings. A deliverable chart from a student team is illustrated in Fig. 3.

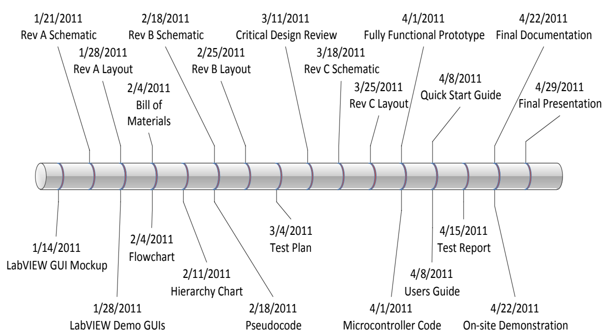


Figure 3. Deliverable chart example

Preliminary Design Review

A preliminary design review is held in the first semester. A go/no go decision is made by the faculty advisers, capstone director, and the industrial sponsor. If a go decision is made, the project is carried through. If a no-go decision is made, the students must make major changes to the project or select a different project.

Performance Specifications

The document of performance specifications defines the quantitative and detailed values for the system requirements. It expands on each of the functional requirements and is used to transition from the conceptual to functional block diagram. The performance specifications should be specific and measurable. They are used to create the test plan detailing how each of the requirements will be tested and validated. Sample performance specifications developed by student teams are listed below:

- Interfaces
  - User I/F – serial > 9.6Kbps
  - Location Det – serial > 9.6Kbps
  - Wireless Comm – TCP/IP > 56Kbps
- Small Size
  - Thickness must be less than 2 in.
  - Length and width should be less than 5 in.
- Light Weight
  - Less than 4 oz

Test Matrix and Test Plan

A test plan is created based on the performance specifications. A test matrix is a table that relates performance requirements to tests that will be performed. Each test must validate one or more requirements and all requirements must be validated by at least one test. A portion of a test matrix created by a student team is illustrated in Table 1.

Technology Survey

A technology survey is required for each student team. Simply providing a solution to a problem is not enough. An effort should be made to come up with an optimal solution in terms of performance and cost. Students must evaluate a minimum of three potential solutions for each major functional requirement. The evaluation includes creating a list of pros and cons. Justification must be provided for selecting a specific solution. In addition to the optimal solution of the technology, the survey process also provides students an opportunity for independent research. For example, a product that identifies location could use either GPS, Inertial Navigation, or StarVision Module. GPS was chosen based on accuracy, cost, and ease of integration.

Table 1. A test matrix example

	Comm. SCADA to VSD	Comm. SCADA to IEB	IEB Power Indication	Position Detection	Vibration Detection	Strain Detection	Temperature Detection	Motor Speed Control	Bluetooth Comm.	Surface Card Gen	Dyna-Card Gen.	Data Portability	GUI User Input
Inclinometer Tests				X									
Accelerometer Tests					X								
Load Cell Tests						X							
Zener Breakdown Voltage							X						
OpAmp Current to Voltage							X						
5V Reg. Tests							X						
3.3V Reg. Tests			X										
Current Tansmitter Tests							X						
VSD Control								X					
SCADAPack Controlling VSD	X							X					
PIC Analog Input			X		X		X						
PIC/SCADAPack Comm.		X	X										
Update Settings Remotely									X				X
Set User Boundries										X			X
Surface Card									X	X			
SCADA reading Sensors				X		X				X	X		
Downhole Dyna-Card Gen.				X		X				X	X		
Data Storage												X	

Detailed Functional Block Diagram

A detailed functional block diagram depicts chosen technology solutions with part numbers, pin numbers, interfaces, and power requirements. It can be used to request parts samples, generate schematic and GUI Mock Ups, and support software development and system testing.

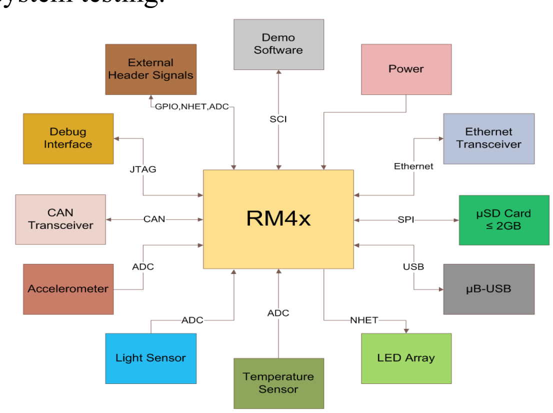


Figure 4. Detailed Functional Block Diagram

An example of a detailed functional block diagram is illustrated in Fig. 4.

Sensor Characterization

Sensors are important for embedded systems, which are the focus of the technical areas within the EET curriculum. Most capstone designs involve some sort of sensor. It is important to understand the sensor selected. Sensor characterization includes finding/deriving the transfer function by means of using the manufacturer's data or empirical data.

The circuitry required by the sensor also needs to be studied. The capstone teams should explain how the sensor signal will be processed and what hardware, such as filter and amplification, needs to be designed. Software issues such as sampling time and A/D conversion time should also be discussed. Other factors that may affect the performance such as noise and calibration also need consideration. Part of a temperature sensor characterization is illustrated in Fig. 5.

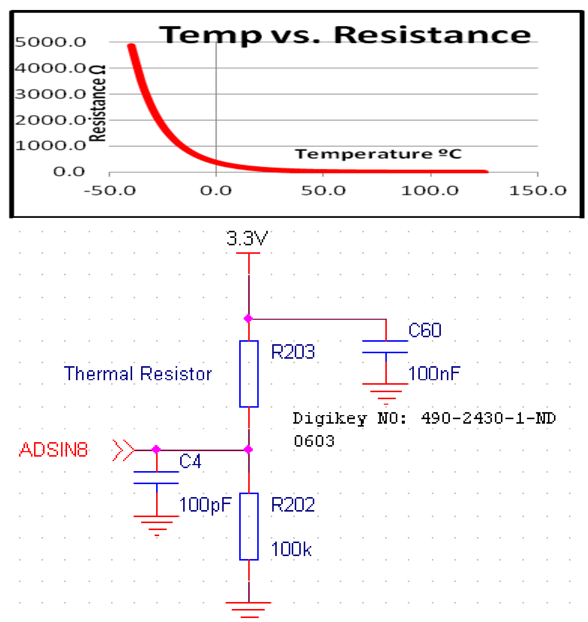


Figure 5. Sensor characterization

Communications Interfaces/Protocols

Communication processes need to be clearly explained. For each communication interface, the protocol needs to be defined. The signals, directions, data rates, and formatting of data/information to be transferred including packet format, checksum, etc., should be described. An example is provided below:

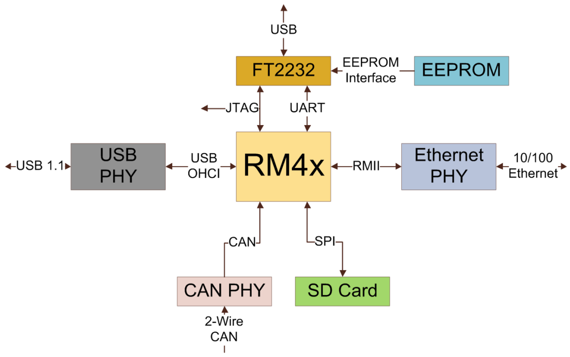


Figure 6. Communication interface and protocols

Technical Merit

A unique aspect for education is evaluation of the overall knowledge and skills learned by students. Even though a real product may only use some of these knowledge and skills, capstone design teams are evaluated based on the technical merit of their projects. Table 2 lists the criteria for determining the technical merits of the capstone design project. A maximum of 1.8 can be achieved for technical merit. The value of the technical merit has an impact on the grade the capstone team receives at the end of their capstone projects. If the technical merit is too low, the project may be rejected by the faculty adviser and capstone director.

Table 2. Technical Merit

Technical Merit Factors	Weight (max.)
Contains a clearly described and completely understood technical challenge	0.1
Contains a requirement for system integration	0.2
Contains a requirement for system testing	0.2
Contains a requirement for theoretical analysis and simulation	0.2
Contains hardware design, development and test	0.3
Contains software design, development and test	0.3
Contains an enclosure design/fabrication requirement	0.2
Contains a requirement for documentation other than the project related	0.2
Contains a requirement for intellectual property protection	0.1

Critical Design Review

A critical design review meeting is held in the second semester. A go/no go decision is made by the faculty advisers, capstone director, and the industrial sponsor. A no go decision requires the capstone design team to revamp their design or potentially start from scratch in the next semester.

Demonstration

Students are required to fabricate a working prototype and conduct a demonstration in order to receive a passing grade for the capstone design project. This requirement contributes to the reputation of the engineering technology programs for emphasizing the hands-on ability of their students. A paper design without a working prototype is not acceptable for the EET capstone design courses.

Final Documentation

Documentation is an important part of the project deliverables. Students are trained to file useful project information into appropriate documents. Typical documents created by capstone teams include a final project report, user manual, software code, test plan/data and report, hardware schematic, weekly review presentation, and final presentation.

4. Use of PDP in other courses

While the capstone design courses provide students with an opportunity to fully implement the product development process illustrated in Fig. 1, the learning of such knowledge is certainly not limited to capstone design courses. Following the successful implementation of product development process in the capstone design courses, efforts are being made to use similar processes in other courses as a part of the curriculum integration effort [34]. The EET program is undergoing a curriculum revamping effort so that the entire program will have a focus on product/system development [22]. The name of the program is also in the process of being changed to Electronics System Engineering Technology. A junior level product development process course is being offered beginning in the Fall semester of 2012 [23]. This will provide students with early exposure to the predevelopment process concept. Students will be familiar with the process and more prepared for their capstone design projects. A new junior level course in PDP will be added to the curriculum. A sophomore level system course will be added to enhance system engineering and system thinking. PDP will also be introduced through course projects [35].

Another major effort made by the Department of Engineering Technology and Industrial Distribution (ETID) is the creation of the Institute of Innovative Product Development. The main goal of the institute is to create opportunities for students to develop commercial products [36]. Multi-disciplinary teams will be formed for different potential products. The product development process will be rigorously followed by the teams.

5. Conclusions and future work

Many engineering technology programs focus on educating their students in technical design. However, technical design is only one aspect of the overall product design process. Other components, such as market analysis, project management, and cost analysis, are all critical to the success of a product launch. This article discussed the process implemented in the capstone design courses in the EET program at Texas A&M University as a part of the major curriculum revamping effort begun in the Fall semester of 2008. The process is based on product development processes used in industry with minor modifications to fit the unique educational requirements of the EET program. Students first learn the PDP used in industry and then follow the revised process to design their own products. Many tools commonly used in industry are introduced to students. By using project management tools and following a rigorous process, students have better control over time and budget. Students improve soft skills in addition to acquiring new technical skills.

After the capstone course, students possess a clear understanding of the product development process and the benefit of using it when designing a new product. The gap between what they learn in college and what they will face after graduation is greatly reduced. Learning by using the product development tools and process has proven very effective. Very positive feedback has been received from industry though the formal survey from the Industrial Advisory Committee and other informal surveys. Majority of the surveys indicated that the EET graduates were better prepared for real-world challenges.

The product development is also introduced to students in several other courses within the ETID department. Details of these efforts are discussed elsewhere.

6. References

[1] J. M. Barker and D. Hall, "Teaching Innovative Product Development Skills to Freshmen Engineering Students," *Proceedings of American Society for Engineering Education Annual Conference*, 2004.

[2] J. E. Bartolomei, S. L. Turner, and C. A. Fisher, "Using the Systems Engineering Method to Design a System Engineering Major at the United States Air Force Academy", *Proceedings of American Society for Engineering Education Annual Conference*, 2004.

[3] W. Birmingham, B. Allison, and J. Dupree, "Entrepreneurship via Multidisciplinary Product Development," *Proceedings of American Society for Engineering Education Annual Conference*, 2007.

[4] S. L. Brown and K. M. Eisenhardt, "Product development: past research, present findings, and future direction," *Academy of Management Review*, Vol. 20, No. 2, 1995, pp. 343-378.

[5] L. E. Carlson and J. F. Sullivan, "Exploring Entrepreneurship through Product Development: A Hands-on Approach," *Proceedings of American Society for Engineering Education Annual Conference*, 2002.

[6] L.P. Chao, I. Tumer, and K. Ishii, "Design Process Error-Proofing: Benchmarking Gate and Phased Review Life-Cycle Models" Proceedings of the ASME Design Engineering Technical Conference: Long Beach, CA, 2005.

[7] S. Corns, C. H. Dagli, and I. G. Guardiola, "SE Capstone: Integrating Systems Engineering Fundamentals to Engineering Capstone Projects: Experiential and Active," *Proceedings of the American Society for Engineering Education Annual Conference,* 2011.

[8] R.G. Cooper and S. J. Edgett, “Maximizing productivity in product innovation,” *Research Technology Management*, Vol. 51, No. 22, 2008, pp. 47-58.

[9] G. E. Crain and M. P. Tull, “A Capstone Course Targeting Industry Transition,” *Proceedings of the American Society for Engineering Education Annual Conference*, 2004.

[10] P. Daneshgari and P. E. Nimmo IV, “Learning Based Product Development,” *Proceedings of American Society for Engineering Education Annual Conference*, 2002.

[11] A. Dutson, “Using Principles of Design to Develop a Capstone Course”, *Proceedings of American Society for Engineering Education Annual Conference*, 2006.

[12] A. .J. Dutson, R. H. Todd, S.P. Magleby, and C.D. Sorensen, “A Review of Literature on Teaching Engineering Design Through Project-Oriented Capstone Courses,” *Journal of Engineering Education*, 86(1), 1997, pp. 17-28.

[13] H. Kerzner, “Project Management, A System Approach to Planning, Scheduling, and Controlling”, 5th ed. New York: Van Nostrand Reinhold, 1995.

[14] A. Khurana and S. R. Rosenthal, "Towards Holistic "Front Ends" in New Product Development". *Journal of Product Innovation Management* **15** (1), 1998, pp. 57–75.

[15] J. Kim, D. M. Kim, S. Consiglio, S. Severengiz, G. Seliger, L. Patil, and D. Dutta, “A Global Collaboration to Teach Global Product Development: Faculty Perspectives,” *Proceedings of American Society for Engineering Education Annual Conference*, 2006.

[16] L. King, M. El-Sayed, M. S. Sanders, and J. El-Sayed, “Job Readiness through Multidisciplinary Integrated Systems Capstone Courses,” *Proceedings of the American Society for Engineering Education Annual Conference*, 2005.

[17] M. Mendelson and C. Caswell, “Integrated Product Development in the Classroom,” *Proceedings of American Society for Engineering Education Annual Conference*, 1997.

[18] MIL-STD-1629A, "Procedures for Performing a Failure Mode, Effects and Criticality Analysis,” Department of Defense, Washington DC, November, 1980.

[19] K. Muci-Küchler, J. Weaver, and D. Dolan, “Establishing Functional Requirements and Target Specifications: A Key Component of Product Development Projects,” *Proceedings of American Society for Engineering Education Annual Conference*, 2007.

[20] R. Noorani, O. Es-Said, J. Foyos, A. Barrata, and B. Fritz, “Impact of New Technologies on Integrated Product Development,” *Proceedings of American Society of Engineering Education Annual Conference*, 1999.

[21] L. L. Pauley, J. S. Lamancusa, and T. A. Litzinger, “Using the Design Process for Curriculum Improvement”, *Proceedings of American Society for Engineering Education Annual Conference*, 2005.

[22] J. R. Porter, J. A. Morgan, and W. Zhan, “Product and System Development: Creating a New Focus for an Electronics Engineering Technology Program,” *Proceedings of the American Society for Engineering Education Annual Conference*, 2012.

[23] J. R. Porter, M. J. Leonard, J. A. Morgan, and W. Zhan, “A New Course on Product Development for Electronics Engineering Technology”, Submitted to the *American Society for Engineering Education Annual Conference,* 2013.

[24] N. B. Reilly, "Successful Systems Engineering”, Chapman & Hall, 1993.

[25] R. Rodriguez, “Understanding the Medical Product Development Process: Continuing Professional Development for Life Science Professionals,” *Proceedings of American Society for Engineering Education Annual Conference*, 2007.

[26] P. Sanger, C. Ferguson, and W. Stone, “Integrating Project Management, Product Development, and Senior Capstone into a Course Sequence That Creates New Products and Patents for Students,” *Proceedings of American Society for Engineering Education Annual Conference*, 2009.

[27] K. G. Sheppard, J. Nastasi, E. Hole, and P. L. Russell, “SE Capstone: Implementing a Systems Engineering Framework for Multidisciplinary Capstone Design,” *Proceedings of the American Society for Engineering Education Annual Conference*, 2011.

[28] P. G. Smith and D. G. Reinertsen, (1998) *Developing Products in Half the Time*, 2nd Edition, John Wiley and Sons, New York, 1997.

[29] M. Smith, D. Mahoney, W. Owen, H. Prasad, and W. Seering, "PD21: An Education Consortium for Product Development Leadership," *Proceedings of American Society for Engineering Education Annual Conference*, 2002.

[30] K. T. Ulrich and S. D. Eppinger, "*Product Design and Development*," 5th Edition, McGraw-Hill, Irwin, 2011.

[31] J. A. Untener, "Product Development in the Curriculum: One Clean-Sheet Approach," *Proceedings of American Society for Engineering Education Annual Conference*, 1996.

[32] J. Weaver and M. Vinarcik, "Combining Systems Architecture and Systems Engineering in an Engineering Management Program," *Proceedings of American Society for Engineering Education Annual Conference*, 2006.

[33] W. Zhan and J. A. Morgan, "Visual project management tools and their application," *Journal of Management and Engineering Integration,* Vol. 4, No. 1, 2011, pp. 137-144.

[34] W. Zhan, A. Goulart, J. A. Morgan, and J. R. Porter, "Vertical and horizontal integration of laboratory curricula and course projects across the electronics Engineering Technology program," *American Journal of Engineering Education*, Vol. 2, No. 2, Fall 2011, pp. 67-80.

[35] W. Zhan, B. Zoghi, and R. Fink, "The Benefit of Early and Frequent Exposure to Product Design Process", *Journal of Engineering Technology*, Spring 2009, pp. 34-43.

[36] W. Zhan, J. Wang, and M. Vanajakumari, "High impact activities to improve student learning", Submitted to the *American Society for Engineering Education Annual Conference,* 2013.

A University-Industry Research Collaboration for the Optimization of the Machining Processes of Multilayer Materials for the Aerospace Industry

Jean-François Chatelain
Department of Mechanical Engineering, École de technologie supérieure (Université du Québec), 1100 Notre-Dame West, Montreal, Quebec Canada H3C 1K3
jfchatelain@mec.etsmtl.ca

Abstract

The use of composite materials is increasing rapidly in the aerospace industry. Their specific strength and stiffness, as well as their relative light weight, compared to metallic alloys, convey them a net advantage for the production of lighter aircrafts. Even though composite components are produced to near net shape, additional machining operations are often required for assembly purposes; the most frequent of these operations are the drilling of holes for screws, bolts or rivets, as well as the trimming of openings or edges according to specific sizes and geometric tolerances. Unlike metallic materials, composite materials raise some specific problems during machining. Damage, in the form of delamination, cracks, matrix thermal degradation, etc., is observed as a result of tool wear or improper machining conditions. The specific objectives of the proposed research is to optimize the processes, develop new methodologies and cutting models in order to improve quality, productivity and machining costs for the aerospace industry. The research is carried out with the collaboration of four industrial partners, three universities and one college research center. This paper presents the research in general, and the benefits for industry, while focusing on results specific to the trimming process of Carbon Fiber Reinforced Plastic (CFRP). A cutting model based on instantaneous cutting force is proposed, and it is shown that tool helix angle and shape largely influence the force and resulting quality of parts. It is also found that an increase in the feed rate would degrade the surface roughness, while the influence of the cutting speed on the latter is much less significant.

1. Introduction

A composite material is usually formed from two materials joined or assembled together in a specific manner. The reinforcement material provides high stiffness and strength to the matrix material in preferential directions. The matrix shields the reinforcement material, distributes the applied stresses, and forms the final shape of the part. Three physical properties of composites radically affect the efficiency of the machining processes used to produce parts: non-homogeneity, anisotropy and brittleness. In addition, each composite has its own particular mechanical and machinability properties according to the orientation and types of reinforcement used as well as their proportion in volume as compared to the volume of the matrix material. The composite materials can be clustered in three matrix-based categories, namely: metal matrix composites (MMC), ceramic matrix composites (CMC) and polymer matrix composites (PMC). The latter are of particular interest in this research since the aerospace industry largely utilizes the Carbon Fiber Reinforced Plastic (CFRP) composite material. When such a material is stacked with metallic materials like aluminum and/or titanium alloys, such assemblies can be referred to as "multi-layer materials".

With the development of cutting tool materials and coatings over the years, accompanied by significant R&D effort, the CNC machining of composites has recently evolved into a realizable production method for the industry [1, 2, 3]. The fact that the machining of composites differs significantly in many respects from that of conventional metals and alloys certainly explains the difficulties and delays encountered. In such applications, the cutting tool encounters critical temperatures for epoxy as well as hard and abrasive carbon fibers, in the case of CFRP. This raises important problems, such as excessively rapid tool wear as well as delamination of the work piece material. Despite the fact that more performing tools and technologies are now available, the challenge faced by the industry is machining these materials at a cost-effective price, with highest possible level of quality.

Several research works covering the machining of composites can be found in the literature. Drilling, in particular, is one of the most common operations applied to composites, and several papers have been published on the subject [4-13]. For its part, the trimming operation has also been covered in many research endeavours. However, very few works have examined the multi-axis surface machining of these materials. The number of technical papers found dealing specifically with the multi-layer materials (CFRP/AL/Ti) is also very limited. The following paragraphs present some works that relate to the machining of CFRP, and introduce our research objectives and the on-going work being done on composite machining with the collaboration of industry.

2. Drilling and detouring of multi-layer materials

From several research works, it has been demonstrated that the cutting tool material and geometry, as well as the cutting parameters, have a significant influence on the delamination of carbon fiber reinforced plastics. Because key parameters need to be assessed for this material in order to ensure part quality, adding up stacks of material to the CFRP renders the problem even more complex. Brinksmeier and Janssen [14] studied the drilling operation of a multi-layer material made up of a 10 mm CFRP layer, a 10 mm layer of Titanium and a 10 mm layer of Aluminum alloy. Four different carbide drill designs with improved geometries and coatings were compared by characterizing the cutting forces, tool wear, hole quality and chip formation. It was found that because of the different material properties, holes with small diameter tolerances were difficult to obtain, but "step" geometry was the best performing tool tested. They also demonstrated that the combination of TiB2 coating and MQL significantly improved the tool life and the chip removal of metallic materials. Reduced velocity also reduced the delamination and erosion damage produced by the hot and sharp titanium chip.

Ramulu et al. [15] also studied the drilling of multi-layer materials. In their case, the work piece material was a stack of a 3.1 mm thick titanium (Ti6Al-4V) alloy sheet and a 38-ply (7.62 mm) thick graphite/bismaleimide (Gr/Bi) composite supplied by Boeing. Cutting tools with standard geometry made of different materials were used in the drilling experiments. The delaminating factor, the thermal matrix degradation, the surface roughness and the tool wear were studied as responses. They found that dissimilar thermal and mechanical properties of the stacks affect the tool life, resulting in increased matrix degradation and burr formation for titanium sheet, regardless of the cutting tool material. In this work, cutting parameters related to quality and tool selection are proposed for their application.

Experiments have also been conducted for the orthogonal machining of fiber reinforced plastics. According to Klocke [16], the machining of FRP is largely influenced by the orientation of fibers with respect to the cutting direction. Machining in the thickness of the material and parallel to the orientation of the fibers (0 degree) compresses the material below the cutting edge, which produces delamination, matrix fracture and cracks between the fibers and matrix. At 90^{o} with respect to the fiber orientation, the machining process shears off the fibers. Again, the pressure induced on the material results in cracks extending beyond the machined area. The best angle found for cutting the material is 135 degrees. The milling process is however more complex in terms of cutting force orientation than in orthogonal milling, and more work is needed in that regard [17].

Most experts agree on the fact that the dominating criterion for the selection of a milling tool for CFRP composites is the tool material. High abrasion and chipping wear results from the machining of hard materials such as carbon fibers. Therefore, polycrystalline diamond (PCD) or fine grain carbide tools have been found to be ideal for their cutting properties as they are highly resistant to these types of wear [2]. The tool geometries required are similar to those related to aluminum machining. According to Klocke and Wuertz [18], PCD tools are better than carbide tools for milling CFRP since the diamond grains in the former are less affected by the friction wear. This results in an 18% tool cost saving, compared to carbide tools [2].

Davim and Reis [19] also tested carbide (K10) tools to study the effect of cutting parameters on the surface roughness and delamination of CFRP. They tested a 2-flute and a 6-flute configuration of end mills 6 mm in diameter. The tool paths considered were linear slotting (one direction of cut), with a 2 mm depth of cut, for a supported 4 mm thick laminate work piece. Unlike all other studies presented in this survey, for which the laminates were made of multiple ply orientations, they used a laminate with only two alternating orientations of 0 and 90 degrees ($[0/90]_{16}$ laminate), respectively. The results clearly show that the feedrate has a significant effect on the surface roughness average “Ra”. It was found that “Ra” increases with the feedrate and decreases with the cutting velocity. The authors proposed empirical relationships to estimate the roughness value and the delamination factor according to the feedrate and cutting speed for a two- and six-flute cutter.

3. Research objectives

The current collaborative research program investigates and proposes new cutting practices for the trimming and drilling of the CFRP and a special multi-layer material obtained by stacking carbon-epoxy laminates with sheets of aluminum and titanium alloys. As a first objective, the state of the art cutting tool geometries, for the trimming operation, are studied to find the best cutting conditions adapted to our materials as well as to propose new concepts for improved performance in CNC and robotized applications. The tools are required to best perform in terms of resulting quality for the laminates, tool life, and global operating costs. To help in this development, exhaustive quality evaluation of the test coupons is performed as a response of the plans of experiments. Different NDI techniques are studied and thorough analyses of the effects of the CFRP ply orientation on roughness, based on the raw signals of a profilometer measurement system is also proposed. Unlike many other researches, which base their analyses on unidirectional laminates machining, our approach considers a multilayer quasi-isotropic material used in the aerospace. industry (e.g., 0°, 45°, 90° and 135°), in examining the interaction of the different plies, which may affect the resulting surface finish during the cutting process.

Beside the trimming process, we are also interested in the drilling of stacks of materials as well as the multi-axis milling of complex surfaces for mating in assemblies or surface repairing applications. As for the trimming operation, another objective of the research is the optimization of cutting conditions for these processes. For the complex problem of multi-axis surface machining, the resulting quality of the surface is expressed as a function of the different cutting parameters, but also as a function of the tool trajectory and the cutter orientation with respect to the part surface. A cutting model currently in development will help NC programmers to optimize their cutting strategies to avoid or reduce quality issues and enhance tool life as well. The machining of thin parts, such as composite laminates, also requires special set-ups in order to reduce deformations due to the cutting forces. The project considers this aspect as well, for the drilling problem, as it is a source of quality issues.

As summarized above, the research is composed of many projects, which are realized concurrently by collaborators and graduate students. In this paper, the methodology and some results regarding the optimization of the trimming of CFRP are specifically presented. We focus on experiments that helped propose excellent performing cutting tools and optimal machining conditions for these CFRPs, to our industrial partners. These experiments were also conducted in order to develop and validate an original cutting force model, which emphasizes instantaneous cutting force signals, taking into account each tooth per tool revolution during the trimming process [20].

To that end, the following section is organized in three parts: the first one deals with the methodology proposed for the generation of the machined surfaces resulting from the trimming operation. This is followed by a presentation of results and a discussion regarding the benefits for industry.

4. Trimming of CFRP

4.1. Methodology

A typical example of a plan of experiments related to the trimming of CFRP is presented in Table 1 [21]. Typically, six cutting speeds and federate values were tested for different thicknesses of materials. The cutting stability and forces were recorded during the experiments for each condition. Figure 1 presents a set-up for the dry trimming experiments. As shown in details A and B, each side of a coupon is cut using different parameters and/or direction of cut, and is maintained using a central screw. One square foot plate fixed to the dynamometer table enables the testing of more than 150 cutting conditions.

This plan was employed to test the performance of different cutting tools. After the machining, the quality of each test coupon is evaluated in terms of material integrity and surface roughness. The material integrity is evaluated using scanning electron microscopy (SEM), C-scan and thermography techniques to verify the delamination, fibers pull-out or damaged resin from the cutting surfaces [22]. The surface roughness is measured and evaluated using different statistical parameters.

An exhaustive study of this aspect is conducted in a bid to propose the proper methodology and parameters for such an evaluation in a typical production environment, as they are different from the case with metallic materials [23].

Table 1. Example of plan of experiments [21]

Cutting speed (m/min)	Feed (in/rev) / (mm/rev)	Thickness
200	0.004 / 0.10	24 plies 3.47 mm
300	0.008 / 0.20	
400	0.010 / 0.25	32 plies 4.63 mm
500	0.014 / 0.37	
650	0.016 / 0.4	40 plies 5.79 mm
800	0.020 / 0.5	

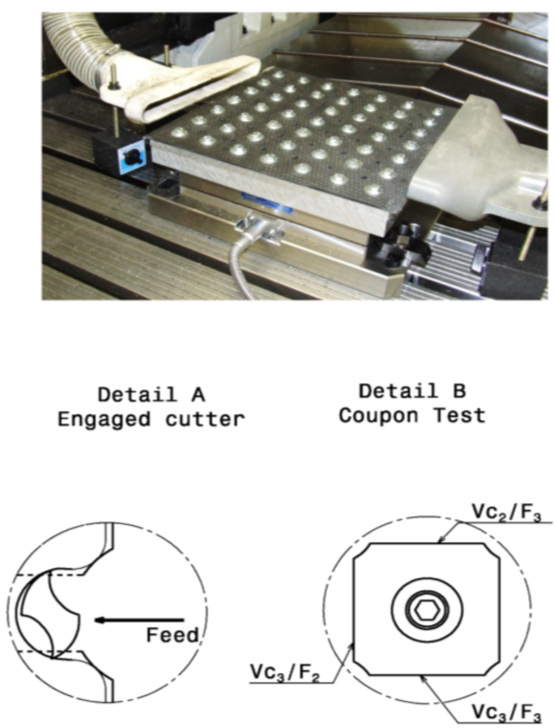


Figure 1. Set-up for the trimming [21]

4.2. Results

To illustrate how the cutting tools' geometry and cutting parameters influence the forces and the resulting quality of cut, Figures 2 and 3 show some surface finishes of test coupons. We can see uncut fibers and the surface roughness, which varies significantly, depending on not only on the ply orientation, but also on the cutter geometry (cutters C1, C3 and C6) for constant machining conditions (650 m/min). Figure 4 shows the relationship between the cutting force and the cutting parameters for the three different cutters [21]. The cutters were different in their helix angle and shape specifications (standard, cross-cut or grooved teeth). The results of the study conclude that helix angle as well as introduction of special geometry features for trimming tools has a significant effect on axial forces, stability of cut and resulting quality of parts. This detailed study, found in Chatelain [21], is useful to industry since it helps in properly selecting detouring tools and providing guidelines and a methodology for the design of performing cutting tools. A deeper look at the forces also helps in the comprehension of the cutting mechanism, which is required in tool design and process optimization. A model has been proposed to predict the cutting forces for specific material and cutting conditions. The model innovates as it proposes to predict the instantaneous cutting forces per revolution during the cutting operation (Figure 5) [20].

Finally, the effect of the ply orientation of the CFRP laminate on the surface finish for the trimming operation has also been thoroughly analyzed. The roughness across the laminate was measured using a repeatable procedure for different fiber orientations (e.g., 0°, 45°, 90° and 135°) of the laminate. It was found that the roughness profiles measured longitudinally, ply-by-ply, on the machined surface shows a significant correlation between the surface quality and the ply orientation, whatever the cutting conditions. Indeed, several tests were conducted, and all repeatedly demonstrated that there are 4 typical roughness profiles related to the 4 ply orientations in the laminate (Figure 6).The fact that the 135° ply orientation clearly represents the worst case should be noted, and is probably due to a fiber bending during machining. The magnitude height is clearly greater than for other ply orientation, and this is confirmed as well in the micorgraph, as shown in Figure 3. From the roughness profile measured all along the machined surface, which is over 10 mm long, we can deduce the ply orientation at any given point, even if the measurement is not perfectly perpendicular. This is due to the typical roughness profile signature for the cut surface. This result has significant benefits for industry since it may lead to methodology improvements for the quality control of surface finish for CFRP laminates. An analysis of roughness profiles and statistical indicators, with respect to the machining parameters, leads to the conclusion that a lower feed rate produces a better surface quality, whatever the ply orientations and the cutting speeds examined. However, while the cutting speed effect is not as significant as the feed rate effect, a higher cutting speed however seems to result in better surface finishes in most cases. All the details of this thorough analysis are found in Chatelain [23].

Figure 2. Uncut fibers of CFRP [21]

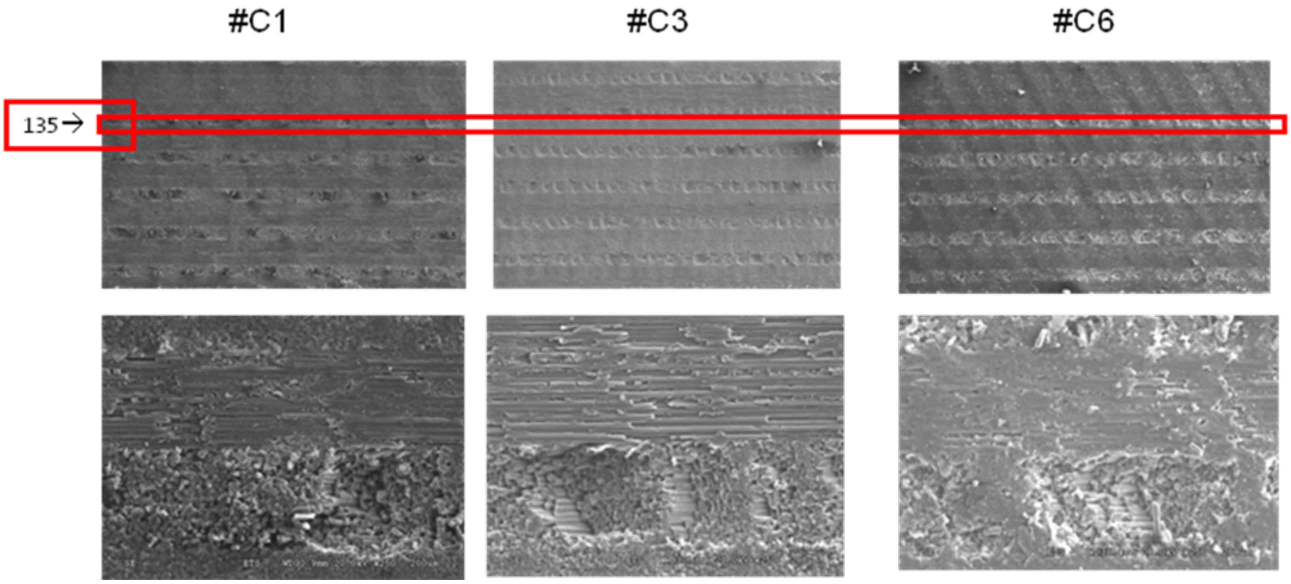


Figure 3. Micrographs related to three test coupons [21]

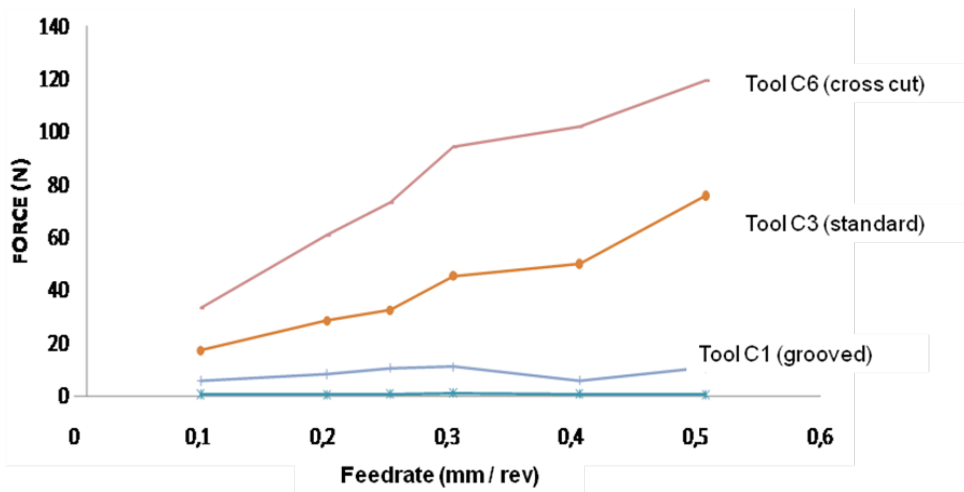


Figure 4. Axial force component as a function of feedrate (Vc=650 m/min) [21]

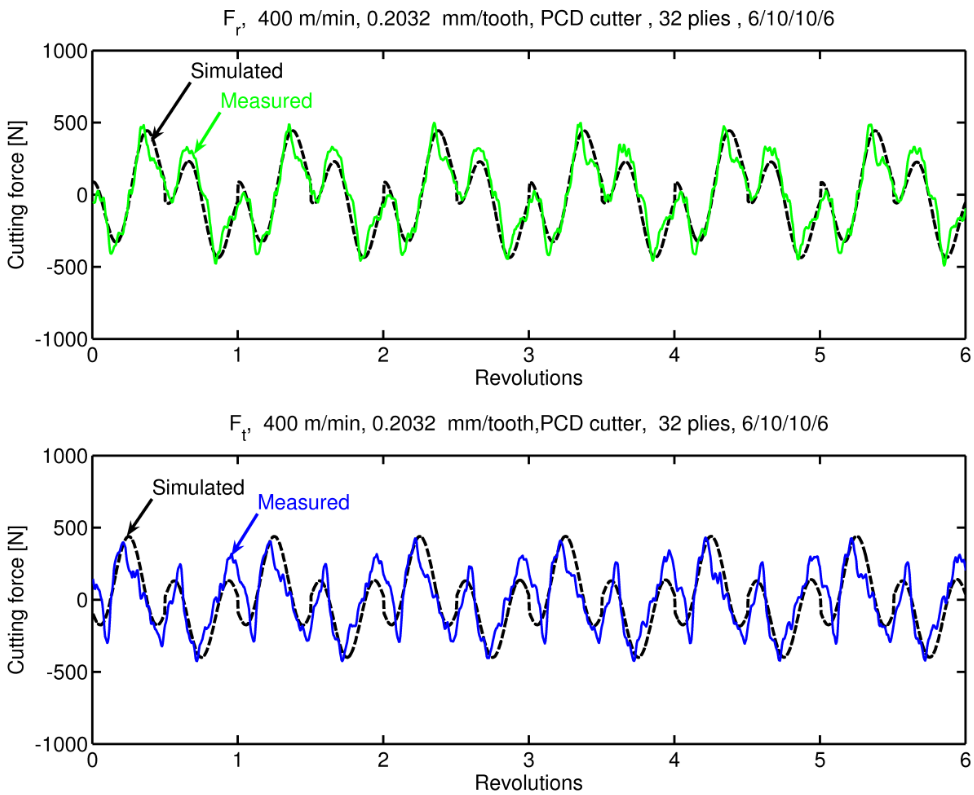


Figure 5. Prediction of forces for 32 plies CFRP configured as 6/10/10/6 [20]

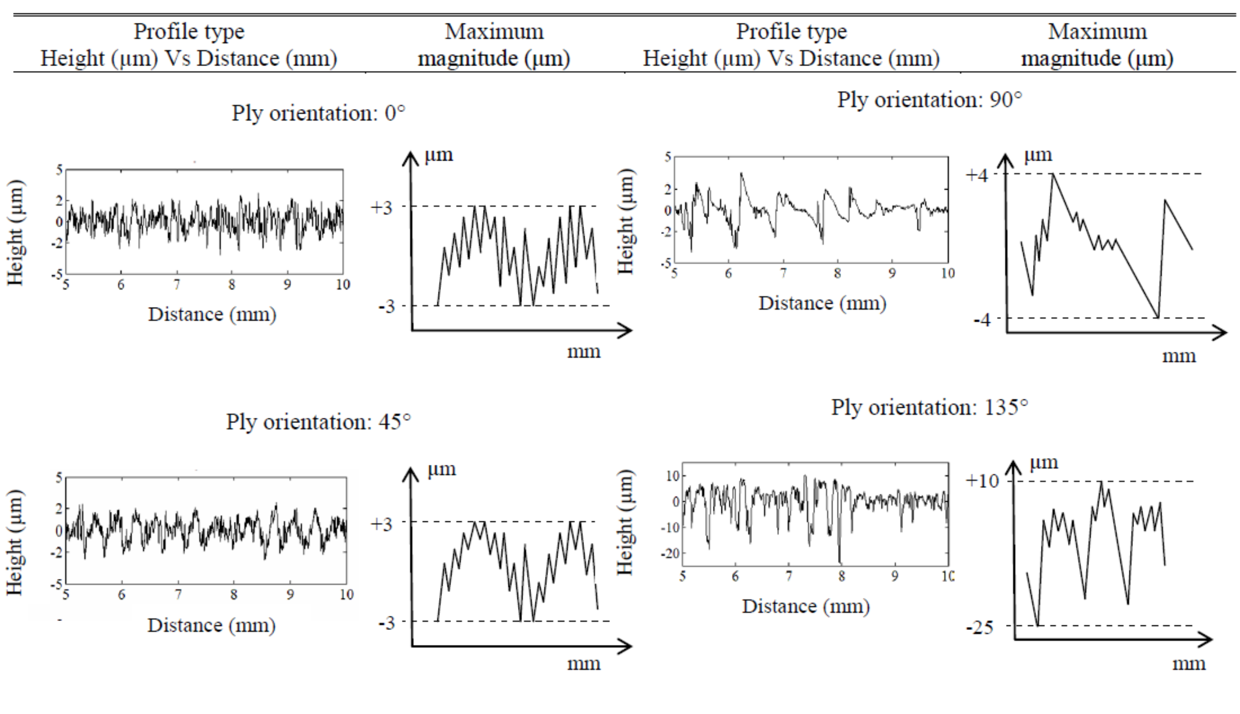


Figure 6. Roughness profile “signature” for each ply orientation [23]

4.3. Benefits and collaboration with industry

To date, the research team working on this collaborative project has brought together six professors from three different universities; five experts from industry, one representing each partner; two specialists from a college research center, as well as more than 12 graduate students. In such a project, partly funded through industrial contributions as well as public grants, some results are expected to be deliverables sensitive to the competitive context of the partners, and remain confidential, under an intellectual property agreement.

In addition to providing significant results to improve methodologies, productivity and quality of parts for industrial partners, another very appreciable benefit from developing such collaboration is that it allows the training of highly qualified personnel, who may eventually be recruited by the industrial partners as specialists. There is indeed a recognized lack of specialists in this area. The students enrolled in the program benefit significantly from the collaboration. Throughout their research project, in addition to working on real industrial challenges, they get the chance to actively contribute through 4- or 8-month work terms at the sites of one or more partners, thereby securing a better understanding of real problems and developing a useful contact network. They have the chance to present their project advancement to the research team at regular meetings. In terms of deliveries, the students generally produce a technical report including results of interest for industry, in addition to their theses and scientific papers. The four-year project should train over 20 graduate students, including post-doctoral and research associates.

5. Conclusion

The on-going research program brings together six professors from École de technologie supérieure, École Polytechnique de Montréal and Université du Québec à Trois-Rivières, as well as four partners from the aerospace industry and two specialists from the Centre technologique en aérospatiale - Aerospace technology center (CTA). The main objective of the program is the optimization of machining processes, e.g., trimming and multi-axis surface machining of CFRP as well as the drilling of stacks of materials in order to reduce global production costs and enhance the quality of parts.

This paper focuses on the CFRP trimming process, with results presented and discussed. The experiments lead to a recommendation for specific cutting tools and machining parameters. While it has been mentioned that special geometrical features and the helix angle directly influence the stability of cut, the axial force magnitude component and the quality of cut, in terms of uncut fibres, fibre pull-out and surface roughness. Some results are also presented on the influence of the cutting parameters on surface roughness, based on a realistic per-ply longitudinal measurement scheme. It is stated that each ply orientation has its own roughness profile “signature” regardless of the machining parameters involved. Further, an increase in the feed rate would degrade the surface roughness, while the influence of the cutting speed on the latter is much less significant. These are important results that may benefit industry in terms of inspection and detouring methodologies for CFRP laminates.

Upon culmination of the research, more than twenty students and research assistants are expected to graduate from this collaborative research program and become qualified in this area, which as earlier indicated, currently faces a lack of technical experts capable of developing and optimizing complex manufacturing processes for composite materials.

6. Acknowledgement

This work was funded by the Consortium for Research and Innovation in Aerospace in Québec (CRIAQ) and its partners, the Natural Sciences and Engineering Research Council of Canada (NSERC), MITACS, Bombardier Aerospace, Avior Integrated Products, Delastek and AV&R Vision & Robotics.

7. References

[1] Kamanduri, R., "Review article: Machining of Fiber Reinforced Composites", Machining Science and Technology, 1 (1), 113-152, 1997.

[2] Teti, R., "Machining of composite materials", CIRP Annals - Manufacturing Technology, 2002. **51**(2): pp. 611-634.

[3] NCDMM Project no.05005602, "F-35 Composite Edge of Part Machining", Diamond Tool Coating web site, 2008.

[4] Lachaud, F., et al., "Drilling of composite structures", Composite Structures, 2001. **52**(3-4): pp. 511-516.

[5] Dharan,C.K.H. and M.S. Won, "Machining parameters for an intelligent machining system for composite laminates", International Journal of Machine Tools & Manufacture, 2000. **40**(3): pp. 415-26.

[6] Tsao, C.-C. and W.-C. Chen, "Prediction of the location of delamination in the drilling of composite laminates", Journal of Materials Processing Technology, 1997. **70**(1-3): pp. 185-189.

[7] Hocheng, H. and C.C. Tsao, "The path towards delamination-free drilling of composite materials", Journal of Materials Processing Technology, 2005. **167**(2-3): pp. 251-264.

[8] Durao, L.M.P., de Moura, M.F.S.F., Marques A.T., "Numerical prediction of delamination onset in carbon/epoxy composites drilling", Engineering Fracture Mechanics, Vol. 75, 2008, pp. 2767-2778.

[9] Bathnagar, N., Ramakrishnan, N., Naik, N.K., Komanduri, R., "On the Machining of Fiber Reinforced Plastic Composite laminates", Int. J. Mach. Tool. Manuf., 35(5), 701-716, 1995.

[10] Langella A., Nele L., Maio A., "A torque and thrust prediction model for drilling of composite materials", Composites Part A: Applied sciences and manufacturing, Vol. 36, 2005, pp. 83-93.

[11] Murphy, C., G. Byrne, and M.D. Gilchrist, "The performance of coated tungsten carbide drills when machining carbon fibre-reinforced epoxy composite materials", Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2002. **216**(2): pp. 143-152.

[12] Karnik, S.r., Gaitonde V.N., Campos Rubio J., Esteves Correia A., Abrao A.M., Paulo Davim, J., "Delamination analysis in high speed drilling of carbon fiber reinforced plastics (CFRP) using artificial neural network model", Materials and Design, Vol. 29, 2008, pp. 1768-1776.

[13] Lin SC., Chen IK., "Drilling of carbon fiber-reinforced composite materials at high speed", Wear, Vol. 194, pp. 156-62, 1996.

[14] Brinksmeier E., Janssen R., "Drilling of Multi-Layer Composite Materials consisting of Carbon Fiber Reinforced Plastics (CFRP), Titanium and Aluminum Alloys", CIRP Annals. Manufacturing technology, Vol. 51, Issue 1, 2002, pp. 87-90.

[15] Ramulu, M., Branson T., Kim D., "A Study on the drilling of composite and titanium stacks", Composite Structures, Vol. 54, 2001, pp. 67-77.

[16] Klocke, F., Koenig, W., Rummenhoeller, S., Wuertz, C., "Milling of Advanced Composites", in Machining of Ceramics and Composites, M.D. Inc., Editor, 1999, CRC Press., pp. 249-265.

[17] Ghidossi P., ElMansori M., Pierron F., "Edge machining effect on the failure of polymer matrix composite coupons", Composites: M part A, Vol. 35, 2004, pp. 989-999.

[18] Klocke, F. and C. Wuertz, "PCD in the

machining of fibre-reinforced materials", Industrial Diamond Review, 1999. **59**(580).

[19] Davim, J.P., Reis P., "Damage and dimensional precision on milling carbon fiber-reinforced plastics using design experiments", Journal of Materials Processing Technology, Vol. 160, 2005, pp. 160-167.

[20] Zaghbani I., Chatelain J-F., Bérubé S., Songmene V, Atarsia A. "A Comprehensive Analysis of Cutting Forces During Detouring of Multilayer CFRP Laminates", *Journal of Composite Materials*, Vol. 46, No. 16,2012, pp.1955-1971

[21] Chatelain J-F, Zaghbani I., "A Comparison of Special Helical Cutter Geometries Based on Cutting Forces for the Trimming of CFRP Laminates", International Journal of Mechanics, Vol. 6, issue 1, 2012, pp. 52-59.

[22] Généreux L-A, Viens M., Lebrun G., "Comparison of Ultrasonic Testing and Infrared Thermography for the Detection of Machining Defects in Composite Materials", Proc. of the 26th Annual Technical Conference of the American Society for Composites/2nd Joint US-Canada Conference on Composites, Montreal, Québec, September 2011.

[23] Chatelain J-F., Zaghbani I., Monier J., "Effect of Ply Orientation on Roughness Parameters for the Trimming Process of CFRP Laminates", Journal of World Academy of Science, Engineering and Technology, Vol. 68, 2012, pp. 1204-1210.

An Integrated Methodology for Supplier Evaluation and Selection Using QFD and DEA

E. Ertugrul Karsak and Melih Ece
Industrial Engineering Department, Galatasaray University, Ortakoy, Istanbul 34357, Turkey
ekarsak@gsu.edu.tr, melihece@windowslive.com

Abstract

In this paper, an integrated decision making framework that employs quality function deployment and data envelopment analysis (DEA) is developed for supplier selection. The proposed approach establishes the relevant supplier assessment criteria considering the customer requirements in a house of quality (HOQ) structure. DEA is implemented in supplier evaluation and selection using the data from the developed HOQ and cost factor components related to suppliers. The potential use of the proposed approach is illustrated through a previously reported data set concerning supplier selection.

1. Introduction

The purchasing function is considered to a greater extent as a strategic issue in supply chain management. Supplier selection is one of the most important decisions among the various activities involved in supply chain management due to its role in reducing costs, and thus increasing profits.

Supplier evaluation and selection can be defined as the process through which firms identify, evaluate, and contract with suppliers. A wide variety of factors can affect the supplier evaluation and selection decision. Dickson [1] analyzed 23 different criteria for vendor selection. Rather than considering internal costs and sustainable quality development, the traditional multiple-source approaches concentrated on the lowest price at a specific time. However, there have been progressive changes in the relationships between companies and suppliers to establish more stable and durable relations with a specific group of suppliers in order to obtain significant cost savings and ongoing quality improvements. Hence, companies have trained their narrow group of suppliers to produce higher quality products and have focused on evaluating them with respect to their performances.

Over the last two decades, supplier evaluation and selection decision has been broadly studied and investigated by a number of researchers [2]. In current research, supplier selection is regarded as a multi-criteria decision making (MCDM) problem [3]. Within the range of supplier evaluation and selection studies, data envelopment analysis (DEA) appears as one of the most powerful techniques. DEA is a mathematical programming technique, which was first developed by Charnes et al. [4], to determine a set of optimal efficiency weights for decision making units (DMUs) with respect to the ratio of outputs they produce to inputs they consume. A typical MCDM model is characterized as a central tendency approach and it evaluates suppliers with respect to an average supplier, whereas DEA is an extreme point method and compares each supplier with only the "best" supplier. DEA is a non-parametric approach that enables efficiency to be measured without having to specify either the form of the function or the weights for different inputs and outputs chosen [5].

This paper aims to propose a comprehensive methodology to evaluate suppliers that allows for both customer requirements (CRs) and supplier characteristics (SCs) that companies request from suppliers to be taken into consideration, and deploys this information throughout the supplier selection process. The proposed framework integrates quality function deployment (QFD) with DEA for supplier selection. QFD is not only a superior design tool to prioritize the attributes of a company, but it is also used as an evaluation technique to assess the supplier performances with respect to customer requirements [6-8]. The proposed approach establishes the relevant supplier assessment criteria considering the customer requirements in a HOQ structure. However, since HOQ is constituted on the basis of decision-makers' subjective judgments, it does not explicitly incorporate objective factors like various cost components during the evaluation stage of suppliers [6-7]. As a relative efficiency assessment method, DEA can incorporate both the information from QFD and cost factors of suppliers. In this paper, DEA is implemented in supplier evaluation and selection using the data from the developed HOQ and cost factor components related to suppliers. The DEA model deploys various SCs from the HOQ matrix and cost factors of suppliers as the output and input parameters of suppliers, respectively. The potential use of the proposed approach is illustrated through previously published data regarding supplier selection [7].

The rest of the paper is organized as follows. Section 2 provides a concise literature review about supplier evaluation and selection process. In Section 3, the basic QFD framework is presented. Section 4 briefly introduces the DEA approach, and delineates the proposed integrated decision making framework employing QFD and DEA. In Section 5, the proposed approach is implemented using a previously reported data set concerning supplier selection, and results are thoroughly discussed. Finally, Section 6 contains the concluding remarks and future research directions.

2. Literature Review

Supplier evaluation and selection problem has been studied extensively by a vast group of researchers. A review of the supplier evaluation and selection literature reveals that DEA is one of the most popular approaches adopted in supplier evaluation [9-21]. DEA has been actively used in supplier selection due to its capability of handling multiple conflicting factors without the need of eliciting subjective importance weights from the decision-makers.

Liu et al. [9] presented the application of DEA for evaluating the overall performance of suppliers in a manufacturing firm. Forker and Mendez [10] implemented DEA to measure the comparative efficiencies of suppliers, and calculated cross-efficiencies to find the best peer suppliers. Narasimhan et al. [11] proposed a framework based on DEA to evaluate alternative suppliers for a multinational corporation in the telecommunications industry. Talluri and Sarkis [12] presented a methodological extension of DEA by improving the discriminatory power of an existing variable returns to scale model for the supplier performance evaluation and monitoring process. Ross et al. [13] used DEA to evaluate the supplier performance with respect to both buyer and supplier performance attributes. Seydel [14] modified DEA to incorporate weight constraints and used this approach to rank the available suppliers. Saen [15] implemented DEA for selecting the best supplier in the presence of both cardinal and ordinal data. Ross and Buffa [16] employed DEA to investigate the effects of buyer performance on supplier performance. Recently, Toloo and Nalchigar [17] developed a new DEA model which is able to identify the most efficient supplier in presence of both cardinal and ordinal data.

Throughout supplier evaluation and selection processes, DEA can be integrated with different kinds of methodologies to deal with the lacking input/output features of DMUs. Talluri and Narasimhan [18] conducted a cross efficiency analysis and grouped the suppliers based on Friedman nonparametric statistical test. Seydel [19] applied SMART, which involves decision-maker preferences, and then evaluated the suppliers using DEA. Garfamy [20] compared suppliers based on DEA and total cost ownership (TCO) concepts. Ramanathan [21] integrated objective and subjective information obtained from the TCO and AHP approaches with DEA for supplier selection.

Although QFD is not a novel method in the field of operations management, it has been recently used for supplier evaluation [6-8]. Bevilacqua et al. [6] evaluated the potential suppliers against the relevant supplier assessment criteria using a fuzzy QFD approach. Bhattacharya et al. [7] proposed an integrated AHP-QFD methodology to rank and subsequently select candidate-suppliers under multiple, conflicting nature criteria environment. More recently, Ho et al. [8] developed a combined QFD and AHP approach to measure the performance of suppliers.

3. Quality Function Deployment

Organizations have been focusing on pursuing higher quality for their products and services to maintain their competitive positions in global marketplace. Since Japanese manufacturers have changed the way of thinking about the development of new or improved products in a revolutionary way, companies operating in diverse industries have emphasized the importance of quality and customer demands in order to sharpen their competitive edges. Quality function deployment (QFD) plays an essential role to link customer requirements with engineering, manufacturing, service and other related functions of the company.

The basic concept of QFD is to translate the desires of customers into engineering characteristics, and subsequently into part characteristics, process plans, and production requirements. In order to set up these relationships, QFD usually requires four matrices each corresponding to a stage of the product development cycle. These are product planning, part deployment, process planning, and production/operation planning matrices, respectively. The product planning matrix, also called the house of quality (HOQ), can be named as the basic tool of QFD. The HOQ is a key strategic tool to help companies in developing products or services that satisfy customer needs. The seven elements of the HOQ shown in Figure 1 can be described as follows [22]:

1. Customer requirements (WHATs): They are also known as customer needs or voice of the customer. As the initial input for the HOQ, they highlight the product characteristics that should be taken into consideration.

2. Engineering characteristics (HOWs): Engineering characteristics are also known as technical attributes or design requirements. They describe the product in the language of the engineer, and thus, are sometimes referred as the voice of the company. They are used to determine how well the company satisfies the customer requirements.

3. Relative importance of the customer requirements: Since the collected and organized data from the customers usually contain too many needs to deal with simultaneously, they must be rated. Furthermore, the diversity of the customer requirements usually prohibits

satisfying all of them, simply because they may be in conflicting nature. Hence, the providers require methods to rank the customer needs.

4. Relationships between WHATs and HOWs: The relationship matrix indicates how much each engineering characteristic affects each customer requirement. This step is crucial as it is used to make the transition from customer requirements into engineering characteristics.

5. Inner-dependence among the engineering characteristics: The inner-dependencies among engineering characteristics given in the HOQ's roof matrix measure the extent that a change in one feature affects another.

6. Competitive analysis: During the competitive analysis, the company's product or service position among its main competitors is identified, underlining company's strengths and weaknesses in terms of customer needs. These findings along with the performance values of engineering characteristics for each provider are used to determine target values for engineering characteristics.

7. Overall priorities of the engineering characteristics: Here the results obtained from preceding steps are used to calculate a final rank order of HOWs.

4. Proposed Decision Framework

Several researchers have claimed that selecting efficient suppliers significantly reduces cost of product and provides a competitive advantage to companies. Moreover, since voice of the customer is perceived in every function of the company related to manufacturing, evaluation and selection of suppliers cannot solely be made by purchasing managers, but other interrelated departments need to take part in the decision process.

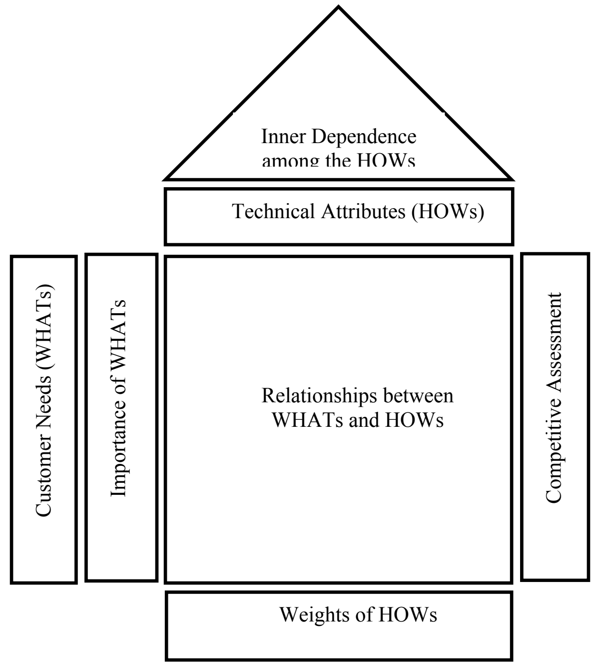


Figure 1. The House of Quality

The decision methodology presented in here integrates QFD with data envelopment analysis (DEA) for supplier selection. The DEA models employed in supplier evaluation and selection use the data from the developed HOQ and cost factor components related to suppliers.

DEA is a mathematical programming technique proposed by Charnes et al. [4] for evaluating the relative efficiencies of decision making units (DMUs) in the presence of multiple inputs and outputs. Inputs are the resources that DMUs utilize, and outputs are the outcomes produced by DMUs. DEA considers n DMUs to be evaluated, where each DMU consumes varying amounts of m different inputs to produce s different outputs.

The relative efficiency of a DMU is defined as the ratio of its total weighted output to its total weighted input. In mathematical programming terms, the objective function for the particular DMU being evaluated is formed by maximizing this ratio. A set of normalizing constraints is used to reflect the condition that the output to input ratio of every DMU be less than or equal to unity. The resulting fractional programming model is represented as follows:

$$\max E_{jo} = \frac{\sum_r u_r y_{ij_0}}{\sum_i v_i x_{ij_0}}$$

subject to (1)

$$\frac{\sum_r u_r y_{ij_0}}{\sum_i v_i x_{ij_0}} \leq 1, \qquad j = 1, \ldots, n$$

$u_r, v_i \geq \varepsilon > 0, \quad r = 1,\ldots, s; \; i = 1, \ldots, m$

where E_0^j is the efficiency score of the evaluated DMU (j_0), u_r is the weight assigned to output r, v_i is the weight assigned to input i, y_{rj} represents amount of output r produced by the jth DMU, x_{ij} denotes amount of input i consumed by the jth DMU, and ε is an infinitesimal positive number. The weights in the objective function are chosen to maximize the value of the DMU's efficiency ratio subject to the "less-than-unity" constraints. These constraints ensure that the optimal weights for the DMU in the objective function do not denote an efficiency score greater than unity either for itself or for the other DMUs. A DMU attains a relative efficiency rating of 1 only when comparisons with other DMUs do not provide evidence of inefficiency in the use of any input or output.

The fractional program is not preferred for computing the efficiency scores of DMUs due to its intractable nonlinear and nonconvex properties [4]. Instead, the fractional program is transformed to an ordinary linear program given below that is calculated separately for each DMU, generating n sets of optimal weights.

$$\max E_{jo} = \sum_r u_r y_{rj_0}$$

subject to (2)

$$\sum_i v_i x_{ij_0} = 1$$

$$\sum_r u_r y_{rj} - \sum_i v_i x_{ij} \leq 0, \; j = 1, \ldots, n$$

$u_r, v_i \geq \varepsilon > 0, \quad r = 1,\ldots, s; \; i = 1, \ldots, m.$

The maximization of the discrimination among consecutive rank positions can be assured by using the maximum feasible value for ε, which can be determined by maximizing ε subject to the constraint set of formulation (2) for $j = 1, \ldots, n$, and then by defining $\varepsilon_{max} = min_j(\varepsilon_j)$.

In this study, DEA is used in conjunction with QFD to compute the efficiency scores of suppliers. Suppliers are considered as DMUs. Supplier characteristics and cost factor components of suppliers are respectively defined as output and input variables in the DEA model. The relative importance weights of SCs are used to determine the priorities of output variables with respect to each other, and thus formulation (2) can be rewritten as

$$\max E_{jo} = \sum_r u_r y_{rj_0}$$

subject to (3)

$$\sum_i v_i x_{ij_0} = 1$$

$$\sum_r u_r y_{rj} - \sum_i v_i x_{ij} \leq 0, \; j = 1, \ldots, n$$

$w_k u_r = w_r u_k, \quad r = 1, \ldots, s \; ; k \in R, k \neq r$

$u_r, v_i \geq \varepsilon > 0, \quad r = 1, \ldots, s \; ; i = 1, \ldots, m$

where, in addition to the earlier notation introduced for formulations (1) and (2), w_k and

w_r represent the relative importance weights of SC_k and SC_r, respectively.

The stepwise representation of the proposed decision framework is as follows:

Step 1. Identify the CRs and SCs that will be represented in the first HOQ.

Step 2. Determine the relative importance weights of CRs.

Step 3. Determine the relationships between CRs and SCs.

Step 4. Construct the DEA models to compute relative importance weights of SCs.

Step 5. Determine the supplier performance ratings with respect to SCs to be implemented in the second HOQ.

Step 6. Identify the cost factor components and determine the cost factor measurements (CFMs) for each candidate supplier.

Step 7. Normalize the data concerning CFMs using max-value normalization to rectify the problems due to scale differences.

Step 8. Construct the DEA models to compute supplier efficiency scores.

Step 9. Select the supplier with an efficiency score of 1.

Step 10. If there exist multiple suppliers with an efficiency score of 1, use cross efficiency analysis to determine the best supplier.

5. Illustrative Example

In this section, the proposed decision framework is illustrated through previously reported data set concerning supplier selection [7], and its robustness is tested via comparing the obtained results with those of the earlier study. The decision framework aims to evaluate the relative efficiency of ten candidate suppliers in the presence of qualitative and quantitative decision criteria.

"Delivery", "quality", "responsiveness", "management", "discipline", and "financial position" are defined as the CRs. "Facility" and "technical capabilities" are defined as the SCs. Numerical data related to Steps 1-6 are partially taken from Bhattacharya et al. [7]. In here, we focus on the remaining steps to show the validity of the analysis.

In Bhattacharya et al. [7], the importance weights of SCs and supplier performance ratings with respect to SCs are obtained by an integrated decision making framework that employs analytical hierarchy process (AHP) and QFD as shown in Table 1.

CFMs are added to the previously defined SCs, namely "facility" and "technical capabilities", while evaluating the candidate suppliers. In order to rectify the problems due to the significant differences in the magnitude of inputs and outputs, max-value normalization is applied to the data concerning CFMs. CFM data and normalized CFM data for candidate suppliers are shown in Tables 2 and 3, respectively. A typical firm aims to achieve the minimum cost and maximum performance from suppliers while enhancing the value creation. Hence, while constructing the DEA models, the attributes to be minimized are viewed as inputs, whereas the ones to be maximized are considered as outputs. The relative importance weights of SCs are used to determine the priorities of output variables with respect to each other in formulation (3).

The maximization of the discrimination among consecutive rank positions and the minimum importance attached to performance attributes can be assured by using the maximum feasible value for ε, which can be obtained by maximizing ε subject to the constraint set of the respective DEA formulation for $j = 1, \ldots, n$, and then by setting $\varepsilon_{max} = min_j(\varepsilon_j)$.

Using data given in Tables 1 and 3, ε is calculated as 0.2254. After setting $\varepsilon = 0.2254$, the efficiency scores of suppliers are calculated using formulation (3). The DEA models are solved by using GAMS 22.5/CPLEX LP solver.

Table 1. Supplier data from the HOQ matrix

Supplier Characteristics	Importance Weights	Relationship matrix of supplier characteristics and suppliers									
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Facility (F)	62.8334	0.2503	0.0626	0.1251	0.0501	0.0313	0.0358	0.0417	0.0287	0.2503	0.1251
Technical capability (TC)	37.1666	0.3511	0.1638	0.0546	0.0468	0.0878	0.1092	0.0409	0.0655	0.0364	0.0439

Table 2. Cost factor measurements (CFMs) for candidate suppliers

Cost Components	Suppliers									
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
C1	7,100	7,800	7,650	11,750	8,100	8,900	8,400	11,900	9,600	7,800
C2	220	210	230	260	320	305	300	350	270	275
C3	190	380	315	210	350	310	180	165	150	260
C4	165	110	100	150	135	200	125	190	180	140
C5	200	155	180	235	170	250	150	190	165	210

Table 3. Normalized cost factor measurements (CFMs) for candidate suppliers

Cost Components	Suppliers									
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
C1	0.5966	0.6555	0.6429	0.9874	0.6807	0.7479	0.7059	1.0000	0.8067	0.6555
C2	0.6286	0.6000	0.6571	0.7429	0.9143	0.8714	0.8571	1.0000	0.7714	0.7857
C3	0.5000	1.0000	0.8289	0.5526	0.9211	0.8158	0.4737	0.4342	0.3947	0.6842
C4	0.8250	0.5500	0.5000	0.7500	0.6750	1.0000	0.6250	0.9500	0.9000	0.7000
C5	0.8000	0.6200	0.7200	0.9400	0.6800	1.0000	0.6000	0.7600	0.6600	0.8400

The supplier efficiency scores are provided in Table 4. The first supplier (S1) is the only efficient alternative among the candidate suppliers. In order to test the robustness of the proposed methodology, rankings are compared with Bhattacharya et al. [7]. As shown in Table 4, both methods identify S1 as the best candidate supplier. Furthermore, both approaches yield identical rankings except the switch in rank positions of S2 and S3.

In Bhattacharya et al. [7], supplier selection indices are obtained by trading-off the results of subjective factor measures (SFMs) and objective factor measures (OFMs). SFMs indicate the rating of a supplier with respect to only SCs, whereas OFMs consider solely the CFMs. On the other hand, the proposed decision making framework evaluates supplier efficiency considering both subjective and objective factor measures in an integrated way.

Table 4. Comparative ranking of the suppliers using the proposed framework and Bhattacharya et al.'s approach

Suppliers	Supplier efficiency scores	Ranking of proposed approach	Ranking of Bhattacharya et al. [7]
S1	1.0000	1	1
S2	0.3820	4	3
S3	0.3985	3	4
S4	0.1478	9	9
S5	0.1655	7	7
S6	0.1656	6	6
S7	0.1594	8	8
S8	0.1224	10	10
S9	0.6013	2	2
S10	0.3166	5	5

6. Conclusions

In this study, a decision methodology is presented that integrates QFD and DEA allowing for a tradeoff among all types of information within the supply chain. Through constructing an HOQ, which enables the relationships among purchased product features and supplier assessment criteria to be considered, the company can develop a supplier selection process to have access to suppliers that ensure a certain quality standard in terms of the characteristics of the purchased products. DEA is employed to evaluate suppliers utilizing the data from the developed HOQ. DEA avoids the critical assumption that the performance parameters are mutually independent. Likewise, DEA disregards the possibility of selecting a suboptimal supplier.

The implementation of the proposed decision making framework is illustrated using a data set from a previously reported supplier selection problem. The proposed approach is a sound and effective tool that enables qualitative as well as quantitative aspects to be taken into account, and thus improves the quality of complex supplier selection decisions.

Although the proposed approach enables to systematically incorporate the qualitative factors into the decision process, subjective judgment may still be required in selecting the inputs and outputs as well as interpreting the results of the analysis. Furthermore, linguistic variables may be used in assessing the relative importance weights of CRs and the relationships between CRs and SCs, which will require imprecise DEA models that can assess fuzzy as well as crisp data to be implemented.

Future research will focus on applying the decision framework presented in here to real-world supplier selection problems in diverse disciplines. Moreover, a user-friendly interface could be developed for decision-makers who are novice in mathematical programming since DEA may appear as a "black box" for decision-makers who are not familiar with mathematical programming.

Acknowledgement

This research has been financially supported by Galatasaray University Research Fund Research Grant Nr. 12.402.001.

7. References

[1] G. Dickson, "An analysis of vendor selection systems and decisions", Journal of Purchasing, 1966, 2, pp. 5-17.

[2] W. Ho, X. Xu, and P.K. Dey, "Multi-criteria decision making approaches for supplier evaluation and selection: A literature review", European Journal of Operational Research, 2010, 202, pp. 16-24.

[3] W.R. Soukup, "Supplier selection strategies", Journal of Purchasing and Materials Management, 1987, pp. 7-12.

[4] A. Charnes, W.W. Cooper, and E. Rhodes, "Measuring the efficiency of decision making units", European Journal of Operational Research, 1978, 2(6), pp. 429–444.

[5] M. Braglia, and A. Petroni, "A quality assurance-oriented methodology for handling trade-offs in supplier selection", International Journal of Physical Distribution and Logistics Management, 2000, 30 (2), pp. 96–111.

[6] M. Bevilacqua, F.E. Ciarapica, and G. Giacchetta, "A fuzzy-QFD approach to supplier selection", Journal of Purchasing and Supply Management, 2006, 12, pp. 14–27.

[7] A. Bhattacharya, J. Geraghty, and P. Young, "Supplier selection paradigm: An integrated hierarchical QFD methodology under multiple-criteria environment", Applied Soft Computing, 2010, 10, pp. 1013-1027.

[8] W. Ho, P.K. Dey, and M. Lockström, "Strategic sourcing: a combined QFD and AHP

approach in manufacturing", Supply Chain Management: An International Journal, 2011, 16(6), pp. 446-461.
[9] J. Liu, F.Y. Ding, and V. Lall, "Using data envelopment analysis to compare suppliers for supplier selection and performance improvement", Supply Chain Management: An International Journal, 2000, 5 (3), pp. 143–150.
[10] L.B. Forker, and D. Mendez, "An analytical method for benchmarking best peer suppliers", International Journal of Operations and Production Management, 2001, 21, pp. 195–209.
[11] R. Narasimhan, S. Talluri, and D. Mendez, "Supplier evaluation and rationalization via data envelopment analysis: An empirical examination", The Journal of Supply Chain Management, 2001, 37 (3), pp. 28–37.
[12] S. Talluri, and J. Sarkis, "A model for performance monitoring of suppliers", International Journal of Production Research, 2002, 40 (16), pp. 4257–4269.
[13] A. Ross, F.P. Buffa, C. Dröge, and D. Carrington, "Supplier evaluation in a dyadic relationship: An action research approach", Journal of Business Logistics, 2006, 27(2), pp. 75-101.
[14] J. Seydel, "Data envelopment analysis for decision support", Industrial Management & Data Systems, 2006, 106, pp. 81-95.
[15] R.F. Saen, "Suppliers selection in the presence of both cardinal and ordinal data", European Journal of Operational Research, 2007, 183, pp. 741–747.
[16] A. Ross, and F.P. Buffa, "Supplier post performance evaluation: the effects of buyer preference weight variance", International Journal of Production Research, 2009, 47(16), pp. 4351-4371.
[17] M. Toloo, and S. Nalchigar, "A new DEA method for supplier selection in presence of both cardinal and ordinal data", Expert Systems with Applications, 2011, 38, pp. 14726-14731.
[18] S. Talluri, and R. Narasimhan, "A methodology for strategic sourcing", European Journal of Operational Research, 2004, 154 (1), pp. 236–250.
[19] J. Seydel, "Supporting the paradigm shift in vendor selection: Multicriteria methods for sole-sourcing", Managerial Finance, 2005, 31 (3), pp. 49–66.
[20] R.M. Garfamy, "A data envelopment analysis approach based on total cost of ownership for supplier selection", Journal of Enterprise Information Management, 2006, 19 (6), 662–678.
[21] R. Ramanathan, "Supplier selection problem: integrating DEA with the approaches of total cost of ownership and AHP", Supply Chain Management: An International Journal, 2007, 12 (4), pp. 258–261.
[22] E.E. Karsak, S. Sozer, and S.E. Alptekin, "Product planning in quality function deployment using a combined analytic network process and goal programming approach", Computers & Industrial Engineering, 2003, 44, pp. 171-190.

Assessment of Cycle Time Reduction Using Monte Carlo Simulation

Ali Ahmad, Abdulrahman Al-Ahmari
Princess Fatimah Alnijris's Research Chair for Advanced Manufacturing Technology (FARCAMT)/Industrial Engineering Department
King Saud University- Riyadh11421 - P. O. Box 800 - Saudi Arabia
ali.ahmad.phd@gmail.com; alahmari@ksu.edu.sa

Abstract

Monte Carlo simulation utilizes random numbers to analyze input/output relationships. It has been successfully applied in Engineering, Statistics, Finance, and Telecommunications, among others. This paper discusses the application of Monte Carlo simulation to test the reduction in cycle time. It outlines a process for cycle time modeling, and uses a combination of historical data and expert judgments to derive probability distributions. The process cycle time is modeled as a function of individual process steps' cycle times. The efficacy of this approach is illustrated using a real-world case study. The paper concludes by providing guidelines for process modeling using Monte Carlo simulation.

1. Introduction

In today's rapidly changing markets, companies need to deliver their products and services to customers in increasingly faster times, and these products and services need to meet and exceed customer expectations [1]. Lean Six Sigma approaches focus on reducing defects, eliminating waste, and speeding up processes [2].

Six Sigma is both a quality management philosophy and a problem solving methodology that is project and team-based [2]. The focus of Six Sigma is delivering bottom line impact, i.e. cost savings by project per year. Many companies and industries have realized improvement in quality and reduction in cost by embracing Six Sigma programs within their organizations [1]. The Six Sigma approach was pioneered at Motorola and then witnessed its glorious application in General Electric (GE) and IBM [2]. It has applications in both service and manufacturing. Six Sigma applies a structured problem solving approach known as Define, Measure, Analyze, Improve, and Control (DMAIC), which results in a continuous improvement culture within organizations [3].

During the Control phase of a Six Sigma project, there is a need to ensure that the implemented improvements are sustainable [4]. In some cases, a Six Sigma project may come to a halt as a result of inability to obtain new process data to validate project improvement. This situation was faced at a large manufacturing company, where a project dealing with reducing the cycle time for engineering change requests couldn't be completed as a result from business down-turn, where no new projects were being negotiated; hence, there were no new change requests.

This paper discusses the application of Monte Carlo simulation to test the reduction in cycle time with the lack of new data. It provides a structured approach to applying Monte Carlo analysis using a combination of historical data and expert judgments to model process cycle time. The paper concludes by providing guidelines for using Monte Carlo simulation to model process cycle time.

2. Background

Monte Carlo simulation is a statistical analysis technique that uses probability distributions to capture the variability in the output due to the randomness of the inputs [5, 6]. It was named after Monte Carlo, Monaco, where the primary attractions are casinos [7].

Monte Carlo simulation is being applied to an increasing number of numerical problems, such as those found in finance, physics, and engineering [8]. Traditionally, it has been applied to generate random numbers, model traffic flow, forecast Dow-Jones, design nuclear reactors, analyze economical situations, among others [5, 7].

Monte Carlo simulation is based on modeling the relationship between an output (or a set of outputs) and an input (or a set of output), e.g., using regression. After that, instead of feeding the model with specific values for the inputs to obtain predicted value of the output, probability distributions are used to model each input, and the result is a probability distribution of the output (s) [7].

On the other hand, Six Sigma utilizes a scientific problem solving approach to address real world problems. Typically, a Six Sigma project is executed using DMAIC [2,4]. The Define phase starts by creating a charter that clearly states project goals, scope and boundaries, project team, business case, and stakeholders affected by the project. It aims to set the rhythm for the project and can be thought of as a contract between the process owner and the project team. The Define phase results include a charter, an overview of the process, and critical to quality information.

The second phase of a Six Sigma project is Measure. It aims to pinpoint where the problem lies in a clear and precise way. The Measure phase establishes a baseline for the process performance in terms of calculating a process sigma. It results in collecting the data that feeds the Analyze phase of the project.

The Six Sigma process proceeds by the Analyze phase, which aims to identify the root cause(s) of the problem under consideration. The results of the analysis phase are the root causes of a particular problem, with a set of potential solutions.

The fourth phase of a Six Sigma project starts upon identifying the root causes of a particular problem. The Improve phase deals with developing, implementing, and verifying solutions. To assess the degree of improvement, a new process sigma is calculated for the improved process. The result of this phase is an implemented solution for the problem.

The last phase of Six Sigma application is the Control phase. It deals with making sure that the improvement stays in place, and that the gains achieved by applying Six Sigma are sustained. Many companies add a fixed period realization phase, where the improved process is monitored to ensure that the gains are sustained.

A situation may take place where during the realization period, no new data becomes available to validate project improvements; hence prolonging project closure. This situation was faced by a large manufacturing company in Orlando, FL. Where, a Six Sigma project dealing with reducing the cycle time of engineering change requests (among other objectives) was put on a halt due to the slow-down in business. In order to evaluate the project outcomes, Monte Carlo simulation was used to model process cycle time with the absence of new data, and demonstrated project success.

3. Method

Monte Carlo simulation was used to model process cycle time. The process cycle time is defined as the sum of individual process steps times. Two Monte Carlo simulation models were constructed and compared, the first model is for the "As is" process prior to implementing project improvements, and the second model is for the "New" process after implementing project recommendations. Historical data existed for the "As is" process, whereas no data were available for the "New" process, and hence expert judgments were used. The simulation models were constructed based on a process value stream map for the "As is" and "New" processes [9]. The approach used to conduct the Monte Carlo simulation analysis is as follows:

1) Develop a Monte Carlo simulation model for the "As is" process using historical data to generate probability distributions for individual process steps' times
2) Validate the Monte Carlo simulation model for the "As is" process
3) Develop a Monte Carlo simulation model for the "New" process using expert judgment data to generate distributions for individual process steps' times
4) Compare the results of the two Monte Carlo simulation models for the "As is" and the "New" processes

A key aspect in the developed simulation models is the need to use bimodal distributions, which is commonly the case when modeling time-based data, such as individual process steps cycle times [10, 11]. The approach suggested by Law and Kelton for obtaining probability distributions when no data is available based on expert judgments and triangular distributions is used for the "New" process simulation model [10]. Both simulation models for the "As is" and "New" processes were based on 1000 sampled points using Crystal Ball simulation software. The simulation sample size of 1000 was selected such that both "As is" and "New" process models average cycle times' confidence intervals are within 10% of the mean.

4. Results

4.1. "As is" process simulation model

The "As is" process had 5 main steps, and historical data was available at both the step level and the overall cycle time. The "As is" process can be described as follows, with the distributions based on historical data for each process step:

- Project Team Review
    - 62% is one day
    - 38% is between 2 and 37 days (no trend or most likely value)
- Review And Approval
    - 76.6% is between 1 and 7 with the most likely value at 2 days
    - 23.4% is between 8 and 39 with the most likely value at 10 days
- Impact Assessment
    - 82.6% is between 1 and 28 with the most likely value at 3 days
    - 17.4% is between 29 and 69 with the most likely value at 35 days
- Routing for Approval and Submission
    - 76.7% is 0.5 days
    - 23.3% is between 1 and 17 days (no trend or most likely value)
    - Includes intermediate revisions
- Revision
    - Between 1.5 and 9 with the most likely value at 2.5 days

The graphical analysis of historical data indicated that bimodal distributions are a better fit than traditional uni-modal distributions, which could be a result of the fact that engineering change requests in the "As is" process require different processing times based on availability of information.

Figure 1 provides the simulation results for the "As is" process. The "As is" process average cycle time and standard deviation based on the simulation results are 37.7 and 19 days, respectively. The 95% confidence interval around the process average cycle time is between 36.82 and 39.18.

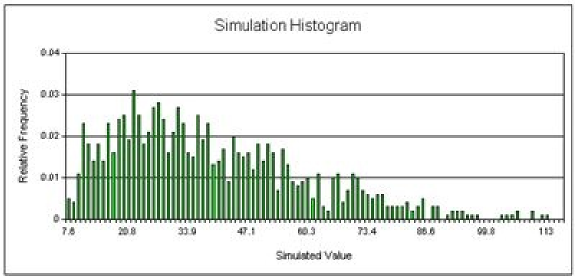


Figure 1. “As is” process simulation results

As indicated in Figure 1, the bimodality of the data is smoothened out as a result of the central limit theorem [10], where the overall cycle time is the sum of individual process cycle times, and since the simulation sample size of 1000 is large, the overall distribution is approaching a uni-modal normal distribution.

4.2. “As is” process simulation model validation

The “As is” simulation model was validated based on the historically available aggregate cycle time. The validation included comparing the simulation-based process cycle time mean, standard deviation, and shape to the historical process cycle time [10, 11]. Table 1 provides the resulting mean and standard deviation comparison, and Figure 2 illustrates the shape comparison. There was no statistical difference between the historical data and simulation results means and standard deviations, as indicate by p-values of 0.551 and 0.141, respectively.

Table 1. Simulation Validation Results

Statistic	Historical Data	Simulation Results
Mean (days)	36	38
Standard Dev. (days)	22	19
N	45	1000

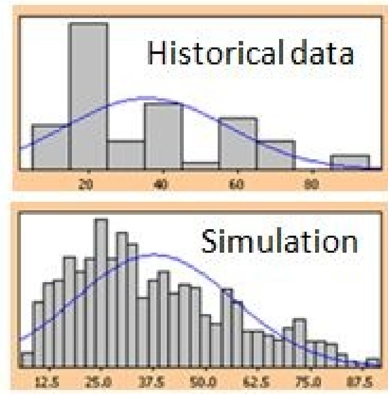


Figure 2. Shape comparison

4.3. “New” process simulation model

The “New” process had 3 main steps (with more streamlined sub-steps), and no data was available. The “New” process exhibits less bimodal distributions as the implemented Six Sigma project improvements resulted in more streamlined information; hence less bimodal distributions are needed to describe the individual process steps distributions. The “New” process can be described as follows, with the distributions based on expert judgments for each process step:

- Project Team Review
  - Receipt and log of customer change request (between 1 hr and 1 day with the most likely value at ½ day)
  - Initiate customer change request form (between ½ and 2 with the most likely value at 1 day)
- Kick off Meeting
  - Schedule (between 1 hr and 2 days with the most likely value at 1 day)

- Conduct (70% is between 1½ and 4 with the most likely value at 2½ days, and 30% is between 1¾ and 5½ with the most likely value at 3¼ days)
- Resolve (60% is between ½ and 2 days with the most likely value at 1 day, and 40% is between 1 and 10 days with the most likely value at 5 days)

- Review
  - Initiate (between 1 hr and 1 day with the most likely value at ½ day)
  - Approve (between ½ and 2 days with the most likely value at 1 day)
  - Impact Assessment (90% is between 1 and 10 days with the most likely value at 5 days, and 10% is between 4 and 40 days with the most likely value at 20 days)
  - Transfer Impacts (between 1 hr and 2 days with the most likely value at 1 day)
  - Route for approval (2 steps)
    - Step 1 (between ½ and 3 days with the most likely value at 1 day)
    - Step 2 (between 1 and 5 days with the most likely value at 2 days)
  - Revise (between 1.5 and 9 days with the most likely value at 2.5 days)

Figure 3 provides the simulation results for the "New" process. The "New" process average cycle time and standard deviation based on the simulation results are 22.9 and 6 days, respectively. The 95% confidence interval around the process average cycle time is between 22.63 and 23.37.

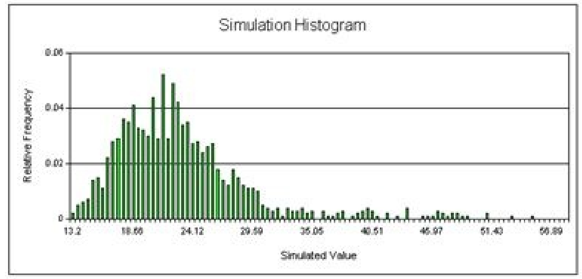


Figure 3. "New" process simulation results

4.4. "As is" and "New" process simulation models comparison

Table 2 provides the results of comparing the "As is" process simulation model to the "New" process simulation model. There was a statistical difference between the "As is" and the "New" simulation process means (P-value < 0.005).

Table 1. Simulation Comparison Results

Statistic	"As is" Simulation Results	"New" Simulation Results
Mean (days)	38	23
Standard Dev. (days)	19	6

5. Discussion and Conclusions

When a situation was faced at a company to assess whether a Six Sigma project improvements were 'real', and no data was available for the "New" process cycle time; Monte Carlo simulation provided a novel solution to that situation. The present paper discusses how simulation can be used to assess Six Sigma project improvements during the Control/Realization phase of a DMAIC project; nevertheless, it can be also applied during the Measure or Improve phases of a Six Sigma project [2].

Monte Carlo simulation requires a model of the relationship between inputs and outputs, and probability distributions for the various inputs [6]. The process cycle time was modeled as the sum of the individual steps' times. For the aforementioned situation, probability distributions for individuals steps' times were derived based on historical data for the "As is" process and based on expert judgments for the "New" process that has no data [10, 11]. The "As is" process simulation model was validated against historical data to ensure that the findings are representative [10]. The results of comparing the simulation models of the "New" and "As is" processes showed that improvements exist, and the Six Sigma project was closed.

The findings in this paper extend applying Monte Carlo simulation to cycle time modeling [5, 7]. A similar Monte Carlo approach can be applied in many situations where an overall process performance measure can be constructed as a function of individual steps' measures, examples include projects dealing with manufacturing lead time reduction and modeling projects that involve multiple business entities.

Some guidelines for applying Monte Carlo simulation to analyze cycle time include:

- Check data carefully and look for bimodality
- If bimodality exists, make sure that it is properly modeled in the Monte Carlo software
- Validation is important to ensure that simulation results are representative
- Monte Carlo simulation requires the generation of hundreds to thousands of samples, and hence when a comparison is needed, it should be done on a model-to-model basis to avoid possible scale issues

6. References

[1] George, M. (2003). Lean Six Sigma for Service. McGraw-Hill Companies, New York, NY.

[2] Breyfogle Forrest W. III (1999). "Implementing Six Sigma: Smarter Solutions Using Statistical Methods". John Wiley, New York, NY.

[3] Phadnis, S. (2001) Design for Six Sigma Roadmap. Please see: http://www.isixsigma.com.

[4] Rath & Strong (2002). "Six Sigma Pocket Guide". Rath & Strong, a subdivision of AON Management Consultants.

[5] Rubinstein, R.Y., & Kroese, D.P. (2008). Simulation and the Monte Carlo Method. Hoboken, NJ: Wiley.

[6] Robert, C.P., & Casella, G. (2005) Monte Carlo Statistical Methods, 2nd Ed.. New York: Springer.

[7] Sobol, I.M. (1994). A Primer for the Monte Carlo Method. Boca Raton, FL: Champan & Hall/CRC Press.

[8] Research and markets: Handbook of Monte Carlo Methods. (2011, Jul 04). Business Wire, pp. n/a. http://search.proquest.com/docview/874495301?accountid=44936

[9] Rother, M., & Moody, P. (2001). Learning to See: Value Stream Mapping to Add Value and Eliminate Muda. Brookline, MA: The Lean Enterprise Institute.

[10] Law, A.M., & Kelton, W.D. (2000). Simulation Modeling and Analysis, 3rd Ed., McGraw-Hill.

[11] Banks, J. (Ed., 1998). Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice. Wiley-Interscience.

Cost Effective Green Grid System (Grid-tied Photovoltaic System): A Simulation-Based Optimization Study

Hema Sudarsanam, Chien-Yi Peng, Mohammad M. Hamasha, Susan Lu and Charles R. Westgate
Center for Autonomous Solar Power, State University of New York at Binghamton, Binghamton, New York 13902, USA
mhamash1@binghamton.edu

Abstract

Inspired by the recent interest in solar power and varied advantages of modeling and simulation tools this paper concentrates in modeling a grid tied solar system and help in deciding the type of solar cell that can be used for a particular location. The model of a grid tied photovoltaic (PV) system was developed on ARENA, commercially available simulation software. The developed model is used to determine the average cost of electricity generation using a grid-tied solar system at any given place for different types of solar cells. Through this model the nominal amount of fuel energy that should be produced the following week at a given place can also be determined. The model is verified by sensitivity analysis.

1. Introduction

The current grid system that provides energy to the consumers was built 100 years ago [1]. As a result of which the present grid system is considered to be inefficient as it is also responsible for the production of 29.5% of global carbon-di-oxide emission [1]. The existing grid challenges are power congestion due to the high power demand in the cities and interruption of power that causes loss of production. Also the increasing power demand due to industrial and population growth is a motivating factor insisting on the need for integration. Thus in order to meet the existing grid challenges integration of renewable energy into the grid system will help in meeting the demand and solving the power quality issues. Photovoltaic (PV) energy generation is considered to be of more advantageous than any other renewable form of energy [2]. Some of the distinct advantages of solar is that is virtually maintenance free, no fuel required to generate energy and easiness in allocation. These advantages are overshadowed by its disadvantage of uncertainty and risk factors caused by weather conditions.

The percentage of renewable energy within the electric generation portfolio is expected to increase exponentially over the next few decades due to the increasing concerns on the change of climatic conditions and cost of fossil fuels [3]. Statistics from the American Physical Society shows that there is 8000 GW of solar power capacity available in America [3]. Need for energy security along with the enforcement of Renewable Portfolio Standards (RPS) where the government encourages increased production of renewable energy by the energy providers is another motivating factor for the adoption of solar energy [3]. Need for integration arises while considering the fact neither the solar energy not the present grid system can server to meet the growing power demand independently as mentioned above. Hence integrating PV along with its battery into the grid to meet the power demand will ensure more stable and reliable power [4]. The need for modeling such a system is to know the effects/verify the results due to implementation with greater control of parameters in less time and at low cost [5].

This paper discusses in detail the modeling of a grid- tied solar system with a battery to store the extra energy in order to minimize the waste in solar power generation in a commercial available software ARENA. ARENA is simulation software which is generally used to help in demonstrating an idea, predict the future response and to optimize the user defined factors in order to obtain better system efficiencies [5].

The model consists of five modules which can be seen in any basic grid- tied PV system. First the solar module is connected to the inverter module which connected to a switch(power interchanger module) and this switch operates on the logic developed and would supply power to the load based on the demand from the power generated and the stored power thus ensuring stable and reliable power.

2. Literature Review

Reliable studies on different instruments that were used to produce energy from the photovoltaic (PV) systems, including solar modules, inverters and battery bank have been studied. In 2011 Etier et al, modeled a system to find the optimal number of solar panels to be used to generate electricity for their campus and integrate this solar energy with that of the grid with the help of power meters. The objective of their model was to explore the feasibility of such a system [6]. Assi used Matlab to design the panel and developed proper inverter selection topology for a grid connected system [7]. Singh S.N developed a simulation model on grid assisted system with PV system, intelligent batteries for proper charging and discharging along with bidirectional inverters [8]. More research was done in individual system components rather than looking at one integrated system. Bagul et al presented a statistical approach to optimize the size of PV system and battery capacity to be used for a hybrid grid connected system.

Johnstone et al had developed a simulation based decision support tool to help in finding out how the supply matches the demand for a given type of renewable energy at a given place [9]. Problems such as instability in controlling voltages and imbalance between the demand and the supply while studying large scale solar and grid integration between two cities [10]. Ropp used Simulink to simulate a single phased grid connected solar system with averaged power converters [11].

Kala et al used Power Simulator to perform load analysis of the grid-tied PV model and the financial analysis of the resulting system was done to understand the transmission cost of the system [12]. The load analysis showed that the resulted PV system seemed to improve the voltage stability and lower the line loading. Their model supplied 30% of the grid power.

Kumar and Chowdhruy designed a model to control the variable nature of power output obtained from a photovoltaic system [13]. Here the photovoltaic array is connected to a bulk convertor then connected to the load via inverter. This model is used to control the varying nature of the active power produced by the solar cells. This control is essential for optimal storage of solar energy in case of islanding. Ideally an effective integrated system should prevent islanding but this model can be used as a model to that helps in controlling active power over frequency and also in effective storage of energy. This model is largely used for micro grid but the control algorithms can be used to effectively control the output of the photovoltaic cells this minimizes the use of bulky power electronic components

However, few researches is been done in modeling the grid tied solar system to study the overall reliability of the system. Characteristics of PV cells, along with the typical connections and control strategies of grid-tied PV system are yet to be analyzed and modeled. Until recently Makhlouf et al tried to model a grid tied PV system with battery using MATLAB to ensure stability and reliability of power supply [14]. The reliability of the system for maximum power tracking of solar energy was also included in the model. Power was balanced between the given demand and the power generated by the PV system. This paper dealt with the technical details of the grid- connected PV system though risk and cost determine the practical limits in implementing such a system. Hence this model aims in obtaining the average cost of electricity generated by the grid in a PV-grid integrated system.

3. System description

The entire system consists of five main processes. Battery is also included in the model which helps when the solar output is not sufficient to meet the demand.

Stability in power supplied and cost analysis of the electricity produced by the grid is analyzed in this model. A simple diagram representing the proposed model is show in the figure below.

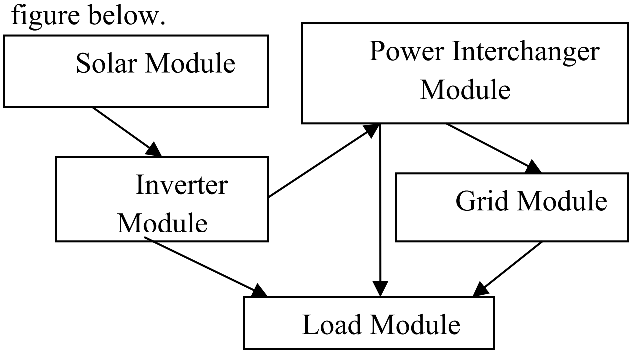


Fig 1 Basic Block Diagram

Solar Module

The first process consists of the solar module which converts the solar radiation input into electric energy which in the form of direct current. Here ARENA does not generate any values of current and voltage but instead generates value of power depending on the solar radiation input and the efficiency of the given solar cell. Solar radiation input is the amount of electromagnetic energy emitted by the sun that falls on the earth surface. This electromagnetic energy is trapped by the solar cells and then converted into electric current depending on the type of solar cell used. The efficiencies of the two different solar cell used is obtained from the leading manufactures in solar industry. Among the two types of solar cells used in this model CIGS (Copper Indium Gallium Selenide) type of cell is considered to be on a flexible substrate. The solar cell has a life span of 20 years after which its efficiency is said to reduce of 10%.The reliability of the type of solar cell used in the system is also considered. The power output from the solar module is the input to the next process in the model.

Inverter Module

The inverter module consists of an inverter that basically converts the direct current to alternating current so that it can be used at the consumer end. The inverter efficiency is assumed to follow a normal distribution with a mean of 0.9 (90% inverter efficiency) and a standard deviation of 0.2. The wear and tear of the inverter is considered to be negligible when compared to that of a solar cell [13]. Here the output of the inverter varies depending on the solar output and the inverter efficiency which can be changed by the user depending on his specification.

Power Interchanger Module

The power interchanger module will aide in switch between inverter power output, battery and grid power modules depending on the electric demand of the particular location which is given as input. First the switching circuit checks the power output of the inverter and stores the extra power if any in the battery. If power output from the inverter does not suffice then it checks if it can meet the demand when it adds the power from the battery. Finally if the power to be supplied still fails to meet the demand then the grid supplies the power to the load. The load here is the consumer end.

Grid Module

The grid module is the one from which its comfortably assumed that one can draw infinite power whereas the battery is assumed to have a limited capacity and solar power is limited by the weather condition and solar radiation. The aim is to minimize the use of fuel energy which helps in reducing the use of non-renewable resources and also increases the penetration of green energy.

Load Module

The load module is described as the consumers end where power from both the solar and the grid is drawn to the load. The demand data used as an input to compare between the various output powers. The limitation in this model is that the demand input is considered only for the month of June and the input is not updated from time to time.

4. Proposed model

In the proposed model the objective is to find the optimal cost of electricity generation for a grid-tied solar system at a given place for two different types of solar cells.

In this simulation model uses hourly data and it assumed that the solar radiation is constant for the entire hour. The model is simulated for a length of 30 years which consists of 365 days /year and 24 hours/day and it is equivalent to a total of 262,975 hours and it runs for only one replicate. Since the grid tied photovoltaic system is a non-terminating system, steady state analysis is need for such systems hence the warm up period is decided as 12 hours [15]. The data used in the model is fitted into a distribution by collecting the hourly solar radiation from 2001-2003 at a place in Turkey. There were 26,280 data points and since ARENA software uses different theoretical distributions the data points obtained are fitted into these distributions each of which as its own probabilistic characteristics in creating random variables [16].

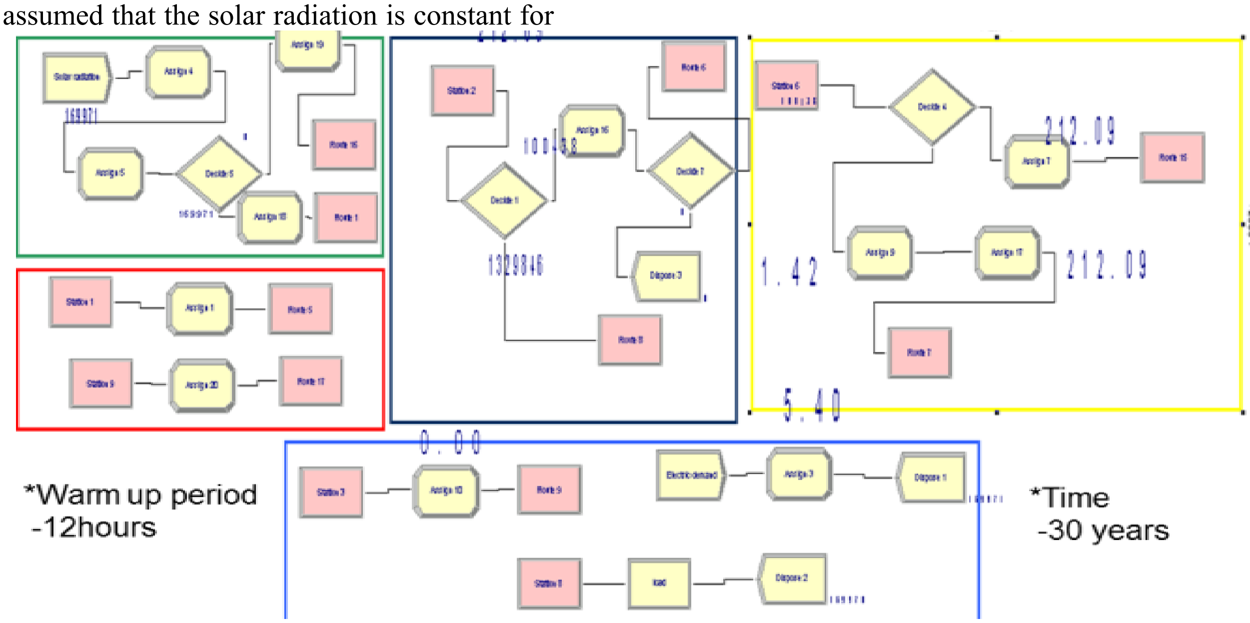


Fig 2: Model in ARENA

The solar radiation data is obtained from the data collected by Ekren et al. in 2009 and it was said that the data points represents average values of hourly solar radiation that falls on the solar panel which is inclined at an angle (i.e. 38). Also the hourly distribution of data represents that the solar radiation varies according to the distribution every hour of the given month of June which is difficult to predict in advance. Similarly the electric consumption data was said to have collected for 15 random days and are then fitted into theoretical distributions without considering the seasonal effect.

Both the inputs are assigned as schedules and a random variable was generated for every hour which is given as input to these developed schedules. The values are then multiplied with the efficiency of the solar cell which is again fitted to a normal distribution to generalize the variation in efficiencies of the particular type of cell. Provision to check the degradation of the cell is also included in the solar module which will degrade the efficiency of the solar cell by 10% after the first 20 years as mentioned by the manufacturer. Then the entities enter the inverter module and the output of this module is considered as the power output of the solar system. The switch on doing the comparison with given/ recorded electric demand regulates the system entities to the respective modules. There are some mathematical equations that adhere to this logic of the model.

Initially the extra power from the solar system it is stored in the battery which has a capacity of 5000kW. This is given by a simple formula

$$Pb = Pb + (Poin - PD)$$

Where Pb is power stored in the battery, Poin is power output from the inverter and PD is power demand or the given energy consumption data. Equation for obtaining power from the battery when the power from the solar system is not sufficient to meet the demand is given by

$$Pb = Pb - (PD - Poin)$$

Finally the extra power that is needed to meet the demand is obtained from the grid and the battery is reset to zero every time the grid power (Pog) is used. The same model is simulated twice for two different cells used. The cost of the electric power depends on the amount of electric power that is drawn from the grid for a given type of cell. The cost of grid power is calculated based on the cost data given by the government of Turkey and this value varies for different types of cells.

The optimal cost of the grid power is calculated by simulating the model in OptQuest in ARENA. The results of this sensitivity analysis is close to those values obtained in running the model for 30 years and this proves the robustness of the model.

5. Sensitivity Analysis by OptQuest

Since this is an immerging concept it is very difficult to validate the model at this point of time as research and decisions are still being made to integrate solar energy into the current grid system. Apart from providing an insight about models robustness in making decisions sensitivity analysis is also used for model verification and validation [17]. OptQuest is an iterative heuristic tool which randomly changes the parameters and analysis the sensitivity/the impact on the model while changing different parameters within the limits defined. We used m=5 (replicates) in this case ran the simulation model for 95% of CI and defined the criterion for stopping as after 50 non improving solutions with 0.1 tolerance value [15]. OptQuest allows the user to define constrains and the objective variables. Our objective was to minimize the cost of the grid system by maximum utilization of solar power. The optimal cost was 0.655 which corresponds to CIGS type of solar cell. The optquest tries enormous number of alternative designs while trying to find the optimal solution which takes a very long time to find the solution.

6. Results and Discussion

For a Si (Silicon) based cell the values are shown in the tabular column below. It is given that the maximum cost incurred to the grid during the entire simulation period is 2.69 USD and it also shows an average of 0.66 USD which is almost equal to the average value of CIGS type of cell which has a lesser efficiency value and is also lower in cost when compared to that of a Si type of solar cell. The CIGS has a flexible substrate and is also said to be reliable for 20 years by the manufacturer. All these advantages make CIGS type of solar cell to be the most efficient type that can be used for this location in Turkey. The limitations of the this model is that line losses are not considered, ARENA considers loss in time due to the transformation and conversion of power but fails to provide the liberty to consider the power loss in transmission and conversion. The model is simulated for only one replication hence more replication is needed to minimize the rate of error. Inverter assumption is another limitation to the model. Analysis must be done before selecting the inverter efficiency that should be used in a grid tied solar system. The entire system cost must be considered so that the capacity of the battery can be justified by considering the effect of cost. [Deleted few lines to concentrate more on specific results]

Name	Average	Minimum	Maximum
Cost-grid	0.6609	0.0000992	2.69
Pb	199.61	0	1234.61
PD	1.9260	0.1754	5.3976
Poin	30.3174	0	263.48
Pog	1.3219	0.0001985	5.3978

Table 1: Results for Si type of cell

Name	Average	Minimum	Maximum
Cost-grid	0.6554	0.00002006	2.6988
Pb	120.09	0	764.91
PD	1.926	0.1754	5.3976
Poin	18.5324	0	164.75
Pog	1.3109	0.00004013	5.3976

Table 2: Results for CIGS type of cell

All the values are given in kWh. From these results we can also infer that more power is wasted in Si solar cell model and hence the justifying the variation in cost between the two types of cells. Thus it can be concluded that using CIGS type of cell for this particular location and for the given values of inverter efficiency and battery capacity will give the optimal grid cost. This is a flexible model which will let the user to play around with different parameters in order to obtain the optimal values for the variables used in a grid tied solar system. This model will help in decision making, cost analysis and also will increase the rate of adoption of solar energy.

7. Conclusion

The OptQuest results shows that the using CIGS type of cell will help in obtaining optimal cost of electric power from the grid when compared to that of the Si type of solar cell. Various other types of solar cells can be used for analysis and considering the cost of the entire system will help in providing better analysis of the grid tied solar system.

Further generalization of data will help in making decisions on selecting various parameters in implementing the grid tied photovoltaic system for general places like shopping mall, clubs etc.

8. References

[1] Frye, Wes et al., "Smart Grid" CISCO internet business solutions group, 2008, pp.1-13.

[2] Adele, "One Block off the Grid: The Smart New Way to go Solar-Advantages of Solar Energy vs. Other Renewable Energy Sources" http://1bog.org/blog/the-advantages-of-solar-power-vs-other-renewable-energy-sources/, July 2010, Accessed Feb 2012.

[3] American Physical Society, "Integrating Renewable Electricity on the Grid," www.aps.org/policy/reports/popareports/upload/integratingelec-exsum.pdf, 2010, Accessed June, 2011.

[4] Howard F. Dustin, "Modeling, Simulation, and Analysis of Grid Connected Dish-Stirling Solar Power Plants", (Thesis, Georgia Institute of Technology, 2010).

[5] "Arena Simulation Software by Rockwell Automation: Home." Arena Simulation Software by Rockwell Automation: Home. http://www.arenasimulation.com/Arena_Home.aspx (accessed April 10, 2012).

[6] Etier, I., Ababneh, M. and Tarabsheh, A., "Simulation of a 10 kW Photovoltaic System in Areas with High Solar Irradiation," American Journal of Applied Sciences, Vol. 8, No. 2, 2011, pp. 177-181.

[7] Assi, A. and Jama, M., "MATLAB – Based Software for Modelling and Studying Grid – Tied Photovoltaic Systems" published under the working title "Matlab - Modelling, Programming and Simulations," (Thesis, UAE University, 2010).

[8] Singh, S.N and Singh, A.K, "Simulation of grid-assisted solar power convertor: An effective solution of power crisis in rural India," Asian Journal of Energy and Environment, Vol. 10, No. 2, 2010, pp. 96-102.

[9] Born, F. and Clarke, J.A. and Johnstone, C. "Development of a simulation-based decision support tool for renewable energy integration and demand-supply matching" In Proceedings of ESim 04 Conference, Vancouver, 2004

[10] Bagul A.D., Salameh Z.M., Borowy B. "Sizing of stand-alone hybrid wind–PV system using a three event probability density approximation". Solar Energy, Vol. 56, No. 4, 1996, pp. 323–335

[11] Ropp, M.E. and Gonzalez, S., "Development of a MATLAB/Simulink Model of a Single-Phase Grid-Connected Photovoltaic System", IEEE Transactions on Energy Conversion, 2009, pp 1-8.

[12] Meah, Kala et al, "Integrating wind and solar electric energy into the power system teaching," American Society of Engineering Education, nv, 2007, pp. 1-12

[13] Kumar and Chowdhruy, "Two stage power conversion method for active power control of solar photovoltaic plants and storage in micro grid" In Proceedings of 3rd Annual ISCRS, Missouri, 14 April 2009.

[14] M, Makhlouf, Messai F, and Benalla H. "Modeling and Simulation of Grid-connected Hybrid Photovoltaic/Battery Distributed Generation System", Canadian Journal on Electrical and Electronics Engineering Vol 3, No. 1, 2012, pp. 1-10.

[15] Law, M. Averill, Simulation Modeling and Analysis. McGraw Hill, 2007.

[16] Ekren, Orhan, and Banu Ekren, "Size Optimization of a Solar-wind Hybrid Energy System Using Two Simulation Based Optimization Techniques", Fundamental and Advanced Topics in Wind Power, InTec, 2011. pp. 379-398.

[17] Frey, C and Patil, R.P., "Identification and review of Sensitivity Analysis Methods", North Carolina State University

Development of CAD and FE Models of a Transfemoral Limb Prosthetic Interface

Ryan Richardson, Matthew Richardson, Bernadette Quijano, Emanuel Wong and Alexandra Schönning
University of North Florida, 1 UNF Drive, Jacksonville, FL 32224, USA
Ryan.Richardson@unf.edu; m.richardson.129960@unf.edu; b.quijano.92467@unf.edu; e.wong.154851@unf.edu; aschonni@unf.edu

Abstract

A surface scan of the transfemoral limb geometry has been used in developing Non-Uniform Rational B-Spline (NURBS) surfaces of the residual limb and prosthesis. The prosthesis model is a custom fit cup-like model with the inside matching perfectly to the patient's limb. Both the limb and prosthesis models have been used in creating a finite element model (FEM) with advanced loading conditions and material properties to be used in computing the stresses at the contact surface. This paper addresses geometry abstraction and noise reduction of scanned residual limb data, the development of a custom-fit cup-like prosthetic, and the preparation of a finite element model.

Introduction

The extensive use of FEM and simulation software for engineering stress analysis is an irreplaceable tool in the modern engineering workplace; the use of these techniques can allow medical and engineering professionals to develop more accurate models of organic tissue to prosthesis interfaces. The ability to accurately develop the geometry for a residuum and prosthesis is essential to the determination of accurate simulation results; an emphasis must also be placed on the development of models which can be collaborated through empirical patient medical trials i.e. surface pressure distributions, limb deformation. Therefore investigation into the resultant stresses at the contact interface of a residual limb to prosthesis may be modeled using geometry gathered through high accuracy instrumentation such as triangulation or time of flight scanners [1].

Although the use of FEM techniques in manufacturing environments is not a recent development, use of simulations environments have not been extensively employed in the study of transfemoral residuum. Transfemoral residuum's have many complicating factors that deter analysis; the presence of a large soft tissue volume which are non-load bearing in nature, non-linear substances with high morphology and hyper-elastic material properties all increase computational considerations dramatically. Therefore early model developments have been lacking in model complexity for numerous reasons; the ability to model surface to surface contact friction was not available in early simulation packages, access to high resolution skeletal structure scans were either rare or inaccessible, and advanced non-linear material properties were not yet determined for organic structures such as human muscular and fatty tissues [2]. In an effort to expand the knowledge base in how to use computer-aided engineering techniques in improving the fit of a prosthesis to a patient's residuum, this paper addresses the data collection and manipulation phases of both the residual model and of the cup-like custom-fit prosthetic.

Geometry Abstraction

Initial surface scans must be as accurate as possible in order to develop a model with applicable surface stress results. Currently the most widely used instrumentation for gathering 3-D point cloud data are triangulation and time of flight scanning devices which produce high resolution point cloud data. The initial surface scans presented herein were conducted by Florida State University's Advanced Material department of a plaster mold created from the prosthesis of a transfemoral adult male amputee. The quality of the scan is dependent on the testing conditions and the device configuration. Small movements by the test subject can result in irregularity which must be addressed. The medical personnel scanning the subject determine if the movement of the patient is within acceptable limits to generate acceptable scans. While acceptable scans can typically always generate valid three-dimensional data, the accuracy of those models is dependent on the quality of the original scan. Generally, the process of removing noise doesn't notably change the volume of the model nor are the stress results negatively affected. It can be argued, that the noise reduction provides more reliable stress results, as the original model doesn't contain stress raisers on the surface.

The resultant scans produced a point cloud of approximately 70,000 data points for the residuum surface topography, shown in Figure 1. The processing of all point cloud data during the research investigation was conducted in the *GeoMagic Studio 12* geometry manipulation software [3].

The raw data cloud must then be manipulated to reduce the presence of noise, voids, and sharp contours that are not representative of the organic surface geometry. At least one method of noise reduction, which may reduce the overall density of the point cloud data via averaging or weighting functions, should be applied to the point cloud. Special attention must be taken not to remove important curvature from the model during automated noise reduction in order to maintain model integrity. Erroneous data points will be present in all time of flight or triangulation data which must be carefully removed, if left sharp fragments will be generated during the subsequent polygon phase and result in inaccurate stress concentrators as shown in Figure 2.

The compressed residual limb geometry can be extracted from the point cloud by defining polygon elements. The polygon elements are flat surfaced elements which do not truly represent the surface curvature, therefore additional processing was performed to define regions of similar curvature. The regions may serve two purposes during geometry development; definition for the extraction of B-splines which constitute the NURBS surface, and the declaration of high interest and loading regions for simulation considerations. Organic analyses are highly complex surface condition scenarios, and therefore the use of anatomically significant regions may be advantageous to model development. After declaration of similar regions of curvature the software can then create a high resolution grid which combined with the polygon elements can serve as a basis for the B-Spline surface. The NURBS surface is a fully functional modeling surface which is an accurate representation of the scanned topography, and is compatible with modeling and simulation environments. A rendered compressed residuum is shown in Figure 3. It should be noted that this figure shows the residuum from a different angle than the one shown in Figure 1.

A customized prosthesis cup geometry can be developed through the surface topography generated from the residual limb scan. Prosthetics for transfemoral amputees have a socket thickness between 1-5mm dependent on construction material; therefore projection of the residual limb surface a distance of 1-5mm will produce a geometry accurate prosthesis.

The incorporation of an accurate skeletal structure into the simulation environment can be accomplished through access to the Visible Human Project through the National Library of Medicine. Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) techniques have been applied to both male and female cadavers with the resultant cross sectional data available through request. The cross sectional images are 12 bit gray scale images totaling 1871 for the entire body [4]. The gray scale images are used with an intensity threshold to determine the boundary between soft tissue and skeletal structure in the volumes of interest. The resultant boundary structures can then be stacked together to form a three-dimensional geometry through interpolation algorithms

Organic Residuum FEM and Simulation Considerations

Organic systems pose additional simulation considerations not associated with static linear analysis. The vast majority of the soft tissue material can best be modeled as non-linear due to the hyper elastic nature of fat and muscle. This creates the need for a non-linear material model such as, Ogden or Mooney Rivlin. The general forms of the Mooney Rivlin equation is given below in Equation 1, where C_{01}, C_{10}, and D_1 are the experimental material coefficients. The general form of the Ogden equation is given in Equation 2 where μ_p and α_p are the material coefficients and the symbols λ_1 and λ_2 are the strain energy functions [5].

$$W = C_{01}\ (\bar{I}_2 - 3) + C_{10}\ (\bar{I}_1 - 3) + D_1\ (J - 1)^2 \qquad \text{Eq1}$$

$$W(\lambda_1, \lambda_2) = \sum_{p=1}^{N} \frac{\mu_p}{\alpha_p} \left(\lambda_1^{\alpha_p} + \lambda_2^{\alpha_p} + \lambda_1^{-\alpha_p} \lambda_2^{-\alpha_p} - 3 \right) \qquad \text{Eq2}$$

Use of either material model requires experimental data which is not readily available; the majority of material property testing is done through destructive tests which cannot be applied to in vitro human soft tissues. The current state of material research into the mechanical properties of muscle and fat tissue have been limited to swine; this has been deemed the closest approximation to a test of in vitro human tissue due to the similar nature of human and pig tissues [6]. While the material properties of swine and human tissue are presumably slightly different, it is assumed that the effect of using properties of swine tissue rather than those of human tissue is relatively insignificant in the end result when studying the interaction between the prosthetic and the limb. Since the difference in material behavior of the engineered material of the prosthetic and that of the limb is so significant, it is assumed that the small variations between the material behavior of swine and human tissue will be insignificant for the purpose of this study.

Mechanical properties of human bone also vary depending on many factors; including age, sex, and the density of the bone itself [7,8]. In addition to the variation of mechanical properties across test subjects, bone displays orthotropic properties and therefore determination of material orientation is essential to such simulation trials. Current studies suggest that the although bone may be orthotropic, the statistical different in the isotropic density based model Equation 3 and the orthotropic model Equation 4 yield statistically similar results in preliminary simulations [9]. Where the directions and Poisson ratios for the orthotropic model are as follows; (1) medial lateral, (2) anterior-posterior, (3) superior-inferior and λ_{12} =.4, λ_{23} = λ_{31} =.25. Poison's ratio for the isotropic model is 0.3 The range of density for cortical bone was is be between 1.25 and 1.49 g/cm^3. The Modulus of Elasticity, E_i, for the orthotropic model are expressed in Equation 3, and for the isotropic model in Equation 4.

$$E_1 = E_2 = 2314\rho^{1.57}, \qquad E_3 = 2065\rho^{3.09} \quad \text{Eq 3}$$

$$E = 2065\rho^{3.09} \quad \text{Eq 4}$$

Where E is the Modulus of Elasticity in units of MPa, and ρ is the material density in units of g/cm^3.

Consideration must also be paid to the orientation of the skeletal structure within the soft tissue. During the course of geometry abstraction no two volumes were modeled synchronously in the same environment. Therefore manual orientation and placement of each volume is critical to the surface to surface interactions in the modeling and simulation environment. Researchers should attempt to align soft tissue volumes on a surface to surface contact basis; the soft tissue volumes are rigid no slip connections between subsequent layers with the presence of contact friction at the outer proximal soft tissue layer to prosthesis interface. The ability to model the surface to surface friction increases the accuracy and reliability of simulation results, with acceptable values of the static coefficient of friction ranging from μ_s =0 .4 to 0.7 in value.

Research has shown that previous models have incorporated one of two different load scenarios to replicate a real world transfemoral load scenario. The outer prosthesis surface can be set with boundary conditions and the pressure or force load can be applied to the femoral head to simulate weight transfer through the skeletal structure. The second scenario is the simulation of the applied pressure field to the exterior surface of the residuum; this model does not incorporate an actual prosthesis and therefore was not the subject for initial investigations. Incorporation of the residual limb and prosthesis into the simulation was determined to be an important parameter during the course of research [10].

Conclusion

A model of a femoral residuum has been developed from a scanned point-cloud, which was then manipulated using advanced modeling software in an effort to generate a NURBS surface. This NURBS surface was then used in developing a custom fit prosthetic cup-model. Both the cup model and the residual limb were brought into a finite element environment where contact conditions, boundary conditions, advanced non-linear material models, and loads were applied. An image of the current model is displayed in Figure 5. This figure shows the model from an angle different than that shown in Figures 1 and 3. Future work will include solving the model and analyzing the stress, strain, and deformation results.

References

1. *Triangulating Point Set Surfaces with Bounded Error.* **Scheidegger, C., Fleishman, S. and Silva, C.** s.l. : Eurographics Symposium on Geometry Processings, 2005.

2. *State-of-the-art research in lower limb prosthetics biomechanics - a socket interface review".* **Mak, Arthur, Zhang, Ming and Boone, David.** 2, 2001, Journal of Rehabilitation Research and Development, Vol. 38, pp. 161-174.

3. **GeoMagics.** GeoMagic 12 Tutorial and Self Teach Information. 2010.

4. **United States National Library of Medicine.** *The Visible Human Project.* United States National Library of Medicine. 2010.

5. *A theory of large elastic deformation.* **Mooney, M.** 1940, Journal of Physics, Vol. 11.

6. *Stress relaxtion of porcine gluteus muscles subjected to sudden traverse deformation as related to pressure sore modeling.* **Palevski, A., et al., et al.** 2006, Journal of Biomechanical Engineering.

7. **Federation Europeenene et Internationale des Patrons Prothesistes Dentaires.** *Bone Properties.* 2010.

8. University of Washington, Osteoporosis and Bone Physiology: bone density, http://courses.washington.edu/bonephys/opbmd.html (accessed on 9/28/12)

9. *Comparison of isotropic and orthotropic material property assignments on femoral finite element models under two loading conditions.* **Peng, Liang, et al., et al.** 2006, Medical Engineering and Physics, Vol. 28, pp. 227-233.

10. *A review of prosthetic interface stress investigations.* **Silver-Thorn, M. Barbara, Steege, John W. and Childress, Dudley S.** 3, 1996, Journal of Rehabilitation Research and Development, Vol. 33, pp. 253-266.

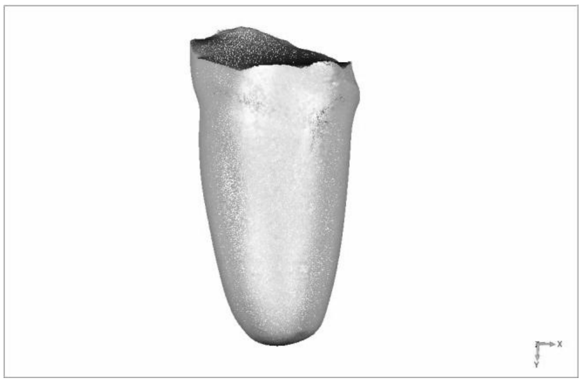


Figure 1 - Raw Point Cloud Compressed Femur

Figure 2 - Resultant stress concentrators from unresolved noise

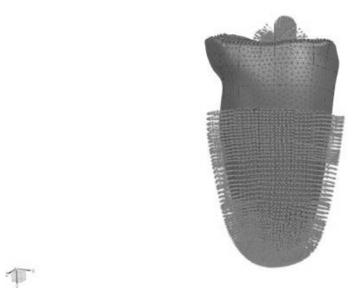


Figure 5 - Fully constrained model

Figure 3 - NURBS surface compressed residuum

Figure 4 - Processed femur point geometry

Improving Patient Check-In and Check-Out Processes Utilizing Six Sigma DMAIC Tools at A Medical Clinic

Hemaid Alsulami, Ahmed Mohamed and Ahmad Elshennawy
University of Central Florida, Orlando, Florida 32816, USA
aamohamed@aol.com; hemaid@al-sulami.com; ahmade@mail.ucf.edu

Abstract

Check-in and check-out processes are critical factors for patients' satisfaction during their clinic appointments. In a major medical clinic in Orlando, Florida, the goal is to provide the best healthcare experience to its patients by improving the patient's check-in and out processes. The clinic has recognized the importance of Six Sigma as a powerful approach for process improvement. The target is to ensure better patient satisfaction while they are checking-in and out to see healthcare providers. In the course of employing the DMAIC methodology, collection of data has indicated the identification of six sources of nonconformance in the check-in process, operating at 1.7 Sigma level and four other sources of nonconformance in the check-out process that makes 1.56 Sigma level. After the root causes of the problem have been identified and operational metrics were developed, a proposed improvement and control mechanisms were introduced. Such mechanisms involve the introduction of new procedures to optimize and standardize the check-in and out process and the elimination of non-value added steps. The implementation of the new procedures has resulted in an improvement in process performance and achieving greater Sigma level for the process.

1. Introduction

Research has shown that the implementation of Lean Six Sigma in the healthcare industry can achieve breakthrough results in process improvement by reducing variation and defects in this important sector that seeks to attain zero defects. A major medical clinic in Central Florida that serves about 90,000 patients has tasked the team to assist in improving the current check-in/out processes to increase customer satisfaction and eliminate additional non-value procedures to the processes.

The team started by reviewing the current processes and providing recommendations for improvement using the DMAIC methodology. DMAIC (Define, Measure, Analyze, Improve and Control) is a Six Sigma approach for process improvement. . The goal of this project is to provide recommendations that improve and optimize the check-in/out processes in a way that enhances each patient's satisfaction and clinic's staff experience.

Accordingly, the team proposed improvement and control mechanisms that management can use to assure better process performance. New procedures to optimize and standardize the check-in/out processes were established in such a way that eliminates the non-value added steps. In addition, other tools such as the 5S (sorting, straightening, systematic cleaning, standardizing, and sustaining) methodology and the layered process audit were suggested to improve the work environment at the medical clinic.

2. Lean Six Sigma in Healthcare

Lean Six Sigma is a business management methodology that was developed by Motorola in 1986. After its implementation of Six Sigma, General Electric has achieved sustained quality improvements in their processes. In addition, they have made Six Sigma methodology a well-known approach to reduce process variation [1].

After its breakthrough results in the manufacturing industries, Six Sigma was introduced to the service sector [2]. Lean Six Sigma has been applied to many different industries, including healthcare, to reduce waste, add value, and provide quality with success. Hospitals have adapted Six Sigma to improve their processes and increase patients' satisfactory experience [3]. Lean Six Sigma succeeds to reduce patients waiting time in a primary care. This result has sustained over the time using the Six Sigma tools in control phase [4]. Research shows that "variation in the delivery of care far-out weights the variation in the demand" [5]. Overall, Six Sigma has made a significant result on improving the healthcare processes. Consequently, the team decided to use the DMAIC tools to improve the check in/out process in this Medical clinic.

3. Define Phase

In the Define phase, the Six Sigma Team (SST) worked with customer to identify the problem and determine the scope of work. Stakeholders were defined along with their roles; impact and concerns about the project. In this phase, the SST created the project charter to provide a condensed overview of the project and to allow all parties involved in the project to document the agreed upon the problem statement, scope and objectives, approach, and major deliverables of the project.

3.1 Current State of Process

The clinic consists of several teams that provide check in/out services to patients. The teams are facing variety of daily issues that contribute to patient's dissatisfaction. The current procedure contains a widespread of non-compliance for check in/out processes. Indeed, the processes vary from one team to another based on their staff experience, which cause some delinquency in updating demographic and insurance information of patients. The teams struggle with multi-tasking, high volume workload and the multiple steps required for check in/out processes. Staffing levels are not consistent among Health Administration Service (HAS) teams. Moreover, Staff is complaining about equipment failures such as scanners and printers, which is making them to skip some steps of the process.

3.2 Problem Statement

There is inconsistent behavior among HAS check in/out teams. The process variations cause a 53% delinquency in updating patients' insurance and 23% of not updating demographic information of patients. Missed appointments, mailing prescriptions to the wrong addresses, increased return mail and an inability to collect co-payments in a timely manner are results of this problem leading to the Clinic not capitalizing on $721,689 per month.

Based on problem analysis and the associated business case, the following objectives were established for the project: a) streamline the process, b) improve patient satisfaction, and c) increase the efficiency of the process by eliminating duplicate tasks and rework.

4. Measure Phase

The second phase of the project focuses on collecting requirements and data that help identify the root cause of the problem. The voice of the customer is captured through various visits and interviews with the check in/out stakeholders. Important key metrics and critical to quality (CTQ) characteristics are defined and a high level SIPOC diagram is established.

4.1 Process Flow Chart

Figure 1 shows the check in/out process flowchart.

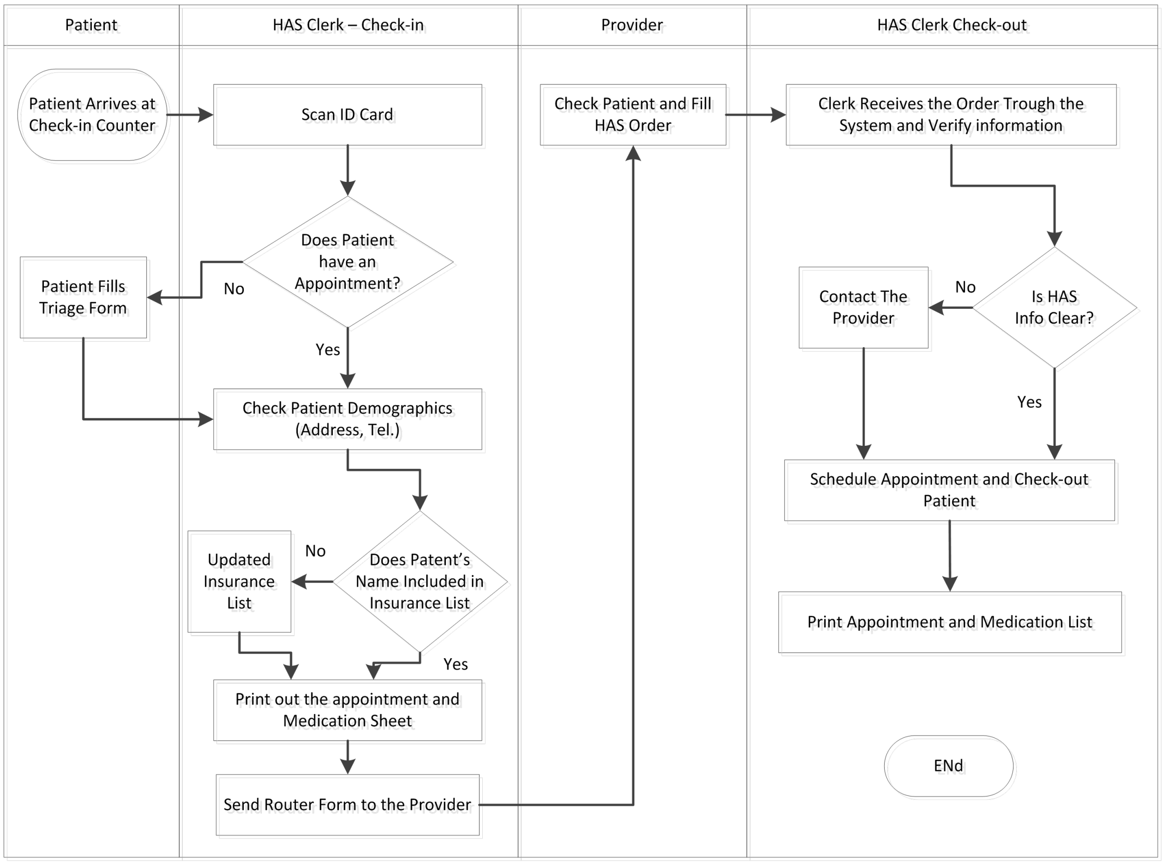


Figure 1 Process Flow Chart

The check-in process starts with the arrival of the patient to the check-in counter. The clerks apply the following steps:

1) Scan the patient ID card.
2) Determine if the patient has an appointment, if there is no assigned appointment, the patient should fill the triage form which includes patients information
3) Check patient demographics
4) Ensure that the patient's name is included in the insurance list, if not the clerk should update such list and add the patient's name.
5) Handle the patient a hard copy of the medication and the appointment sheets.
6) Send the router form to the provider; this form summarizes the patient's condition and status.

In the check-out, clerks process orders (such as assigning new appointments, scheduling lab tests) that providers entered into the system. Then, they print the appointments and medication sheets for the patients.

4.2 Voice of Customer

Voice of Customer VOC can be collected in a variety of ways: direct discussion or interviews, surveys, focus groups, customer specifications, observation, field reports, etc. The team has used some of those techniques in order to define the customer requirements. In the beginning, the team had direct discussions with project champion, project sponsor, and other project stakeholders. This direct discussion provided information helped in defining, from management point of view, the main requirement of the "check in/out process" is updating the patient's insurance and demographic information. The team interviewed several clerks, within the scope of the project, to understand their needs and requirements in order to make their work more efficient. In addition, the team has interviewed some of the clinic patients to have their feedback about the check in/out process. Patients look for having an updated medication list, avoiding repetitive questions at different stops every time they are in the clinic, and having an efficient experience while they visit the clinic. Table 1 summarizes findings from the surveys, interviews, and observations made on the requirements of the stakeholder.

Table 1 Voice of the Customer

Requirements	Stakeholders			
	HAS	Supervisor	Clerks	Patients
Standardize process	Y	Y	Y	Y
Avoid repetitive questions	Y	Y		Y
Scan insurance	Y	Y		
Update demography		Y		
Answer Patients Questions				Y

Y= Indicates stakeholders requirements

4.4 Strengths, Weaknesses, Opportunities and Threats (SWOT) Analysis

The team used SWOT analysis technique in order to have clear understanding of the check-in/out process' environment and to define its internal and external factors that could affect the flow of the process. The analysis is summarized in table 2.

5. Analyze Phase

One of the most important findings made in this phase, was that the HAS management has no well-defined audit system for evaluating the clerks performance levels. Thus, most of the clerks misunderstood the benefits of updating the demographics, and the insurance information, which lead to skipping those steps.

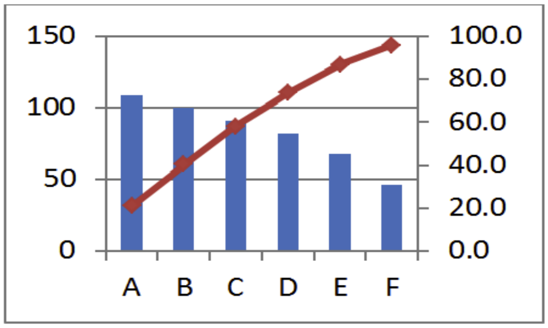
The team used collected data to develop Pareto charts that identified the main problems in the system. This also helps to set a baseline for future reference once improvements have been made to the system.

As it can be determined from the Pareto chart in Figure 2, the activity that appeared the most was when the clerk got up and transported the router physically.

Table 2 SWOT Analysis

Strength	Weakness
• System Capability • Qualified Staff	• Inability to modify the system • Uncontrolled work environment • End of life equipment
Opportunity	**Threat**
• Management Support • Co-payment from insurance companies • Reduce the number no show patients	• Incomplete HAS orders • Delayed HAS orders • High volume of incoming calls

This activity was considered a waste because of the fact that transportation; being qualified as one of the seven wastes. This is one error that the team will target to eliminate which is one of the recommendations proposed. Moreover, the activity with the second highest number of occurrences is when the clerk does not verify if the patients name is in the insurance list. This is one tied back to the original purpose of the project, which is to increase the time that patient's insurance is updated. Skipping this simple step is causing the Medical Clinic to miss a big percent of opportunities to charge third party insurance companies for patients care. Because patient's insurance is not updated, the HAS teams do not end up talking to the right people which results in them missing out on cash flow. Another problem that needs improvement are when demographics are not checked and the patient does not provide the clerk with the ID card.



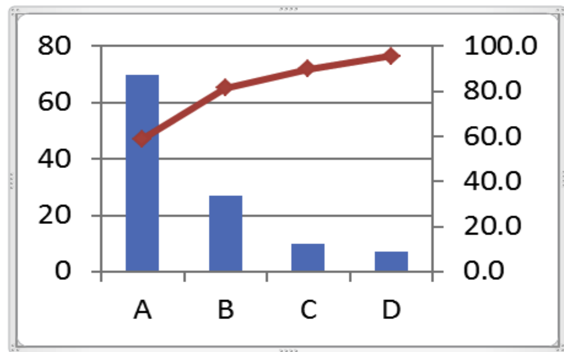
Legend:
A: Hand the router form physically
B: Skip checking the insurance list
C: Skip provide patient with medication list
D: Skip scanning ID card
E: Skip checking demographic
F: Scanner failing

Figure 2 Pareto Chart of Check-In Error Occurrences

The Pareto chart shown in Figure 3 is a representation of the errors encountered in the check-out process ranked from highest to lowest occurrences. As it is shown the problem that occurs the most is the ID card not being scanned. Also, the clerks are not trained using the card scanner as a tool to bring up a patient's information when they are checking them out.

5.1 Current Check-in Process Analysis

From the collected data, the team found that around 43% of the check-in times clerks did not swipe the ID card to pull up the patient's information. This thing could increase the probability of pulling the wrong patient's information and will increase the process time of the check-in. In addition, from reviewing the current check-in process, the team found that around 23% of the check-in times the clerks did not check if the patients have any changes in their demographic. In addition, 53% of the check-in times the clerks did not check the name of the patient on the insurance list. Out of 8 times that the clerks needed to use the scanners to update the insurance information, only 3 times it worked (37%) and 5 times it did not work (63%) as shown in Figure 4.



Legend:
A: Skip scanning ID card
B: Miss printing the appointment
C: Miss entering the HAS order
D: Skip checking other HAS order

Figure 3 Pareto Chart of Checkout Error Occurrences

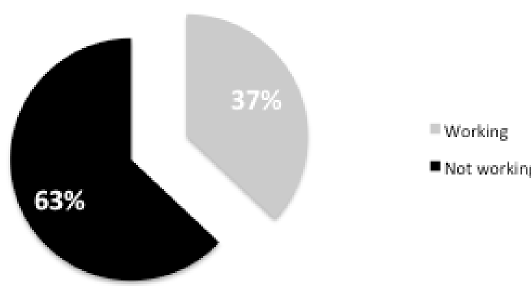


Figure 4 Scanners performance

5.2 Current Checkout Process Analysis

The SST team has observed many issues during the checkout process. One of the sources for these issues of the checkout process is the HAS order. Clerks cannot start the check-out process if there is no HAS order released by the provider. In addition, If the HAS order was not in active status, or it was in active status but its instruction were not clearly written, clerks cannot proceed or perform the checkout. The team has observed that a lot of the clerks violate the Clinic policy by performing the HAS order while the HAS order is not in active status. Also, they miss the opportunity of interacting with the patient face to face in order to get know the patient's desired schedule. In addition, if the HAS order is not clear, the clerk will delay the check-out process by asking for clarification from the patient's provider for the purpose of clarifying the HAS order. The team has analyzed the check-out process and found that about 8 % of times that the HAS order is not available. Also around 87% of the times the clerks do not scan the ID card when they check-out patients. Moreover, between the check-in and check-out processes, around 55% of the clerks did not use the ID card to pull up the patient's information.

5.3 Value-Added/Non-Value-Added Analysis

In addition to check in/out process analysis, the team conducted a value-added/non-value-added analysis to identify improvement opportunities for both check-in and check-out processes. The results of these analysis found that four value added steps, which are (updating patient's information, scanning the new insurance card both side, writing patient arrival time on the router and updating the medications list). On the other hand, three waste steps were identified (Entering patient information manually, opening pre-registration window and handling the router to the nurse)

In the same manner, value added analysis were made for the check-out processes that result in three value added steps which are (scheduling the Lab appointment, Print out the appointment list and hand out to the patient and Change the status of the HAS Order to be completed). On other hand, two waste steps were identified which are (contacting the provider to sign the HAS order and contacting the provider to clarify the HAS Order)

5.4 Sigma Score Calculator

It is important that knowledge of the Sigma score for the process be defined. by determining the defects per million opportunities (DPMO) in the process, which is used to determine the Sigma at which the process is operating. It was determined that the check-in processes is operating at 1.77 Sigma, as shown in Table 3.

Table 3 Check-in Process Six Sigma Calculator

Check-In Process		
Defects	Count	Total
Check-ins	202	202
Total units:	202	
Defect opportunities:	6	
Total opportunities:	1,212	
Defect W-X-Y-Z actuals:		
Scanner not working	125	62%
Reader not working	38	19%
ID card unavailability	69	34%
Insurance Card Index	107	53%
Missing medication update	91	45%
Demographic Update Index	46	23%
Total defects:	477	
DPU:	2.36	
DPMO:	393,333	
Sigma Score:	**1.77**	

On other hand, the check-out process was operating at 1.56 Sigma as shown in Table 4.

Table 4 Check-out Process Six Sigma Calculator

Check-Out Process		
Defects	Count	Total
Check-outs	131	131
Total units:	131	
Defect opportunities:	4	
Total opportunities:	524	
Defect W-X-Y-Z actuals:		
Reader not working	38	19%
ID card unavailability	176	87%
Unavailability of HAS order	16	8%
Incompletion of order status	20	10%
Total defects:	250	
DPU:	1.91	
DPMO:	478,015	
Sigma Score:	**1.56**	

6. Improve Phase

The team has come up with numerous solutions to tackle the check in/out problems as illustrated below:

6.1 Optimized Check in/out Procedures

Procedures manual is a critical part of getting the HAS team to actually work for the right goal and have a crystal clear implementation of the work process. Also, it is trying to perfect everyone's work, ensure the quality of the service. The team has developed standard procedures for the check in/out process that are compatible for all the clinics in order to ensure that the HAS staff are all on the same page and have the same level of customer service. After analysis, the team recommends a new simple system to eliminate the forming of queues, which will reduce the clerks stress when dealing with a large amount of patients.

6.2 Take a Number system

At the time when the data were collected, the team observed that some of clerks skip some of the process due to the long waiting line. Clerks often feel stressed when there are patients waiting in a long line. In the same way, the older patients feel tried from standing for a long time. Therefore, the team recommends they use a number system in the check in/out process in order to increase the productivity and improve efficiency. Using a number system has enormous advantages such as increasing productivity. The system provides the number of patients served by each clerk. Also the system provides the idle time of each clerk. It provides the average time for check in/out process for each clerk and the average waiting time for each patient.

6.3 Proposed Check-In Process

The team has come up with new design of the check-in process to speed up the system and eliminate any non-value added process. In order to ensure high customer service and efficiency, the team standardized a new check-in process and set requirements for the proposed check-in processes.

6.4 Proposed Checkout Process

From analyzing the current check-out process, the team found that one of the main inputs, or the raw material, for this process is the HAS orders which is supplied by the provider. Thus, the absent of “Active” and clear HAS order in the beginning of the check-out process will prevent the ability of performing the HAS order on spot with the valuable input from the patient.

6.5 Using the 5S Methodology

Through several visits that were conducted at the Clinic, it was noticed that the clerks offices were not well organized which can add obstacles & frustrations to the clerks work. The 5S system consists of five basic steps, which are: Sort, Set in order, Shine, Standardized and Sustain. Therefore, the team implemented the 5S to enhance profitability & efficiency through reducing time wasted looking for documents and improves clerks’ moral and pride by creating a pleasurable workplace. Also, 5S will help the clerks to organize & layout the work area and make it easier to communicate with everyone.

6.6 Sigma Score Improvement Plan

As part of the improvement plan, the team introduced a “Sigma Score Improvement Program” which will be an ongoing competition for all clinics (Primary Care as well as specialty) with the main focus on improving on pre-determined criteria. This program is designed to be a fun activity that will be in the back of everyone’s mind (clerks, supervisors, and managers) and will provide rewards to the best team. A successful program will get all clinics involved and conscious of their performance, enforcing a continuous improvement mentality. The way this will work is by comparing all clinics’ Sigma score in a monthly basis to see which one had the best performance. Therefore, supervisors will be required to calculate the Six Sigma level and display them in the performance board. The final Sigma score should be e-mailed to the director for tracking performance as well as to pick the month’s winner. This will serve as a dashboard to grade the performance of every clinic for check-in and check-out. Supervisors will be responsible for updating it every month with monthly operating percentages, which will be subject to change according to the current system capabilities. Some of the information that goes in the calculator is the same as the one that will be looked at for the proposed Layered Process Audits, so it will overlap making easier on the HAS team.

7. Control Phase

In this phase the team proposed the Layered Process Audits (LPA) to control the process. It is a system of audits performed by multiple levels of supervision and management to monitor key process characteristics and verify process conformance on an ongoing basis. LPA provides an excellent tool for minimizing variation in processes and error-proofing systems and making significant progress to meet the goal of zero process defects.

Proposed LPA for HAS

The team proposed three layers to control process in check in/out as shown in Table 5

Table 5 Layers Classification

Layers	Classification
Layer I	Personal responsibility-examining employee performance
Layer II	Team responsibility-Examining team performance
Layer III	Department responsibility-Examining department performance

With three indexes illustrated in table 6

Table 6 Indexes and Equations

Indexes	Equations
Insurance Card Index (ICI)	ICI[%]=100*(A/B)
Demographic Update (DUI)	DUI[%]=100*(C/D)
Retuned Mail Index (RMI)	RMI[%]=100*(E/F)

Where
A: Count of insurance updates properly
B: Count of insurance updates that were supposed to be performed
C: Count of all demographic updates properly executed
D: Count of all patients checked-in
E: Count for returned mail
F: Count of sent mail

The result will be represented as shown in Table 7

Table 7 Layer II Results

Team	ICI [%]	DUI [%]	RMI [%]
1	●	○	○
2	○	∆	∆
3	∆	●	○
4	●	●	○

Where symbols indicates the targets as shown in Table 8

Table 8 Targets Symbols

Symbol	Target
●	> 97 %
○	Between 94% & 96%
∆	< 93 %

8. Results

The ultimate goal to improve any process is to streamline it, minimize defects and decrease variance to minimum. These efforts also provide a control mechanism for the process and ability to measure and analyze results.
Based on our findings, we can quantify a missed opportunity or potential cost benefit of this project as up to $721,689 per month. This amount is a targeted as a potential cost benefit of introducing the quality management into the check-in/-out process.

Current rate of ICI (Insurance Card Index) is 58%. That means that only 58% of the insurance cards that were supposed to be scanned were actually scanned.

On average, $996,617 is collected per month from third party (insurance) sources. Therefore, a missing opportunity (or potential project cost benefit) on outstanding 42% is potentially equal to $721,689 per month. This is a rough estimate that does not include lost time by rework, returned mail etc. and it is solely based on linear extrapolation of insurance card scanning and third party contribution.

9. Conclusions and Recommendations

In conclusion, the team found inconsistencies between what should be done during check-in/-out processes and what was actually happening. There are issues that are causing inefficiencies in the system, which lead to a high amount of variation between processes. In addition, the SST found that the current staff, more specifically the clerks, was unfamiliar with their job descriptions, resulting in differences in each clerk's responsibilities and what they are actually doing.

The major findings indicates that at 34% of the check-in times, the clerks did not swipe the ID cards to pull up the patient's information, 23% the clerks did not check if the patients have any changes in their demographic, and 53% the clerks did not check the name of the patient on the insurance list. As per the checkout, 7.63 % of check-out times, the HAS order was not available and 87% of the check-out times the clerks did not scan the ID card when they checked out patients. End of life equipment caused many hardware failures that contributed on skipping steps by clerks. The work environment is different from one team to another with limited space led to unorganized workstation.

The team proposed improvement and control mechanisms that the clinic management may employ to achieve continuous improvement. The team has introduced new procedures to optimize and standardize the check in/out process in a way that assures performing the value added steps, and eliminates the non-value added steps. A motivation plan was recommended for continuous improvement throughout all clinics, which will in turn work as dashboards and performance measurements. Also, 5S was suggested as a tool to improve the work environment at the Clinic.

References

[1] Hilton R., Balla M., Sohal A., (2008), Factors critical to the success of a Six-Sigma quality program in an Australian hospital, Total Quality Management & Business Excellence, Vol. 19 Issue 9, pp. 887-902.

[2] Ayon Chakrabarty, Kay Chuan Tan, (2007) "The current state of Six Sigma application in services", Managing Service Quality, Vol. 17 Issue: 2, pp. 194 – 208

[3] Mozammel, A., & Mapa, L. (2011). Application of Lean Six Sigma in healthcare – nursing shift directors process improvement, The Journal of Management and Engineering Integration, Vol. 4, No. 2, pp. 58-65.

[4] Nicholas M., Robb M., Betsy S, Timothy I., Paul C., Darren D. & Michael P., (2007), Use of patient flow analysis to improve patient visit efficiency by decreasing wait time in a primary care-based disease management programs for anticoagulation and chronic pain: a quality improvement study, BMC Health Service Research 2007, 7:8doi:10.1186/1472-6963,p7-8

[5] Haraden, C., & Resar, R. K. (2004). Patient flow in hospitals: Understanding and controlling it better. Frontiers of Health Services Management, 20, 3–11.

[6] H. Harrington, P. Gupta & F. Voehl (2009). The Six Sigma Green Belt Handbook, Paton Professional Press, Chico, CA.

Acknowledgements:
The authors would like to acknowledge the contributions made by the following individuals: René Burt, Fatina Gammoh, Juraj Haas, Abdullah Halawany, Allen Levy, and Tariq Yassin. They have provided valuable inputs while being members of a Six Sigma project team, as part of the requirements for the Total Quality Improvement course at the University of Central Florida.

Modeling Operator Performance of a Compact Rescue Crawler Using Digital Humans

Charles Chung, Steven Jiang, Silvanaus Udoka, Zongliang Jiang
Department of Industrial and Systems Engineering, North Carolina A&T State University, Greensboro, NC 27411, USA
xjiang@ncat.edu; zjiang@ncat.edu

Abstract

Compact rescue robots play a significant role in urban search and rescue missions and operator performance depends on how well they interact with the robots. Recently, there are efforts to apply fluid power to designing a compact rescue crawler. To avoid costly mockups and prototypes, human performance modeling tools were used in this research to study operator performance. Digital humans as well as the compact rescue crawler were developed using Jack™. An empirical study was conducted using those models to investigate the impact of task type and orientation of the haptic controls on operator performance. Results indicated that task type and orientation had significant effects on operator performance. Findings of this research will help rescue robot designers to improve their design.

1. Introduction

Rescue robots have become an important part of search and rescue mission where certain areas are deemed too risky for human rescuers. They are being used in finding survivors after terrorist attacks, natural disasters or even local incidents [1]. There are certain places that humans do not want to or cannot enter during a rescue mission. Some examples of such places include under water or outer space, places with tight spaces where humans cannot comfortably fit, or places in danger of collapsing, or filled with harmful chemicals or smoke [2]. Rescue robots are often used in disasters to provide real-time video and other sensory data such as auditory input to the human rescuers. Efficient interaction between the human rescuers and the rescue robots is therefore a really important factor of the mission. The human rescuers and the rescue robots need to cooperate in order to save lives in a limited period of time.

Many rescue robots that are currently deployed are powered by battery. They are often bulky and can operate for only short periods of time. Recently, there are efforts to use fluid power as the power supply for the rescue robot.

Fluid power is a technology used to generate, transmit or control power using pressurized fluids such as liquids or gases [3]. Fluid power systems that use liquids are called hydraulic systems while the ones that use gases are called pneumatic systems. Fluid power systems are great contributors to the industry and they are being used in nearly every industry including construction, agriculture, transportation, mining, military, manufacturing, recreation and others. Applications of fluid power include backhoes, tractors, airplanes, ships, automobiles, robots, controllers, automated manipulators, and even in amusement park rides.

When compared to electrical and mechanical systems, fluid power systems offer many advantages. Two of the most important advantages are multiplication of force and its ability to change direction quickly without damaging the system [3]. Fluid power can generate a substantial gain of force and provides easy control with great accuracy. Fluid power systems also have some disadvantages that include safety issues due to the high pressure, fluid leakage, and noise of pneumatic systems. Despite those disadvantages, fluid power technology has so many advantages that make it a good candidate for supplying the power for rescue robots. Both hydraulics and pneumatics are currently being applied in some rescue robots. Fire fighting robots were developed using hydraulics, especially water hydraulics for their high power density and heat resistibility [4]. On the other hand, because of flexibility and lightness of the pneumatics, robots with multi-degree of freedom and small robots can jump over the obstacles that other robots cannot perform [4]. These robots have shown that fluid power is one of the useful technologies to be applied in search and rescue robots. With the development the new fluid power technology, its application in rescue robot seems very promising as evidenced by a recent effort of applying fluid power to a compact rescue robot.

One of the important issues in designing a new system in Ergonomics, or human factor, is to design work environment to maximize safety and efficiency. Galer commented that "Ignorance of Ergonomics by designers, planners, and other decision makers can result in a poor fit between user, equipment, and environment" [5]. Unfortunately, many designers and engineers today still tend to ignore the importance of ergonomics and mainly focus on performance of the machine. Ignoring ergonomics in the design process can lead to expensive replacement and/or redesign, therefore, ergonomics needs to be considered very carefully in order to design an effective and inexpensive system [6].

Most of fluid power systems are considered to be complicated and expensive to make. Consequently, companies that design and build these types of systems, often build a prototype and/or mockup before actual production [7]. Like many other fluid power applications, operator performance is very important in the effectiveness of a rescue robot. For example, to operate a fluid power rescue robot, operators need to put a lot of effort and focus on saving people's lives. Therefore, engineers and designers have a very important responsibility to make sure that operators can achieve the best performance with comfort, less fatigue or stress on the operator as hallmarks of their design. The human element must be considered in parallel with the equipment or workspace in order to have an effective and reliable system [8].

Assessing operator performance can be done by observing operators interacting with the actual rescue robot. However, it is very costly and time-consuming to build a prototype or mockup. Digital modeling techniques therefore need to be used.

Digital human modeling (DHM) enables designers and engineers to study comfort, safety, performance, and efficiency of the design of systems in an environment [9]. Jack™ is one of the 3D digital human modeling tools that are available for designing and building a system with virtual humans and performing ergonomic analyses. Jack™ lets user know what operator can see and reach, how comfortable they are, when and why they are getting hurt, when they are getting tired, and other important ergonomics questions can be answered. It is a powerful ergonomic tool that can help in designing a safe and efficient system or work environment. In this research, Jack™ is selected as the digital human modeling tool to predict operator performance of a recue robot.

The objective of this research is to develop digital human models for a compact rescue crawler (CRC) and use those models to predict operator performance by conducting an empirical experiment.

2. Method

A task analysis was conducted to examine the tasks that an operator of a rescue crawler would perform normally. With a good understanding of the tasks, digital human models and compact crawler models were developed. With those models, an empirical study was conducted to predict operator performance. The following sections describe each of these procedures in greater detail.

2.1. Task analysis

The purpose of using a task analysis is to examine and organize what kinds of tasks rescue robot operators do when performing their job. In this study, a hierarchical task analysis, where tasks are broken down from top to bottom to show a hierarchical relationship amongst them, was conducted. There are various ways to access the task information such as observing actual tasks performed in the field, interviewing experts, or reviewing any documentation that describes the operating procedures. Since severe disasters where the rescue robots actually get participated are rare, it is really difficult to observe rescue crawler operators in the actual field. Thus, surveys and interviews of rescue robot experts were conducted in this study along with reviewing documents that contain human-robot interaction information such as recorded videos and operational manuals. Findings of the task analysis were then used to develop digital human models and the rescue crawler environment using the 3D digital human modeling tool, Jack™.

2.2. Digital human model and compact crawler model development

Since Jack™ has anthropometrically and biomechanically accurate digital human models with broad anthropometric database sets, developing digital human models is simple. Using the given human library, various types and sizes of the digital human models can be developed. Since a typical rescue crawler operator can be a male or a female, both male digital human (Jack) and female digital human (Jill) were built in this study. In this study, eighteen digital humans, nine males (Jack) and nine females (Jill) were developed. Each gender group contains nine individuals (three types of height: 5^{th}, 50^{th}, and 95^{th} percentile, and three types of weight: 5^{th}, 50^{th}, and 95^{th} percentile).

A digital human's work environment can also be created by Jack™. General CAD objects can be created in Jack™. Various figures can also be created from the built-in object library in Jack™, and their geometry can be modified as needed. Small objects can be attached to each other to make a whole and joints can be created to enable angular movements. The compact rescue crawler and its operator workstation used in this research are based on a prototype that is currently under development at Georgia Tech. The information of their dimensions in length and angles for joints were measured. Since this research focuses on the impact of the placement and orientation of the haptic controls, dimensions and angles of the rescue crawler and the workstation without phantom were measured approximately and modeled, whereas dimensions as well as angles of the phantom were measured and modeled more precisely. After obtaining necessary dimensions and joints angles, the rescue crawler, the workspace, and the phantom control were carefully modeled into the Jack™ environment. To model those, primitives from the object library are used mostly and they were modified as needed. Jack™ has a function that measures the distance between two points, so this function was used to scale them in real dimensions. To model the rescue crawler, cubes and cylinders were used and scaled to their real dimensions. The legs of the crawler were made up of cylinders mostly, the wheels were made up of cylinders also, and the cubes were used mainly to model the body of the crawler. They were attached to each other and joints were created to legs of the rescue crawler. The workspace was made up of cubes and was scaled. The operator chair in the workstation was imported from the object library. The base that supports the phantom contains joints to make different placements of phantoms possible. Most of the phantom parts were made up of different kinds and sizes of cubes and cylinders with many joints, with the exception of the tip of the controller which was made up of a sphere.

2.4. Experiment

An empirical study on human performance was conducted using the developed models to investigate the impact of the placement and orientation of the haptic controls in the user workspace of a compact rescue crawler. The following subsections describe the empirical study in further detail.

2.4.1. Stimulus material: Eighteen various types and sizes of the digital human models along with the CRC developed in Jack™ were used in this experiment.

2.4.2. Equipment: A Gateway E-6610D desktop with a Microsoft Windows XP operating system and 2 gigabytes of RAM and Jack™ software was used in this study.

2.4.3. Experimental design: A randomized block 3X2 factorial design was used in this study. The blocking factor is gender. The independent variables include the task type with three levels: walk, shift and push and two levels of control orientations: inside and outside. Figure 1 and Figure 2 show the designs of both control placed inside and outside respectively. The dependent variables are three angles: upper arm elevation, humeral rotation, and elbow included, each measured at three different times: the start position (Time1), the exact middle between the start and the end (Time2), and the end position (Time3).

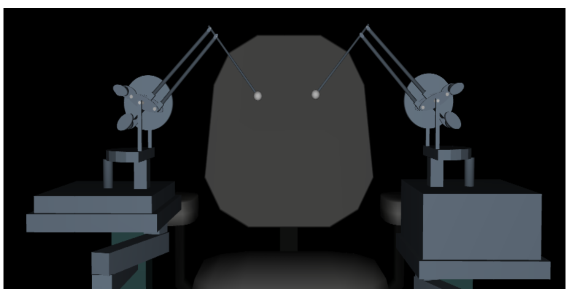


Figure 1 Inside Control Orientation

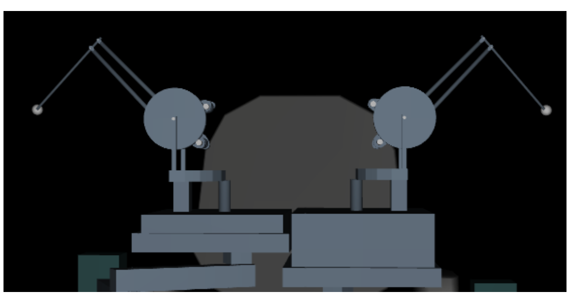


Figure 2 Outside Control Orientation

2.4.4. Procedure: The eighteen digital humans were divided into two blocks (male vs. female). Within each block, each digital human was chosen in a random order to perform the experiment. For each of the digital humans, the nine treatment combinations (task and control orientation) were randomized. The experiment was performed in Jack™. First, selected digital human and control orientation were loaded with an assessment tool. Second, selected task was simulated. Finally, performance was measured and recorded in three different times: Time1, Time2, and Time3. These steps were repeated for each combination with necessary adjustments.

2.4.5: Data collection: The dependent variables were observed from a comfort assessment in occupant packaging toolkit. The comfort assessment shows the comfortable angle ranges for different joints of human body. In this research, angle differences relative to the given modes were used to predict the operator performance and the ranges with the modes for each of the three values used are shown in Table 1. For each setting, operator performance data was recorded by Jack™ and manually exported to an Excel spreadsheet from the output of analysis tools in Jack™. The angle differences relative to mode were calculated and then analyzed using SAS software.

Table 1. Comfortable Angle Range (°)

	Low	Mode	High
Upper arm elevation	0.0	15.0	30.0
Humeral rotation	-60.0	-10.0	40.0
Elbow included	80.0	122.5	165.0

3. Results

Three different operator performance measures, angles for upper arm elevation, humeral rotation, and elbow included, were measured at three different positions on both male and female operators performing three tasks. The following subsections provide both descriptive and inferential statistics results for each measure.

3.1. Upper Arm Elevation Analysis

Correlation analysis was conducted for upper arm elevation measured at three different times. Results revealed that those measures were correlated. To analyze the measures simultaneously, a two way MANOVA was conducted. Results revealed that at the 0.05 significance level, there is a significant interaction effect between task type and control orientation when the three dependent variables were analyzed simultaneously (Wilk's Lambda=0.2044, $F_{6,198}$=39.99, p<0.0001). Significant main effects for task type and control orientation are also found, however since there is a significant interaction effect, the main effect results may not be very meaningful. To further investigate the impact of these effects, an ANOVA for each dependent measure at three different times was analyzed separately.

For Time1, at the 0.05 significance level, there is no significant interaction effect between task type and control orientation ($F_{2, 101}$=0.11, p=0.8944). There is no significant main effect of task type ($F_{2, 101}$=2.21, p=0.1145), but there is a significant main effect of control orientation ($F_{1, 101}$=91.50, p<0.0001) indicating the control placed inside is a better design with respect to the upper arm elevation at Time1. At the 0.05 significance level, there is a significant interaction effect between task type and control orientation for both Time2 ($F_{2, 101}$=5.32, p=0.0064) and Time3 ($F_{2, 101}$=3.24, p=0.0431). Therefore a post-hoc analysis using slicing option of SAS was conducted to investigate the simple main effect. This was done by fixing an independent variable at one level and studies the impact of the other independent variable. For the upper arm elevation at Time2, at the 0.05 significance level, there are significant main control orientation effects for the "push" task ($F_{1, 101}$=27.60, p<0.0001), for the "shift" task ($F_{1, 101}$=72.60, p<0.0001), and for the "walk" task ($F_{1, 101}$=94.25, p<0.0001). At Time3, there are also significant main control orientation effects for the "push" task ($F_{1, 101}$=155.11, p<0.0001), for the "shift" task ($F_{1, 101}$=93.46, p<0.0001), and for the "walk" task ($F_{1, 101}$=82.53, p<0.0001). Thus, the control placed inside is a better design with respect to the upper arm elevation for both Time2 and Time3. There are significant simple main effects of task type when control is placed inside at Time2 ($F_{2, 101}$=4.11, p=0.0193) and at Time3 ($F_{2, 101}$=6.69, p=0.0019) but there are no significant simple main effects of task type when control is placed outside. This indicates that when the control is placed inside, human operator performs better in the "shift" task than the "walk" or the "push" task for both Time2 and Time3.

3.2. Humeral rotation analysis

A correlation analysis revealed that the humeral rotation angles measured at three different times are related. Therefore, a two way MANOVA was conducted.

At the 0.05 significance level, there is a significant interaction effect between task type and control orientation when the three dependent variables were analyzed simultaneously (Wilk's Lambda=0.1828, $F_{6,198}$=44.19, p<0.0001). Significant main effects for task type and control orientation are also found, however since there is a significant interaction effect, the main effect results may not be very meaningful. To further investigate the impact of these effects, an ANOVA for each dependent measure at three different times was analyzed separately.

For Time1, no significant interaction effect between task type and control orientation was found ($F_{2, 101}$=0.23, p=0.7950). There are significant main effects of both task type ($F_{2, 101}$=8.12, p=0.0005) and control orientation ($F_{1, 101}$=201.55, p<0.0001). Even though differences to the mode for all three tasks fall below the threshold, a human operator performs better in the "push" task than the "walk" or the "shift" task for Time1. For control orientation, control placed outside is a better design at Time1 since differences to the mode for the outside is less than for the inside and they were under the threshold.

Results also show a significant interaction effect between task type and control orientation for both Time2 ($F_{2, 101}$=3.74, p=0.0272) and Time3 ($F_{2, 101}$=9.29, p=0.0002). Therefore a post-hoc analysis using slicing was conducted to investigate the simple main effect.

For the humeral rotation at Time2, there are significant main control orientation effects for the "push" task ($F_{1, 101}$=43.50, p<0.0001), the "shift" task ($F_{1, 101}$=93.57, p<0.0001), and for the "walk" task ($F_{1, 101}$=37.31, p<0.0001). At Time3, there are also significant main control orientation effects for the "push" task ($F_{1,}$

$_{101}$=57.37, $p<0.0001$), for the “shift” task ($F_{1, 101}$=112.50, $p<0.0001$), and for the “walk” task ($F_{1, 101}$=20.36, $p<0.0001$). A design with control placed outside is a better design for both Time2 and Time3 also, since differences to the mode for the outside is less than for the inside.

At Time2, there is a significant simple main effect of task type when control is inside ($F_{2, 101}$=12.41, $p<0.0001$) but there is no significant simple main effect of task type when control is outside. This indicates that when the control is placed inside, human operators perform better in the “push” task than the “walk” or the “shift” task for Time2. At Time3, there is a main task type effect when control is placed inside ($F_{2, 101}$=37.58, $p<0.0001$) and when control is placed outside ($F_{2, 101}$=22.79, $p<0.0001$). Again, human operators perform better in the “push” task than the “walk” or the “shift” task for Time3.

3.3. Elbow included analysis

Correlation analysis revealed that the elbow included measured at three different times were related. Hence, a two way MANOVA was conducted.

Again, the result shows that at the 0.05 significance level, there is a significant interaction effect between task type and control orientation when the three dependent variables were analyzed simultaneously (Wilk’s Lambda=0.3057, $F_{6,198}$=26.69, $p<0.0001$). Significant main effects for task type and control orientation are also found, however since there is a significant interaction effect, the main effects results may not be very meaningful. To further investigate the impact of these effects, an ANOVA for each dependent measure at three different times was analyzed separately.

At the 0.05 significance level, there is a significant interaction effect between task type and control orientation at all three times: Time1 ($F_{2, 101}$=5.74, p=0.0044), Time2 ($F_{2, 101}$=35.35, $p<0.0001$), and Time3 ($F_{2, 101}$=11.59, $p<0.0001$). Therefore a post-hoc analysis using slicing was conducted to investigate the simple main effect.

For the elbow included at Time1, at the 0.05 significance level, there are significant main task type effects for the inside control ($F_{2, 101}$=16.80, $p<0.0001$), and for the outside control ($F_{2, 101}$=10.82, $p<0.0001$). At Time2, there are also significant main task type effects for the inside control ($F_{2, 101}$=92.68, $p<0.0001$), and for the outside control ($F_{2, 101}$=5.89, p=0.0038). At Time3, there are also significant main task type effects for the inside control ($F_{2, 101}$=147.35, $p<0.0001$), and for the outside control ($F_{2, 101}$=56.79, $p<0.0001$). Humans’ performance result stays same as the humeral rotation: they are better in the “push” task than the “walk” or “shift” task for all three times.

At Time2, there is a main control orientation effect for the “push” task ($F_{1, 101}$=9.23, p=0.0030), for the “shift” task ($F_{1, 101}$=159.18, $p<0.0001$), and for the “walk” task ($F_{1, 101}$=193.99, $p<0.0001$). Thus, the control placed outside is a better design at Time2. At Time1, there is a main control orientation effect for the shift task ($F_{1, 101}$=37.74, $p<0.0001$), and for the walk task ($F_{1, 101}$=4.14, p=0.0444). At Time3, there is also a main control orientation effect for the shift task ($F_{1, 101}$=73.07, $p<0.0001$), and for the walk task ($F_{1, 101}$=26.35, $p<0.0001$). This indicates that for both the “shift” and the “walk” tasks, the control placed outside is a better design for both Time 1 and Time3.

4. Discussion and conclusion

The goal of this research was to develop digital human models for a compact rescue crawler and use those models to predict operator performance by conducting an empirical experiment. A task analysis was conducted to examine the tasks that an operator of a rescue crawler would perform normally. With a good understanding of the tasks, digital human models and compact rescue crawler models were developed using a digital human modeling tool, Jack™. With those models, an empirical study was conducted to investigate the impact of task type and control orientation on operator performance. Data was collected and analyzed and results indicated that task type and control orientation had an effect on operator performance. The most salient finding of this research is that the digital human modeling used in this research can effectively predict operator performance of rescue robot.

A two way MANOVA was conducted for all three performance measures and there was a significant interaction effect between the two independent variables, task type and control orientation for all three performance measures when all three were analyzed simultaneously. Caution needs to be taken when concluding the impact if the task type and control orientation on operator performance. Since there is a significant interaction effect, the main effect results might not be very meaningful. To further investigate the impact of these effects, an ANOVA for each dependent measure at three different times was analyzed separately. For significant interaction effect found at ANOVA, a post-hoc analysis of slicing was used to investigate the simple main effect. The result of significance effect is summarized in Table 2 where "A" represents the significance effect found from ANOVA, "S" represents the significance simple main effect found from slicing, and a condition for the simple main effects is written in parenthesis.

Table 2 Summary of Significant Effects

Angle Measure	Source	Time1	Time2	Time3
Upper arm elevation	Task	-	S (inside)	A, S (inside)
	Orientation	A	A, S (all)	A, S (all)
	Task* Orientation	-	A	A
Humeral rotation	Task	A	A, S (inside)	A, S (all)
	Orientation	A	A, S (all)	A, S (all)
	Task* Orientation	-	A	A
Elbow included	Task	A, S (all)	A, S (all)	A, S (all)
	Orientation	A, S (shift , walk)	A, S (all)	A, S (shift , walk)
	Task* Orientation	A	A	A

For upper arm elevation, there was a main effect of control orientation at Time1which means that the control placed inside is a better design with respect to the upper arm elevation at Time1. This result was expected since operators have to raise up their arms when they operate in the outside control orientation which would be less comfortable than a rest position in the inside control orientation. For both Time2 and Time3, there were significant interaction effects. Therefore a post-hoc analysis of slicing was used and found that there are significant main control orientation effects for all three tasks despite the significant interaction. This means that the control placed inside is a better design with respect to the upper arm elevation also at Time2 and Time3. There was a simple main effect of task type when control is placed inside which lead to the conclusion that when control is placed inside, human operator performs better in the "shift" task than the "walk" and the "push" tasks at Time2 and Time3. Consequently, with respect to the upper arm elevation, the inside control orientation should be used instead of the outside control orientation for better operator performance.

For humeral rotation, there was no significant interaction effect but there were significant main effects for both task type and control orientation at Time1. This indicates that human operators perform better in the "push" task than the "walk" or the "shift" tasks for Time1. For control orientation, control placed outside is a better design at Time1. This result was expected since preferred angle for humeral rotation (mode value) is -10° which is more close to the outside control orientation. For both Time2 and Time3, there were significant interaction effects between task type and control orientation. Results further revealed that there were significant main control orientation effects for all three tasks despite the significant interaction between task type and control orientation. This again indicates that a design with control placed outside is a better design for both Time2 and Time3. At Time2, there were significant simple main effects of task type when control is inside which means that when control is placed inside, human operators perform better in the "push" task than the "walk" or the "shift" task for Time2. At Time3, a main task type effect for both control orientations was found which means that human operators will perform better in the "push" task than the "walk" or the "shift" task for Time3. Consequently, with respect to the humeral rotation, the outside control orientation should be used compare to the inside control orientation for better operator performance.

For elbow included, there were significant interaction effects between task type and control orientation for all three times. Results further revealed that there were significant main task type effects for both controls despite the significant interaction between task type and control orientation which means that the than the "walk" or the "shift" task for all three times. At Time2, a main control orientation effect for all three tasks was found meaning that a design with control placed outside is a better design for Time2. This result was also expected since preferred angle for humeral rotation (mode value) is 122.5° which is more close to the outside control orientation. At both Time1 and Time3, there was a main control orientation effect for the "shift" and the "walk" tasks which means that for both the "shift" and "walk" tasks, the control placed outside is also a better design for both Time 1 and Time3. Consequently, with respect to the elbow included, the outside control orientation should be used instead of the inside control orientation for better operator performance.

Table 3 suggests the preferred control orientation and the task type that brings the most comfort to human operator for each angle measure.

The inside control orientation should be used to have better operator performance with respect to the upper arm elevation while the outside control orientation should be used to have better operator performance with respect to the humeral rotation and elbow included. For the task types, the "push" task produces better operator performance than other tasks with respect to the humeral rotation and elbow included but it produces poor performance with respect to the upper arm elevation. On the other hand, the "shift" task produces better operator performance than other tasks with respect to the upper arm elevation while it produces poor performance with respect to the humeral rotation and elbow included.

Table 3 Preferred Control Orientations and Task Types

	Control Orientation		**Task Type**		
Angle Measure	Inside	Outside	Push	Shift	Walk
Upper arm elevation	v		2	1	3
Humeral rotation		v	1	3	2
Elbow included		v	1	3	2

Thus, this result brings a dilemma to the rescue robot designer because there is a tradeoff between the two control orientations. Each has advantages and disadvantages. Advantages of using the outside control orientation include comfort on two angle measures: humeral rotation and elbow included and its intuitive design since the control is oriented same way as the robot's legs. On the other hand, advantage of using the inside control orientation is comfort on one angle measure: upper arm elevation. Thus, it is likely to conclude that the inside orientation is a better orientation overall, but with respect to the upper arm elevation, disadvantage of using the inside control is critical. When control is placed outside, the absolute difference of upper arm elevation on average is far greater than the threshold. On the other hand, even though advantage of using the inside control orientation is comfort on only one angle measure, the absolute differences of other two angle measures are not that critical.

As a result, even though the outside control orientation have more advantages, the inside control orientation is recommended at this stage since that discomfort with respect to the upper arm elevation is critical. Therefore, more studies need to be conducted to remove the discomfort with respect to the upper arm elevation to achieve optimal operator performance. There are several limitations in the current study and it is possible to achieve optimal operator performance in the future if they are taken care of.

First, only two phantom control orientations: inside and outside were considered. In the future, more control orientations with some angles between inside and outside can be designed and used to come up with better control orientation that would bring better operator performance.

Secondly, only eighteen digital humans, nine males (Jack) and nine females (Jill) with different combinations of height and weight were developed. In future studies, larger number of digital humans can be used to improve the quality of data. Moreover, if more realistic anthropometric data can be collected from the actual rescue robot operator population, it will also improve the quality of data.

Thirdly, in this study, only task type and control orientation were considered as the independent variables. In the future, more factors such as control position or height of the chair's seat can be studied.

Finally, this study was conducted using a digital human modeling tool and in the future, it can be tested in actual physical setting with real humans. Actual operators' performance or their comfort can be measured when they perform the tasks on different positions and orientations of the phantom control. Outcome can be compared with the result of this study to validate the digital human models.

5. Acknowledgment

This research is partially funded by NSF Engineering Research Center for Compact Efficient Fluid Power.

6. References

[1] B., Siciliano, and O. Khatib, (Eds.). (2008). Springer Handbook of Robotics (1st ed.): Springer.

[2] J. A. Angelo, (2006). Robotics: A Reference Guide to the New Technology: Greenwood Press.

[3] J. Johnson, (2001). Introduction to Fluid Power (1st ed.): Delmar Cengage Learning.

[4] A., Kitagawa, and H., Tsukagoshi, (2002). Utilization of fluid power for rescue operations and robots. Advanced Robotics, 16(6), 513-516.

[5] I. A. R. , Galer, (1987). Applied ergonomics handbook (2 ed.): Butterworths.

[6] J. P. , Kohn, (1998). Ergonomics Process Management: A Blueprint for Quality and Compliance (1 ed.): CRC.

[7] B., Bietzker, O., Karch, & H. , Noltemeier, (2000). Using Randomized Algorithms for Digital Mock-Up in Automotive Industry. Paper presented at the Mexican International Conference on Artificial Intelligence, Acapulco, Mexico.

[8] B., Kirwan, and L. K., Ainsworth, (Eds.). (1992). A Guide To Task Analysis: The Task Analysis Working Group (1 ed.): CRC.

[9] T., Kajaks, A. Stephens, J., Potvin, (2011). The effect of manikin anthropometrics and posturing guidelines on proactive ergonomic assessments using digital human models, International Journal of Human Factors Modelling and Simulation, 2(3), 236-253.

Optimization of Turbine Engine Design Parameters Using Combined Taguchi Methods

J. S. Sutterfield, Paul Nkansah, Asia N. McFarland, Kristin S. Leek, Tajadin I. Muhammad
School of Business and Industry, Florida A&M University, Tallahassee FL 32307, USA
pisces4914@earthlink.net

ABSTRACT

Experimental analysis has the objective of determining which control factors, and combinations of control factors, significantly affect some response variable of interest. Achieving this objective is complicated by the fact that is often necessary at the same time to determine the optimum values for those control factors. Since such experimentation is generally expensive to perform, it is desirable to obtain as much information with as little cost as possible. In this paper we demonstrate how two different Taguchi methods might be employed upon the same data set, first, to determine which control variables are significant; and second, to optimize the values of those control variables found significant. This approach is demonstrated using the data from a turbine engine performance design experiment.

1. Introduction

Experimental method has been widely used in industry for purposes of process improvement and optimization [16, 6]. In large measure, this is due to Taguchi (1986) who devised a simplified and modified DoE approach, which has been widely adopted in industry. Because of the power of Taguchi's approach, it has gained wide acceptance in a broad range of industrial applications in which it is desirable to identify significant control factors, the magnitudes and components of variation, and the interactions among control factors.

Taguchi's methods are greatly versatile as demonstrated by their use in such wide ranging applications. Such applications include cloth quality evaluation, the design of clothing, bearing deflections, electrical power consumption [24], bank and insurance contracting, diesel engine nozzle design, and many other types of problems in engineering and science [26]. One difficulty with employing experimental method is that experiments must be performed using actual production equipment for which a process is to be examined. This often results in disruption to a plant, and may prove to be extremely expensive [17]. This inconvenience has led researchers to develop approaches aimed at minimizing it. In recent years, such approaches as (Neural Networks [5]; and Evolutionary Operations [2] to test process parameters, without production interruptions have been used to minimize any disadvantages attending the use of experimental method.

In a previous paper [21], it was pointed out that in the design of turbine engines it is desirable to have as large a pressure differential across the engine as possible, since this a vital aspect of achieving thrust. In that paper, three of the principal control factors in turbine engine operation were examined. Pressure, temperature and inlet velocity, along with factor interactions, were analyzed using Taguchi's approach to a type of analysis known as a factorial analysis. Data for this analysis were obtained from a rather old experiment cited by [14]. The control factors selected for this experiment were gas temperature, inlet pressure and air inlet speed. Data for the first two factors had been taken at three levels, but for the third factor at four levels. Consequently, in order to avoid unduly complicating the factorial analysis, the original dataset was modified to render the data for all three control factors at three levels. This simplification was performed in such a way as to permit identification of the significant control factors, along with their interactions, without the loss of any information from the experiment.

In this paper, we extend the results of the first analysis by reverting to the original dataset to determine the optimum values of those control factors found significant in the first analysis. In doing so, we employ another Taguchi approach known as the two-way layout method. With this approach, we demonstrate how two Taguchi methods might be applied to one dataset in order to avoid the necessity for a second experiment, thereby avoiding the expense of a second experiment.

2. Literature Review

Experimental investigation is immensely indebted to Sir Ronald A. Fisher of England [4]. It was Fisher who originated most of the ideas used in modern experimental method [1]. Fisher is credited with having developed the foundations of experimental investigation several decades ago [9]. In the early practice of experimental method, assumptions were made about the distribution and the unknown population parameters in order to estimate population parameters and test hypotheses. Fisher demonstrated, contrary to the thinking up to his time, that distribution parameters should be estimated from samples taken from the population [3]. Because of this contribution, the entire field of experimental analysis was revolutionized.

During the next twenty years, the quality movement that began to grow in Japan. As it did so, experimental method began to merge with it, and in doing so grew in importance along with the quality movement. During this period, American industrialists had largely rejected the ideas of Deming. The Japanese, however, were engaged in rebuilding their industrial base after the destruction of WW II. As a consequence, Deming found that the Japanese industrialists readily accepted his ideas concerning quality. The Japanese were interested in reducing costs to the greatest extent possible, and readily grasped the relationship between quality and cost reduction. Moreover, the Japanese were concerned with eliminating as much waste as possible because of limited natural resources, In such a congenial context, Deming's ideas found ready acceptance. Deming had been using statistical methods to improve quality prior to beginning work with the Japanese [20]. The Japanese had also discovered that statistical methods could be employed for monitoring and improving quality [14]. Thus, the Japanese began to employ Deming to teach them Statistical Quality Control. In the same period, experimental method was advanced still further by such pioneers as [7, 8, 12, 13, 22, 23], who began to use it to facilitate scientific experimentation.

Experimental method was given a solid practical foundation when Taguchi published the original version of his monumental work on experimental method in 1956 [23], the third such work. Although many other Japanese scientists have made many substantial contributions to the field of experimental method, it is Taguchi, more than any other, who has advanced this area of science, and after whom the field has been named as "Taguchi Methods". Considering the immense success achieved by the Japanese using designed experiments, it is to be regretted that they have not been more widely used in the West [14].

3. Methodology

The philosophy and approach of experimental methodology are the same no matter which approach is used for the analysis of experimental results. Thus, the experimental methodology is identical whether classical analysis or Taguchi analysis is used. The experimental method has been discussed in detail by its trailblazers [1, 9], as well as in a previous work by one of the current authors [17]. This latter work may be consulted for a concise statement of the methodology of experimental method.

In a previous paper [18] Taguchi's approach was used to analyze a set of experimental turbine engine data to determine which of several control factors significantly affected the response factor, pressure drop across the engine. This response factor was chosen because it is indicative of the performance of the engine, ie, the greater the pressure drop across an engine, the better the performance, and vice versa. Consequently, it is important to know which of the control factors, or combinations of control factors, must be optimized in order to maximize pressure drop.

The methodology applied in that paper was of a type known as Factorial Analysis. Factorial analysis is an experimental method that permits investigation of large numbers of control factors, and their interactions, at several levels. Factorial analysis relies upon a mathematical construct known as orthogonal arrays. These were first studied by the great Swiss mathematician and physicist, Leonhard Euler (1707-1783), and were originally viewed as a type of mathematical recreation (Taguchi, 1988). Since Euler's time, they have been studied extensively by Joseph Leonard Walsh (1895-1973) and others as a part of the general investigation of orthogonal functions [24]. An example of an L_8 (2^7) orthogonal array is shown in Figure 1. Factorial Analysis has been in use for upward of 70 years and was extended considerably through the efforts of Frank Yates [25]. For a more extended discussion of factorial analysis and its uses, see the paper [19].

The original dataset to which the factorial method was to have been applied is shown in Table 1. It will be seen for this experiment that the effect of inlet pressure was examined at three levels: that of gas temperature at three levels and that of speed at four levels. It will further be observed that the experiment was repeated for each of the three inlet pressure conditions. Thus, in order to perform this experiment using an orthogonal array, one of order L_{36} (4^1x3^2) would have been required [10, 11, 15]. This means an orthogonal array with 36 rows to analyze one control factor at four levels, with the remaining two control factors being analyzed at three levels. It was observed, however, that the data in Table I might be modified without the loss of any significant information. This modification was performed by removing the values in Table 1 for airspeeds of 200 ft/sec. This resulted in the remaining airspeeds being equally spaced at 75 ft./sec., and yielded the modified data as shown in Table 2. This modification made it possible to perform the factorial analysis using an orthogonal array of order L_{27} (3^3), thus simplifying the analysis considerably.

Once the resulting dataset was analyzed, it became obvious that inlet pressure, contrary to intuition, had no significant effect upon the pressure drop across the engine. Thus, for the purpose of the instant analysis, it became possible to revert to the original dataset and to analyze it using the two-way layout method, which is well adapted for applications having two control factors. In order to do this, the original dataset was once again modified. This time, however, the adaptation was employed on all of the data. The approach to this adaptation will be described in detail in the following section.

4. Application of Methodology

The experimental data used for this analysis were obtained from a turbine engine analysis performed some years ago. Three control factors were employed in the original experiment, those of pressure, temperature and air speed. The response factor was the pressure drop across the engine. Since the pressure drop across the engine is indicative of a turbine engine's efficiency, it was desirable to investigate which of the control factors, and their interactions, most affected the engine pressure drop. The original data from this experiment are shown in Table 1.

However, from the factorial analysis previously performed upon the data, it had been determined, contrary to expectation, that the control factor of **pressure** had no significant effect upon the pressure drop across the engine. Only the control factors of **temperature** and **airspeed** were found to have a significant effect. As a consequence, it was found possible to perform another modification on the original dataset. In order to make this modification, it was noted that for each temperature and airspeed there were two repetitions for each of the three inlet pressures. But the results of the previous factorial analysis had shown that inlet pressure did not significantly affect the pressure drop across the engine. This means that virtually the same results would have been obtained if the experiment had been conducted at a single inlet pressure. Thus, the two repetitions for each of the three pressures were in effect the same as six repetitions (2x3) at a single pressure for each combination of temperature and airspeed. Consequently, it was possible to rearrange the original dataset into a two-way layout of airspeed versus temperature in which there were six repetitions for each temperature and airspeed combination. It is to be noted that this modification did not result in the loss of any information from the experiment. In the variation calculations, this modification resulted in the slight, but insignificant, variation due to pressure being combined with the error variation term. This is the way that Taguchi methods treat such variation found to be insignificant. The resulting modified dataset is shown in Table 2.

Through modifying the original dataset in this way, it was possible to analyze the dataset without losing any of the information. One of the distinctive aspects of Taguchi analysis is that a working mean is deducted from each of the data points to simplify analysis. In effect, this deducts the effect of the mean variation from the data, along with one degree of freedom. This means that all variations are calculated around this working mean. In the present instance, a working mean of 20 was deducted from each of the data points in Table 2 to yield the values shown in Table 3.

Having modified the dataset in this way, it was then possible to analyze it using the standard Taguchi approach for a two-way layout, which is that of Tchebycheff orthogonal polynomials. This phase of the analysis is shown in the following section.

5. Results

The experimental design used for this analysis is known as a two-way, replicated, 3x4 factorial design: Two-way because two factors are controlled; replicated because each combination of airspeed and temperature is replicated or repeated six times; and factorial because both control factors are tested at varying factor levels. Having eliminated inlet pressure as a significant operational factor in engine efficiency, the objective of this analysis was to determine the optimum conditions of inlet airspeed and temperature to maximize engine efficiency. An additional objective was to determine the level of interactions, if any, between airspeed and temperature. With these objectives in mind, the following calculations were undertaken. First, the correction factor, CF, was calculated. The correction factor may be thought of as the average effect of variation, so that the additional variation is over and above the mean variation. The CF was then calculated from the coded data shown in Table 3.

$$CF = (x_{1,1} + x_{1,2} + x_{1,3} + \ldots + x_{18,3} + x_{18,4})^2/72$$

$$CF = (-2 + 0 - 1 + \ldots - 2 - 7 + 3)^2/72$$

$$\underline{\mathbf{CF = 8.68\ lb./in.^2}}\ \mathbf{(\mathit{f} = \mathit{1})}$$

The total variation for the data shown in Table 2 above is calculated as follows:

$$S_T = x_{1,1}^2 + x_{1,2}^2 + x_{1,3}^2 + x_{1,4}^2 + x_{1,5}^2 + x_{1,6}^2 + \ldots + x_{18,1}^2 + x_{18,2}^2 + x_{18,3}^2 + x_{18,4}^2 + x_{18,5}^2 + x_{18,6}^2 - CF$$

$$S_T = (-2)^2 + (-3)^2 + (-6)^2 + (4)^2 + (-1)^2 + (-2)^2 + \ldots + (-2)^2 + (1)^2 + (-8)^2 + (3)^2 + (1)^2 + (3)^2 - 8.68$$

$$\underline{\mathbf{S_T = 3{,}950.32\ lb./in.^2}}\ \mathbf{(\mathit{f} = \mathit{71})}$$

Now, included in this total variation there is the component of variation within each level of temperature tested at each airspeed and temperature combination. This component is referred to as the second order variation between repetitions, S_{e2}. In order to estimate the net effects for the airspeeds, temperatures and the possible interactions, S_{e2} must be removed from the total variation. Again, using the data from Table 2, S_{e2} is calculated as …

S_{e2} = $\mathbf{x_{1,1}^2 + x_{2,1}^2 + x_{3,1}^2 + x_{4,1}^2 + x_{5,1}^2 + x_{6,1}^2 - ((x_{1,1} + x_{2,1} + x_{3,1} + x_{4,1} + x_{5,1} + x_{6,1})^2)/6 \ \ldots + X_{13,4}^2 + x_{14,4}^2 + x_{15,4}^2 + x_{16,4}^2 + x_{17,4}^2 + x_{18,4}^2 - ((x_{13,4} + x_{14,4} + x_{15,4} + x_{16,4} + x_{17,4} + x_{18,4})^2)/6}$

S_{e2} = $\mathbf{(-2)^2 + (-3)^2 + (-6)^2 + (4)^2 + (-1)^2 + (-2)^2 - ((-2 - 3 - 6 + 4 - 1 - 2)^2)/6 \ \ldots + (-2)^2 + (1)^2 + (-8)^2 + (3)^2 + (1)^2 + (3)^2 - ((-2 + 1 - 8 + 3 + 1 + 3)^2)/6}$

S_{e2} = 1,291.17 lb./in.^{2} (f = 60)

Next it is desired to obtain the variation between the various combinations of airspeeds and temperatures, S_{T1}. This is termed the variation between experiments. In the instant experiment, 12 combinations of airspeeds and temperatures have been examined, with four replications for each combination. In order to calculate this variation, the replications are combined to yield the set of values shown in Table 4.

Proceeding …

$$S_{T1} = x_{1,1}^2 + x_{1,2}^2 + x_{1,3}^2 + + x_{1,4}^2 \ldots + x_{3,1}^2 + x_{3,2}^2 + x_{3,3}^2 + x_{3,4}^2 - CF$$

$$S_{T1} = (-10)^2 + (-27)^2 + (-26)^2 + (0)^2 + \ldots + (-24)^2 + (9)^2 + (-31)^2 + (-2)^2 - 8.68$$

S_{T1} = 2,659.15 lb./in.^{2} (f = 11)

It will be observed that this value is the difference between S_T and S_{e2}, and could have been obtained by subtraction. However, it is here computed independently as a check upon calculations. The variations due just to the airspeed, S_A, and just to the temperature, S_T, are calculated next, as follows:

$$S_A = (A_1^2 + A_2^2 + A_3^2 + A_4^2)/18 - CF$$

$$S_A = (76)^2 + (4)^2 + (-43)^2 + (-12)^2)/18 - 8.68$$

S_A = 423.82 lb./in.^{2} (f = 3)

Continuing, the variation due just to temperature, S_T, …

$$S_T = T_1^2 + T_2^2 + T_3^2 - CF$$

$$S_T = ((-63)^2 + (136)^2 + (-48)^2)/24 - 8.68$$

S_T = 1.023.36 lb./in.^{2} (f = 2)

Now if the variation due to airspeed, S_A, is added to that due to temperature, S_T, it will be found the that sum of these variations is 1,447.18. Deducting this total from that inherent in the various combinations of airspeed and temperature, S_{T1}, shows that this sum does not account for all of the variation in the combinations. Thus, there is an interaction between airspeed and temperature in the amount of 1,211.97. The magnitudes of the components of this interaction are estimated next. In order to do this, three contrasts are formed: One for the linear component of each level of temperature at the four inlet airspeed levels, one for each quadratic component of each temperature level for the four inlet airspeed levels, and one for each cubic component of each temperature level at the four inlet airspeed levels. Thus, there are a total of nine contrasts. Again, using the values in Table 3, the linear contrast for P_1 is …

$$L(T_1) = -3*(-10) - 1*(-27) + 1*(-26) + 3*(0)$$

$L(T_1)$ = 31psi

The coefficients "-3", "-1", "1", and "3" in the above equations are those obtained from the Chebyshev orthogonal polynomial expansion for a linear contrast and are available from tables (Box et al., 1978). The linear components of P_2 and P_3 are obtained in a similar fashion as …

$L(T_2)$ = -368 psi **$L(T_3)$ = 26 psi**

The quadratic component of P_1 is calculated in similar fashion as …

$$Q(T_1) = 1*(-10) - 1*(-27) - 1*(-26) + 1*(0)$$

$Q(T_1)$ = 43 psi

The coefficients "1", "-1", "-1", and "1" are those obtained from the Chebyshev orthogonal polynomial expansion for a quadratic contrast. The linear components of P_2 and P_3 are obtained in a similar fashion as …

$Q(T_2) = 64$ psi

$Q(T_3) = -4$ psi

Finally, the cubic component of P_1 is calculated. As before, the coefficients "-1", "3", "-3", and "1" are those obtained from the Chebyshev orthogonal polynomial expansion for a cubic contrast. For P_1 this component is …

$C(T_1) = -1*(-0.15) +3*(1.72) - 3*(0.47) + 1*(0.64)$

$C(T_1) = 7$ psi

The cubic components of P_2 and P_3 are obtained in a similar fashion as …

$C(T_2) = -196$ psi **$C(T_3) = 42$ psi**

It is now possible to determine the interaction of the temperature with each of the three inlet airspeed components. For the four linear components of inlet airspeed with temperature, this calculation is …

$S(TxS_l) = ((31)^2 + (-368)^2 + (26)^2)/(20*6) - (31 - 368 + 26)^2/(20*6*3)$

$S(TxS_l) = 873.51$psi

The interactions between temperature and the quadratic and cubic components of the four airspeed levels are calculated in similar fashion as …

$S(TxS_q) = 101.03$ psi

$S(TxS_c) = 237.44$ psi

Now, it will be found that summing the linear, quadratic and cubic components of the interaction of speed with temperature will yield exactly the 1,211.97 component of variation that was to be accounted for from the interaction. Having calculated the foregoing variations, it is now possible to construct the analysis of variance (ANOVA) for the experiment shown in Table 5.

6. Analysis of Results

Consulting a table of F values (Taguchi, 1988) for a 99% confidence level with 2 degrees-of-freedom for the numerator and 64 for the denominator, yields a critical value of approximately 4.96. Comparing this value with the F value obtained for our experimental data, it is evident that temperature has a significant influence on pressure drop at well above the 99% level. Once again consulting the F table for 3 degrees in the numerator and 64 in the denominator, we find a critical value of approximately 4.11. Comparing this with the F value of 6.49 for inlet airspeed indicates that that inlet airspeed also has a significant effect upon pressure drop. Lastly, consulting the table of F values for a 99% confidence level with 1 degree-of-freedom for the numerator and 64 for the denominator, yields a critical value of 7.64. Once again, it will be seen that there are significant interactions between temperature and the linear and cubic components for airspeed, $\mathbf{S_{TxSl}}$ and $\mathbf{S_{TxSc}}$, at the 99% level. However, the interaction between temperature and the quadratic component of airspeed $\mathbf{S_{TxSq}}$, was not found to be significant. As a matter of good practice in experimental method, once the significant sources of variation are identified, the ANOVA table is condensed to include only the significant sources of variation. In doing this, those sources of variation found to be insignificant are combined with the random error term, **(e)**. Thus, Table 5 has been modified as shown in Table 6.

Table 6 provides a modification of Table 5 to include only the significant sources of variation for the pressure drop across the turbine engine. These proved to be air temperature (T), air speed (S), and the interaction between temperature and the linear and cubic components of airspeed. It will be seen that Table 6 includes two additional columns not unusually found in an ANOVA. The first is the column labeled ***S′*** and the second labeled ρ (%). The first, ***S′***, is the net variation. The values for ***S′*** were obtained by removing one error variation for each degree of freedom from the values in column ***S***. Thus, the net variation for Temperature, the value of 979.86, was obtained by deducting 2*21.75 from 1,023.36. Other net variations were obtained similarly, any slight differences being due to round-off error. The net error variation was then increased by the amounts deducted from each of the control variables, a total of 152.25, to obtain the net error variation 1,544.47.

The second column, labeled *ρ(%)*, tabulates the percentage of variation attributable to each control variable, as well as that attributable to the experimental error. For example, the percentage of experimental error due to temperature is nearly 29%. Similarly, the remaining percentages refer to their respective components of variation.

It should be observed that the experimental error variation amounted to nearly 40% of the total variation. This was somewhat predictable from a cursory view of Table 1 before the analysis of variance was undertaken. This data has a somewhat erratic appearance, in that there are no discernable patterns in it. Although it cannot be determined with certainty at this late date, this irregular data may be due to a lack of care in setting up the instrumentation for the experiment, a lack of care in reading the instrumentation, or a lack of sensitivity of the instrumentation used. Since the experiment is rather old, it is probable that this accounts for the rather high experimental error. Had the experimental error been less, it is possible that the variation in other control factors would have been found to be significant.

In order to obtain the optimum operating conditions for this particular turbine engine design, a plot was made of temperature versus pressure drop for lines of constant airspeed. This plot is shown in Figure 2.

Figure 2 shows quite clearly that the maximum pressure drop across the engine occurs at a temperature of 75 ^{o}F and inlet airspeed of 150 ft/sec. Thus, the optimum operating conditions for this particular engine are at an inlet temperature of 75 ^{o}F, and an inlet airspeed of 150 ft/sec.

7. Conclusions

The purpose of this paper was to demonstrate how two experimental methods, factorial analysis and two-way analysis, might be employed to analyze the data from a turbine engine experiment. The methods of experimental analysis were those of Taguchi. The first, factorial analysis, is generally used when numerous factors are used at few levels, preferably not more than two (2). Although the present analysis might have been done as a three way layout, the analysis was made much less complex by employing the factorial analysis initially to eliminate any insignificant control factors. In order to simplify the factorial analysis, the 200 ft/sec column of data was eliminated. The 200 ft/sec column was selected for elimination because the three remaining columns were then equally spaced. This made it possible to perform the simplified factorial analysis on the remaining data without the loss of any information from the experiment. For the two-way analysis described in this paper, this column of data was reinserted.

Once factorial analysis had determined that pressure was not a significant factor in pressure drop, the remaining two control factors, temperature and airspeed were examined using two-way analysis, which relies upon the use of orthogonal contrasts to identify the linear, quadratic, etc., components of variation. By way of preparing for the second phase of the analysis, the original dataset was rearranged so that the data for inlet pressures of 75 psi and 85 psi were placed under those for 50 psi. In effect, this yielded six repetitions for each temperature/airspeed combination, where before there had been only two. To understand why this rearrangement is legitimate, it must be remembered that in the factorial analysis pressure had been found to be insignificant as a control factor. This being the case, the data for the two higher pressure conditions amount to no more than additional repetitions at an inlet pressure at 50 psi. By employing the original dataset in this fashion, it was possible to maximize the information obtained from the original data.

With the two-way analysis it was determined that temperature was a significant control factor, along with the liner and cubic components of airspeed. All of these control factors were found to be significant at well beyond the 99% level. These results were then finalized by plotting them in Figure 2. This plot showed clearly that the maximum pressure drop across the turbine engine occurred at a temperature of 75 ^oF and an airspeed of 150 ft/sec. Thus, the optimum operating conditions for the engine were established.

8. References

[1] Box, George E. P., William G. Hunter, J. Stuart Hunter (1978,). *Statistics for Experimenters*, John Wiley and Sons, New York, Chichester, Brisbane, Toronto and Singapore, pg. 15

[2] Cochran, W. G. and G. M. Cox (1957). *Experimental Design*, John Wiley and sons, New York

[3] Fisher, R. A.(1966). *The Design of Experiments*, Hafner Publishing Company, New York, 8th edition,

[4] Fisher, Ronald A.(1942). *The Design of Experiments*, Oliver and Boyd, Ltd.

[5] Guh, R. and Tannock, J.(1999). "A Neural Network Approach to Characterize Pattern Parameters in Process Control Charts", *Journal of Intelligent Manufacturing*, Vol.10 (5), pp.449-462.

[6] Huang, M.F. and T.R. Lin (2004). "Application of grey-Taguchi method to optimize drilling of aluminum alloy 6061 with multiple performance characteristics," *Materials Science and Technology*, Vol. 20 (4), pp. 528-533.

[7] Ishikawa, Kaoru (1952). "Sampling at Plants," *Maruzen*, Tokyo

[8] John, P. W. M. (1971). *Statistical Design and Analysis of Experiments,* The MacMillan Company, New York

[9] Kempthorne, Oscar (1967). *Design and Analysis of Experiments*, John Wiley and Sons, Inc., New York, London and Sydney

[10] Margolin, B. H. (1967). "Systematic Methods of Analyzing 2^n3^m Factorial Experiments with Applications," *Technometrics*, vol. 9, pgs. 245-260

[11] Margolin, B. H. (1969). "Results on factorial Designs of Resolution IV for the 2^n and 2^n3^m Series," *Technometrics*, vol. 11, pgs. 431-444

[12] Masuyama, Motosaburo (1955). Design of Experiments Explained for the Plant Technician, *Japanese Standards Association*, Tokyo, Japan

[13] Masuyama, Motosaburo (1956). *Design of Experiments*, Iwanami, Zensho

[14] Montgomery, Douglas C. (1991). *Design and Analysis of Experiments*, John Wiley and Sons, New York, Chichester, Brisbane, Toronto and Singapore, 3rd edition, pgs. 414-415

[15] Plackett, R. L., and J. P. Burman (1946). The design of Multi-factorial Experiments," *Biometrika*, vol, 33, pgs. 305-325

[16] Singh, Sehijpal, Pradeep Kumar and H.S. Shan (2006). "Quality optimization of surface finishing by magnetic field assisted abrasive flow machining through Taguchi technique," *International Journal of Computer Applications in Technology*, Vol. 27(1), pp. 31-56.

[17] Sukthomya, W. and Tannock, J. (2005). "Taguchi Experimental Design for Manufacturing Process Optimisation Using Historical Data and a Neural Network Process

Model", *International Journal of Quality and Reliability Management*, Vol.22 (5), pp.485-502.

[18] Sutterfield, J. S., Kenneth R. Brown (2011). "Optimization of Turbine Engine Design Parameters with Taguchi Methods," *Proceedings of the 2011 IEMS Conference*, Mar. 27-30, 2011, Cocoa Beach, FL, pgs. 220-229.

[19] Sutterfield, J. S., Dominique D. I. Drake and Conrod S. J. Kelly (2005). Investigation of animal survival times for poison antidotes using standard factorial design methods as computed with Taguchi Methods. *Proceedings of the 2005 IEMS Conference*, Cocoa Beach, FL, pp. 470-478.

[20] Sutterfield, J. S., Conrod S. J. Kelly (2005). "Metrics for Continuous Process Improvement," *Proceedings of the 2005 IEMS Conference*, Cocoa Beach, FL, pp. 370-378.

[21] Sutterfield, J. S., Kenneth R. Brown, Joshua C. Hankins. (2011. "Optimization of Turbine Engine Design Parameters with Taguchi Methods," *Proceedings of the 2011 IEMS Conference*, Cocoa Beach, FL, pp. 220-229.

[22] Taguchi, Genichi (1956). How to Determine Tolerances, *Japanese Standards Association*, Tokyo, Japan

[23] Taguchi, Genichi (1956). *A Text on Design of Experiments*, Electrical Communications Laboratory, Tokyo, Japan, 2nd revised edition

[24] Taguchi, Genichi (1988). *System of Experimental Design: Engineering Methods to Optimize Quality and Minimize Cost*, UNIPUB, Kraus International Publications, White Plains, NY, vol. 1

[25] Yates, Frank (1937). Design and Analysis of Factorial Experiments, *Technical Communication No 35*, Imperial Bureau of Soil Sciences, London

[26] Wright, Paul H. (2002). *Introduction to Engineering*, John Wiley & Sons, Inc., New York, NY

Run Number	Random run order	1 A	2 B	3 AxB	4 C	5 AxC	6 BxC	7 e	Response variable
1	4	1	1	1	1	1	1	1	RV_1
2	8	1	1	1	2	2	2	2	RV_2
3	3	1	2	2	1	1	2	2	RV_3
4	6	1	2	2	2	2	1	1	RV_4
5	1	2	1	2	1	2	1	2	RV_5
6	7	2	1	2	2	1	2	1	RV_6
7	5	2	2	1	1	2	2	1	RV_7
8	2	2	2	1	2	1	1	2	RV_8

Figure 1: Example orthogonal array of type L_8 (2^7)

Pressure (psi)	Gas Temperature (°F) 60 Speed (ft/sec) 150	200	225	300	75 Speed (ft/sec) 150	200	225	300	90 Speed (ft/sec) 150	200	225	300
50	18	20	19	24	34	26	21	13	12	18	19	18
	17	11	12	24	34	20	22	26	12	40	18	21
75	14	15	12	17	42	28	26	15	12	21	11	12
	24	19	18	13	44	26	22	22	23	13	12	23
85	19	16	20	18	40	22	23	15	18	19	16	21
	18	12	13	24	36	20	20	19	19	18	13	23

Table 1 – Original data from turbine engine experiment

Inlet gas temperature (°F)	Inlet airspeed (ft/sec) 150	200	225	300
60	18	20	19	24
	17	11	12	24
	14	15	12	17
	24	19	18	13
	19	16	20	18
	18	12	13	24
75	34	26	21	13
	34	20	22	26
	42	28	26	15
	44	26	22	22
	40	22	23	15
	36	20	20	19
90	12	18	19	18
	12	40	18	21
	12	21	11	12
	23	13	12	23
	18	19	16	21
	19	18	13	23

Table 2 – Modified data from turbine engine experiment

Inlet gas temperature (^oF)	Inlet airspeed (ft/sec)			
	150	200	225	300
60	-2	0	-1	4
	-3	-9	-8	4
	-6	-5	-8	-3
	4	-1	-2	-7
	-1	-4	0	-2
	-2	-8	-7	4
75	14	6	1	-7
	14	0	2	6
	22	8	6	-5
	24	6	2	2
	20	2	3	-5
	16	0	0	-1
90	-8	-2	-1	-2
	-8	20	-2	1
	-8	1	-9	-8
	3	-7	-8	3
	-2	-1	-4	1
	-1	-2	-7	3

Table 3 – Coded data from turbine engine experiment

Inlet gas temperature (^oF)	Inlet airspeed (ft/sec)				
	150	200	225	300	Totals
60	-10	-27	-26	0	-63
75	110	22	14	-10	136
90	-24	9	-31	-2	-48
Totals	76	4	-43	-12	25

Table 4 – Variation among experiments

Source	Component	dof	S	V	F_0(99%)	S'	ρ(%)
S_T	-----	2	1,023.36	511.68	23.52	979.86	0.25
S_S	-----	3	423.82	141.27	6.49	358.56	0.09
S_{TxS}	S_{TxSl}	1	873.51	873.51	40.16	851.75	0.22
	S_{TxSq}	1	101.03	101.03	-----	-----	-----
	S_{TxSc}	1	237.44	237.44	10.92	215.69	0.05
e_1	-----	3	0.00	0.00	-----	-----	-----
e_2	-----	60	1,291.17	21.52	-----	-----	-----
(e)	-----	64	1,392.19	21.75	-----	1,544.47	0.39
Totals	-----	71	3,950.32			3,950.32	100.00%

Table 5: Analysis of variance of turbine engine data

Source	Component	dof	S	V	F_0(99%)	S'	ρ(%)
S_T	-----	2	1,023.36	511.68	23.52	979.86	0.25
S_S	-----	3	423.82	141.27	6.49	358.56	0.09
S_{TxS}	S_{TxSl}	1	873.51	873.51	40.16	851.75	0.22
	S_{TxSc}	1	237.44	237.44	10.92	215.69	0.05
(e)	-----	64	1,392.19	21.75	-----	1,544.47	0.39
Totals	-----	71	3,950.32			3,950.32	100.00%

Table 6: Modified analysis of variance of turbine engine data

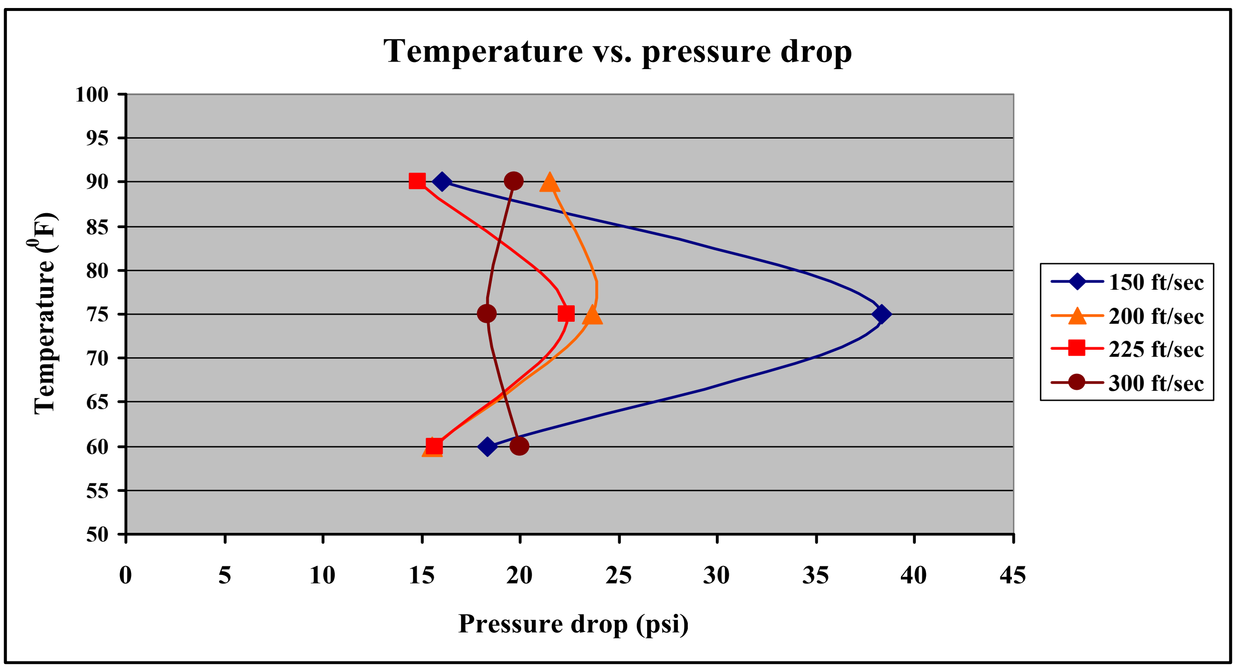


Figure 2: Temperature vs. pressure for lines of constant airspeed

Quality Function Deployment in User-Centered Design

Ali Ahmad and Abdulrahman Al-Ahmari
Princess Fatimah Alnijris's Research Chair for Advanced Manufacturing Technology (FARCAMT)/Industrial Engineering Department, King Saud University- Riyadh11421 - P. O. Box 800 - Saudi Arabia
ali.ahmad.phd@gmail.com; alahmari@ksu.edu.sa

Abstract

Quality Function Deployment (QFD) is often used in quality and marketing applications to relate customer requirements and design features of a product. This paper extends QFD application to user-centered design and usability evaluation. It proposes that user-centered requirements can be used in a QFD. The resulting QFD can then be used for competitive usability evaluations. After that, two real-world applications are discussed: 1) competitive usability evaluation of "indoor grills", and 2) defining usability requirements for a "digital storyteller". The paper concludes by identifying guidelines for using QFD in user-centered design and usability evaluation processes.

1. Introduction

In today's highly competitive markets, companies need to ensure that their products and services meet and exceed customer expectations [1]. QFD is a structured process that takes into account customers' needs and requirements in every step of the design development process [2, 3]. It systematically incorporates customer requirements in design, prototyping, production, and marketing functions [4]. QFD has the potential to increase company's competitiveness by providing better customer focus, reduction in product turn-around time, more streamlined development process, improved documentation, less rework, and enhanced teamwork within the company [1, 5, 6, 7].

User-centered design takes into consideration human capabilities, skills, limitations, and needs into system design and development efforts [7, 8, 9]. According to the International Standards Organization (ISO), user-centered design involves three basic principles [10]:

- End user participation which drives a clear understanding of requirements (user, task, and system)
- Proper functional allocation
- An iterative design process carried out by a multidisciplinary team

This paper discusses the application of QFD within user-centered design activities. Two real-world case studies are discussed. The first case study uses QFD for competitive usability evaluation of "indoor grills". And the second case study uses QFD for specifying usability requirements for a mobile phone "digital storyteller" application. The paper concludes by providing guidelines for using QFD in user-centered design and usability engineering.

2. Background

QFD is traditionally used in engineering and marketing efforts to link customer requirements to product engineering design features [11]. It aims to quantify subjective criteria into objective ones that can be used for product design and manufacturing activities [12]. The following steps are involved in constructing a QFD [13]:

- Determine and weight customer requirements
  - Competitor analysis of customer requirements (Optional)
- Determine design features
  - If known, determine direction of improvement
- Determine interaction between design features
- Determine correlation between customer requirements and design features
- Establish weights for various design features with respect to customer requirements
  - Competitor analysis of design features (Optional)

Several authors, such as [1] and [13], provided reviews on QFD, and discussed its applications, mathematical frameworks, benefits, and possible difficulties in constructing a QFD.

User-centered design deals with evaluating the fitness of use for a product or a service [14]. It emphasizes that a product should be transparent to the task that a user is trying to accomplish and be efficient, intuitive, satisfying, and fun to use [13]. Several tools are commonly used in user-centered design efforts, including [14, 15, 16]:

- User profiling
- Task analysis
- Usability goal setting
- Competitive usability evaluation
- Heuristic usability evaluation
- User-based evaluation

Recently, Hoeft and Mentis identified QFD as one of the contemporary approaches that should be used in user-centered design activities [8]. Nevertheless, no specific guidance was provided on when and how can QFD fit within these activities. Recent literature utilize QFD in user-centered requirements definition for intelligent service systems [17], website design [18], sports earphone design [19], and streamlining e-information for virtual users [20].

This paper discusses two different QFD applications in user-centered design activities: 1) Competitive usability evaluation of existing products, and 2) defining usability requirements for a new product. Hence, the case studies extend QFD application to competitive evaluation and usability goal setting [8, 9].

3. Method

The application of QFD in user-centered design activities is illustrated using two real-world case studies. The first case study uses a QFD for competitive usability evaluation of “indoor grills” for a large US appliance manufacturer. The second case study uses a QFD for defining usability requirements for a new mobile phone “digital storyteller” application for a large Japanese electronics manufacturer. Both case studies included the following activities:

1) Defining and ranking user-centered customer requirements
2) Defining product design features
3) Establishing the relationships between the customer requirements and the design features
4) Determining weighted and relative scores for the different design features with respect to the weighted customer requirements

The lessons learned from both case studies were used to develop guidelines for when and how a QFD can be used in user-centered design activities.

4. Results

4.1. Case Study 1: Competitive Usability Evaluation of "indoor grills"

A major US appliance manufacturer wanted to benchmark the current market for "indoor grills". Three manufacturers of such grills were included in this evaluation: Breville, Cuisinart, and George Foreman. A QFD was used to relate customer requirements to various grill design features, see Figure 1.

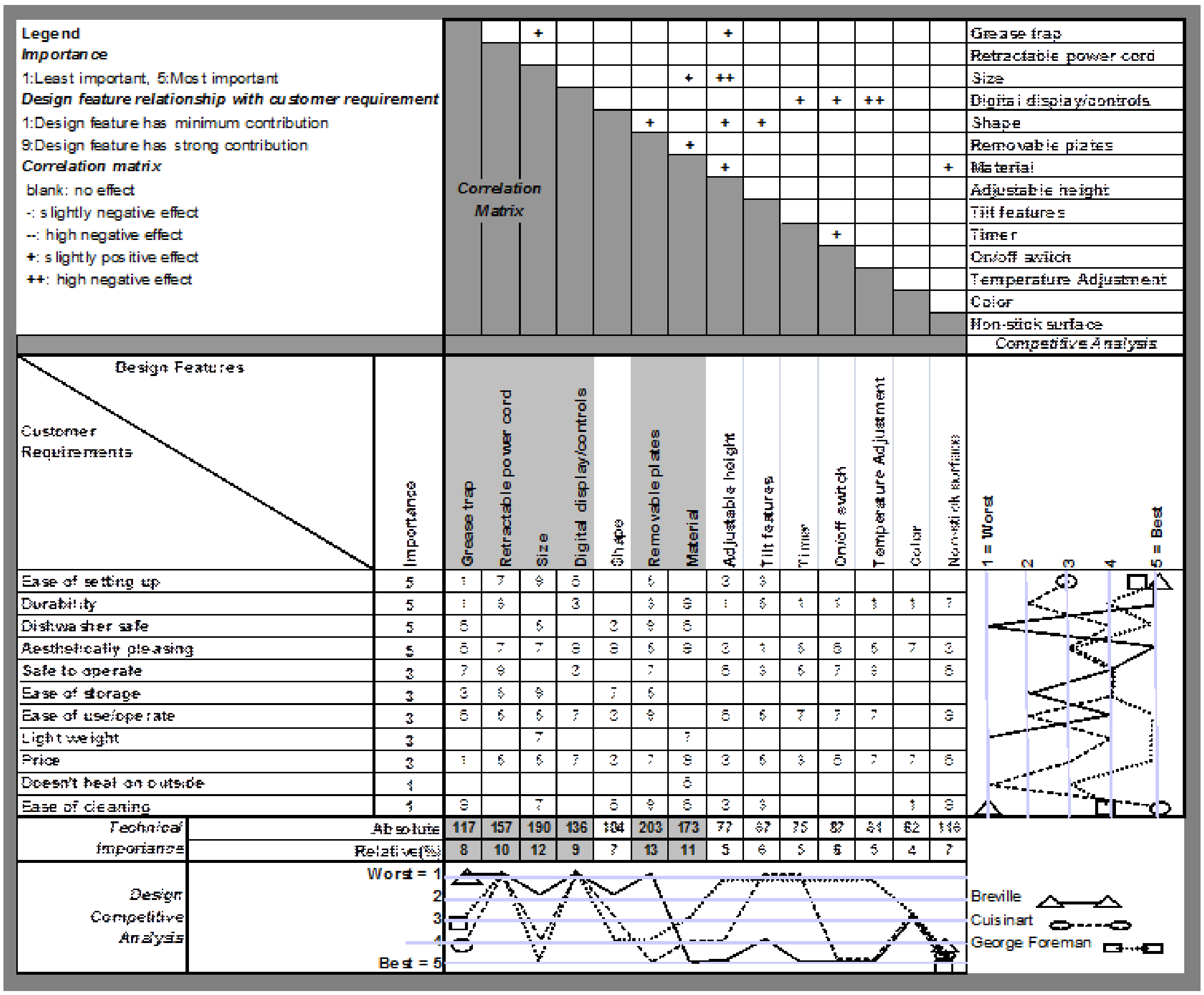


Figure 1. Competitive usability evaluation of "indoor grills"

The process of constructing the QFD started by capturing and ranking customer requirements through a brainstorming session that involved four grill users. The ranked customer requirements appear on the left wall of the QFD. The ranking scheme ranged from 1 (for least important) to 5 (most important). For example, ease of setting up, durability, dishwasher safe, and aesthetically pleasing were identified as the most important customer requirements. After that, various design features were obtained by studying different grills, their manuals, and similar home appliances. The design features appear on the ceiling of the QFD. The design features include grease trap, retractable power cord, size, digital display/controls, and shape, among others. The roof of the QFD establishes the dependencies that may exist between the design features. The coding scheme used was:

- blank: no effect
- -: slightly negative effect
- --: high negative effect
- +: slightly positive effect
- ++: high negative effect

For example, there is a high positive effect between adjustable height and grill size. Then, the grill design features were compared across the customer requirements. If the design feature contributed strongly to a customer requirement, it had a score of 9, if the design feature contributed minimally to a customer requirement, it was given a score of 1; if the design feature didn't contribute to a particular customer requirement, the cell was left blank. The relationship scores between the design features and the customer requirements appear as the main body of the QFD. Once all relationships were mapped, a weighted score for each design feature was obtained by multiplying the importance ranking for each customer requirement with its relationship to the design features and summing them up across the design features. The relative score was then calculated by dividing each design feature score by the total sum across the design features and expressed as a percentage. To determine which design features best address the customer requirements, a cut-off relative percent score of 8 was arbitrary used (see shaded design features). These design features are (in order of priority): Removable plates, size, material, retractable cord, digital display, and grease trap. In addition to comparing design features across customer requirements and among themselves, the QFD conveys two competitive comparisons: 1) across design features are displayed as the foundations of the QFD (based on different grills); 2) the right wall compares the different grills across the customer requirements. For example, the results of the QFD competitive evaluation indicate that Breville may want to benchmark against George Foreman with respect to having removal plates, and that Cuisinart should benchmark against George Foreman in terms of ease of setting up.

4.2. Case Study 2: User-centered design requirements of a "digital storyteller"

A major Japanese electronics manufacturer wanted to determine a set of user-centered usability requirements for a new mobile phone "digital storyteller" application. A QFD was used to evaluate the application concept and relate customer requirements to various design features, see Figure 2. The process of constructing the QFD started by capturing and ranking customer requirements through a focus group involving eight mobile phone users.

The focus group took the form of a discussion session facilitated by the evaluators. The users provided their inputs on what a mobile digital-storytelling application should be able to do. The inputs were then placed on "Post it" notes and displayed on a whiteboard. The facilitators then worked with the users to separate the various inputs into two groups: user-centered customer requirements (what the application does), and design features (how the application does them). After that, the facilitators worked with the users to establish weights for the various customer requirements by counting votes. The ranked customer requirements appear on the left wall of the QFD. The ranking scheme ranged from 1 (for least important) to 5 (most important). The customer requirements include: Easy to use, using narrative, intuitive, and ability to manipulate order/timing of presentation.

After that, additional design features were obtained by studying photo websites and digital storytelling online resources and applications. The design features appear on the ceiling of the

QFD, and include: Adding photo details (description, date/time …), modifying font size, type, and color, adding narrative, having pre-set backgrounds/templates, adding background music, having storytelling templates, recording voice, uploading to home computer for advanced editing, adding motion/animation effects, and sequencing/timing pictures.

The roof of the QFD establishes the dependencies that may exist between the design features. The coding scheme used was: Blank: no effect, -: slightly negative effect, --: high negative effect, +: slightly positive effect, and ++: high negative effect. For example, there is a high positive effect between making a scrap book and adding photo details.

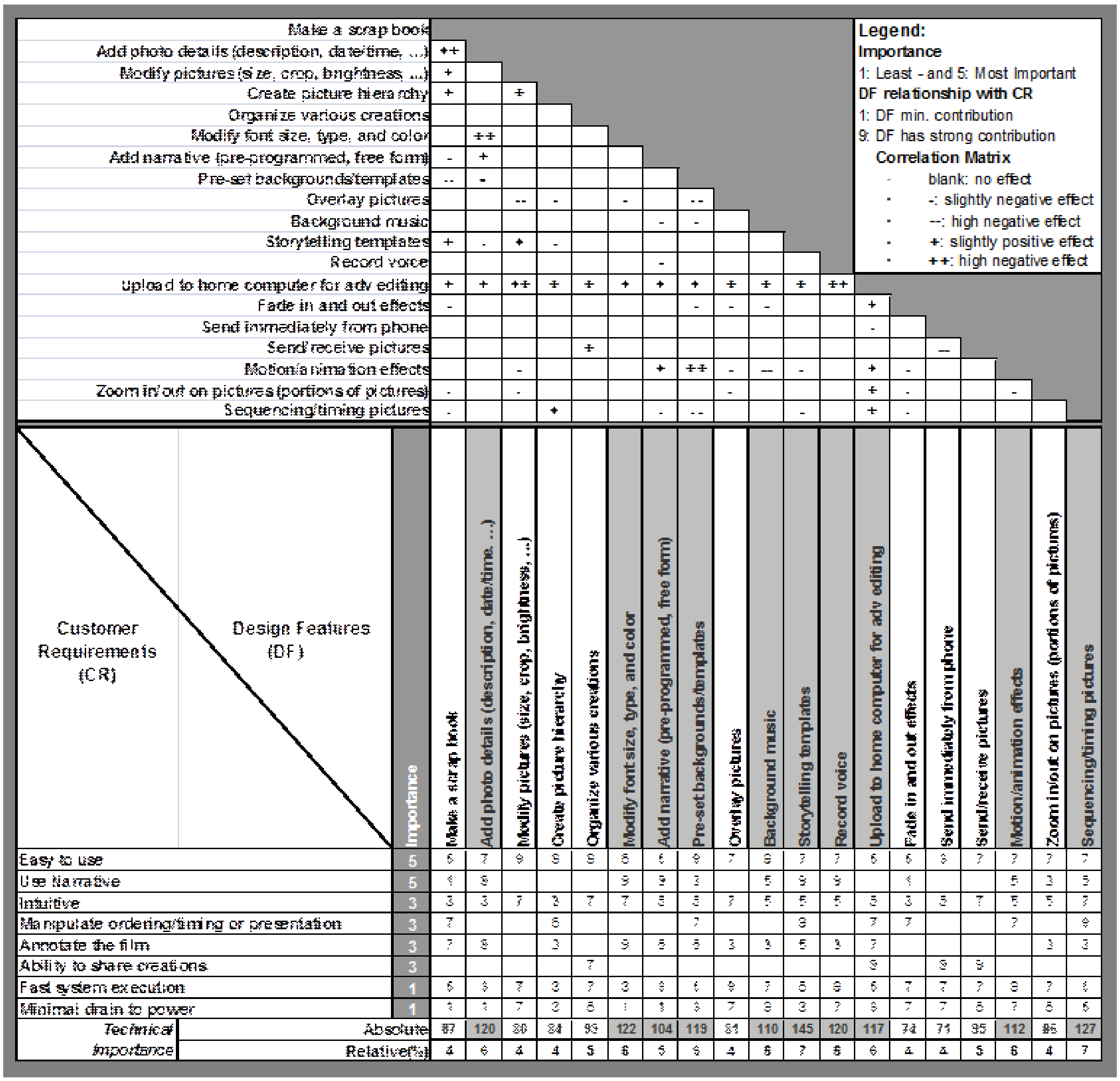


Figure 2. Usability requirements for a mobile phone "digital storyteller" application

Then, the design features were compared across the customer requirements. If a design feature contributed strongly to a customer requirement, it had a score of 9, if a design feature contributed minimally to a customer requirement, it was given a score of 1; and if a design feature didn't contribute to a particular customer requirement, then the field was left blank.

The relationship scores between the design features and the customer requirements appear as the main body of the QFD. Once all relationships were mapped, a weighted score for each design feature was obtained by multiplying the importance ranking for each customer requirement with its relationship to the design features and summing them up across the design features. The relative score was then calculated by dividing each design feature score by the total sum across the design features and expressed as a percentage. To determine which design features that best address the customer requirements, a cut-off absolute score of 100 was arbitrary used (see shaded design features). This led to determining that the design features that best address customer requirements and may lead to a best-in-class design include: Adding narrative, having pre-set backgrounds/templates, having storytelling templates, and uploading to home computer. Hence, the QFD can be used for usability goal setting to determine design features that respond to customer requirements, and potentially increasing their satisfaction.

5. Discussion and Conclusions

Two real-world case studies were used to demonstrate when and how QFD can be used in user-centered design activities. The first case study showed that QFD can be used to conduct a competitive usability evaluation between existing products across both design features and user-centered customer requirements. The second case study showed that QFD can be used to derive user-centered customer requirements and use them to prioritize design features to obtain a best-in-class design.

This paper extends literature by providing two novel QFD applications [1, 3, 13]. It elaborates on how a contemporary tool such as QFD can advance the state-of-the-art in user-centered design and usability evaluations [9, 17, 18, 19, 20], and provides a recipe for QFD construction [8, 14, 15, 16]. Based on the lessons-learned during the case studies, several guidelines can be extracted:

- The key aspect in using QFD in user-centered design efforts is properly defining customer requirements
- Focus groups can be used for QFD construction
- QFD provides a good vehicle to conduct competitive usability evaluations

6. References

[1] Chan, L-K, & Wu, M-L (2002). Quality function deployment: A literature review. *European Journal of Operational Research, 143*, pp. 463-497.

[2] Day, R.G. (1993). *Quality Function Deployment: Linking a Company with Its Customers*, ASQC Quality Press, Milwaukee, WI, USA.

[3] Schauerman, S., Manno, D., & Peachy, B. (1994). Listening to the Customer: Implementing Quality Function Deployment. Community College. *Journal of Research and Practice, 18*, pp. 397-409.

[4] Akao, Y.(Ed., 1990). *Quality Function Deployment*, Productivity Press, Cambridge MA.

[5] Cohen, L. (1988). Quality Function Deployment. *National Productivity Review, 36* (2), pp. 197-208.

[6] Chang, C.A. (1989) Quality function deployment (QFD) processes in an integrated quality information system. *Computers and Industrial Engineering, 17* (1-4), pp. 311-316.

[7] Wang, W-S. (2012). Exploring the quality function deployment method: A case study on the restaurant industry in Taiwan. International Journal of Research Studies in Management. Available online: http://www.consortiacademia.org/index.php/ijrsm/article/view/160, accessed September 22, 2012.

[8] Hoeft, R.M., & Mentis, H.M. (2009). Beyond User-Centered Design: Applicable Concepts from Complementary Approaches. In *Proceedings of the Human Factors and Ergonomics Society 53rd Annual Meeting*, pp. 1844-1848.

[9] Jin B-S, Ji, Y-G, Choi K., & Cho, G. (2009). Development of a usability evaluation framework with quality function deployment: From customer sensibility to product design. Human Factors and Ergonomics in Manufacturing, 19(2), pp. 177-194.

[10] International Organization for Standardization. (1999). *Human-centered design processes for interactive systems* (ISO 13407:1999[E]). Geneva, Switzerland: ISO.

[11] Bahil, A.T., & Chapman, W.L. (1993). A Tutorial on Quality Function Deployment, *Engineering Management Journal, 5* (3), pp. 24-35.

[12] Sullivan, L.P. (1986). Quality Function Deployment. *Quality Progress*, June, pp 39-50.

[13] Carnevalli, J.A., & Miguel, P.C. (2008). Review, analysis and classification of the literature on QFD—Types of research, difficulties and benefits. *International Journal of Production Economics, 114*, pp. 737-754.

[14] Vredenburg, K., Isensee, S., & Righi, C. (2001). *User-centered design: An integrated approach*. Prentice Hall.

[15] Nielsen, J. (1993). *Usability Engineering*. Boston, MA: Academic Press.

[16] Mayhew, D.J. (1999). *The usability engineering lifecycle: A practitioner's handbook for user interface design*. San Francisco, CA: Morgan Kaufmann.

[17] Garzon, V.A. (2011). Application of user involvement and quality function deployment to design intelligent service systems. In Proceedings of the Fourth International Conference on Advances in Computer-Human Interactions (ACHI2011), pp. 48-52.

[18] Islam, R., Ahmed, M., & Alias, M.H. (2007). Application of quality function deployment in redesigning website: A case study on TV3. International Journal of Business Information Systems, 2(2), pp. 195-216.

[19] Tu, N., Zhang, T., He, Q., Zhang, H., & Ki, Y. (2011). User-centered design in new product development: A case study in developing new sports earphone. The 2011 International Conference on Computer and Management (CAMAN), Wuhan, May 19-21.

[20] Taha, A. (2006). Streamline e-information service for virtual users: A quality function deployment (QFD) approach. In C. Khoo, D. Singh & A.S. Chaudhry (Eds.), Proceedings of the Asia-Pacific Conference on Library & Information Education & Practice 2006 (A-LIEP 2006), Singapore, 3-6 April 2006 (pp. 141-147).

Quality Improvement in a Textile Manufacturing Plant Using a Database Management Traceability System

[1]Tamer A. Mohamed and [2]Khaled Nounou
[1]*The British University in Egypt*, *Cairo, Egypt*
[2]*Nountex, Cairo, Egypt*
tamer.mohamed@bue.edu.eg

Abstract

Textile manufacturing is a highly competitive and specialized business that continually strives for high quality fabric as well as higher productivity to meet customer needs or customer goodwill. The manufacturing of textile is complex and composite in its structure, it encompasses multiple treatment and processes during the manufacturing stages. The process starts with raw material (thread) that undergoes different processes to be converted to a finished fabric. In fact, managing the raw fabric production process through each phase is a big challenge. Thus textile companies have to trace the textile from initial raw material step to the finished fabric in order to be able to improve the output quality of the manufactured fabric. The objective of this paper is twofold, first to develop a database management traceability system for a typical textile manufacturing processes, and then the second step is to use this traceability system to highlight the main areas of improvement projects that the company should focus its effort on. This traceability system will assist the company to improve its product quality by targeting the vital few areas of improvement in the production line and thus enhance profitability and improve competitiveness.

1. Introduction

For an adequate understanding of the process, it is crucial to identify the flow process of fabric production. During textile manufacturing; fabric must undergoes a rigid inspection process through each phase, assuring that each sole fabric passes through specified process and treatments. The fabric roll undergoes multiple treatments and processes, i.e., washing, dyeing, stentering, finishing, size and cutting. These processes and treatments include exposure to harsh treatments, such as: water, steam, and cogent chemicals during the dyeing phase, high temperature in the stentering phase and the cutting down into small chunks (during size, cut and sewing phases). The dyeing process is considered to be the main tracing obstacle for any textile industry, because tracing the fabric roll during such a process is an immense challenge. The manufacturing processes must be distinguished, starting from the initial process to the finished fabric process, i.e., from the receipt of yarn, the wrapping process, the knitting process, the dyeing process, the stentering process, and inspection process. Each process needs to be individually identified and then the relationship between the processes would be examined thoroughly. The aim of this paper is to design a traceability system suitable for tracing the textile manufacturing processes, in such a way that provenance of the fabric can be recognized after being sized, cut, sewed and delivered to customers.

Many researchers enlightened different definitions of traceability. Töyrylä [15] defined traceability as the ability to sustain the uniqueness of the product and its provenance and which provides a clear view of the sequence of events that happen during the manufacturing process, the origin of product, and it's not limited to the physical identification of the product. Bulut and Lawrence [3] pointed out that traceability can be defined as the possibility to locate and trace the origin or the usage of the product through identification technique.

Töyrylä [15] claimed that a wide range of technologies can be attributed to automatic identification and data documentation. Documenting data by identifier artifacts is in itself a traceability technique. The identifier means a unique number or name, which uniquely identifies each artifact [8]. Rönkkö [14] believed that automatic identification provides an automated flow of the identity of product. Tracing and identifying products, implementing identity reader and software system for identification code, were needed. Some methods for tracing or extracting product identity include using barcode and radio frequency identification (RFID).

Ilie-Zudor et al. [5] explained that RFID can be used as a technology of high potential feasibility in many areas of supply chain and possess many applications when processes require automatic identification.

Töyrylä [15] stated that the most noticeable application of traceability is the usage of the traced data in the product recall by providing accurate information that helps in identification, tracing and tracking of the defective product, and locating the product from the total population. Traceability is one of the customer requirements, that provides detailed information on the history of product and raw materials used.

Leipziger [9] suggested that the motive for tracing the defective item or product is to determine which batch needs to be recalled and thus keeping up records, leads to a recall of fewer products. Therefore a good traceability system is crucial whenever the cost of product recall is very high.

According to Leipziger [9], to obtain a precise identification of data, manufacturers or companies must store or keep precise records for the following data: First, the ingredients referring to all the data input or use starting from raw material and ingredients until the production of a single product must be recorded; keeping records for all products produced. Second, the products used in each processes to develop the final product. One should keep information about each product and the ingredient used. Finally, the product labeling, that provide better tracing and documentation should also be recorded.

Dejonckheere et al., [6] pointed out that observability (tracing) helps to improve production, delivery, usage, and disposal of products.

Xu [16] believed that implementing RFID technology for product traceability provides solid benefits by improving production planning and scheduling; inventory control by better inventory visibility; process and quality control; and better management of package coding.

Khabbazi, et al. [7] claimed that the aim of any traceability system is gathering the required information within quality factors. Therefore, tracing the product life cycle requires the development of information systems.

Ranasinghe et al. [13] illustrated that the benefits gained from adopting traceability using RFID can be categorized as having tangible and intangible benefits. Tangible benefits are derived from providing an improvement on efficiency and effectiveness; which increase the effectiveness of manufacturing, processing, tailoring and distribution. It can also increase the efficiency of managing orders, utilizing the picking process, and database update timed, so that it is close to real time. On the other hand, the intangible benefits include being able to access better information; such as reliable and more accurate information about each item, tracing of the product through each stage of treatment or process.

An automatic traceability system helps to utilize raw material information efficiently in the forestry-wood production supply chain. This will assist to maximize the raw material yield, and to monitor the environmental impact, by linking the relevant information to the traced objects [2].

Andersen [1] stated that successful exchange of information depends on the ability to manage and maintain data. This can be done by storing information in such a way that it can be easily accessed, kept up to date, and making the optimum use of it.

It is worth saying here that Spekman and Sweeney [12] showed that the use of RFID for product tracing has some limitations on accuracy and interference in addition to some organizational problems like people who have to get used to the new techniques and guidelines.

According to Rönkkö [14], to enable traceability for a supply chain object, two main things must exist: centralized database, and network identity readers.

Access database can store all kinds of information, use queries for analyzing the data and construct and create report and charts with custom need. A database management system offers the user a flexible access to their data, and facilitates the process of transforming the data into useful information. Such a system includes dbase, Paradox, MS-Access and Oracle. These systems provide the users the ability to create and obtain information from their database. The biggest advantage of a computerized database system over a manual filing system is flexible access, speed and accuracy.

The textile industry is missing research on how traceability is beneficial and can be used to enhance improvement. The industry lacks the ability to determine the source of raw material for each fabric roll as well as the ability to record the properties of each roll in the dyeing process. These problems direct us to the main goal which is building a traceability system. Furthermore it leads to the need for an information system to be able to manage, store, and retrieve data, which is going to be carried out using a database system. The data for the whole manufacturing processes should be collected, stored and organized in a way which enables traceability.

The paper consists of 5 sections. Section 2 discusses the methodology in designing the traceability system that represents the database modeling phases and includes a description of database. Section 3 summarizes the use of database for quality improvements. Section 4 provides a discussion on the impacts of implementing traceability system in textile manufacturing. Conclusion and recommendations are discussed in section 5.

2. Methodology

The initial point for designing a traceability system is to study its needs and objectives. The objectives of any traceability system are to provide the identity of items or batches of all raw materials and primary supplied materials which provides information on when, where and how they were processed into finished products; Identify items of all manufactured products and to whom they are supplied, and finally, linking all these data through documentation and record keeping system.

Designing a traceability database is a complex and challenging task because a traceability system is associated with many processes and involves many people. In practice, designing a database for an industrial process involves more than one member: designer, programmer, and the end user (who are only concerned with entering data). The programmers must have the required knowledge for developing the database. The designer, on the other hand, is the one who transform the user requirements into a language that can be understood by the programmer.

The objective of database design is to link all processes and to provide analysis and reports so that a company can trace a fabric roll through its life cycle. The initial goals when developing database are to clarify the information that should be stored in the database; to identify their characteristics; and to develop the relationships between them.

The steps for designing database system are described as follow:

- System Requirements
- Data Modeling
  - Conceptual data model
  - Relational (Logical) data model
  - Physical data model
- System implementation

2.1 System requirements

The data and analysis requirements are crucial parts of database design. They facilitate the communication between the designer, the organization, and the end user. The purpose of this step is to clarify the data requirements of database objects. It requires examining and analyzing the process to recognize and to facilitate the relationship between processes. In this part, the current textile manufacturing processes should be identified. The requirements for attaining a traceability system include but not limited to the following:

- Identification of Lot number.
- Recording supplier and yarn data.
- Setting up relationships between lot number, supplier, and yarn.
- Identification of each knitted fabric.
- Identification of each dyeing batch.
- Provide relationships between the dyeing batch and knitted fabric.
- Recording information on detailed processes and linking all processes together.

2.2 Data modeling

Data modeling is the second step in developing a database. It is a graphical representation of real world complex objects and events. The data modeling illustrates the characteristics and relations of data structure with the purpose of supporting real world problems. The model designs are expect to truly represent the user requirements. The data modeling ought to serve not only to facilitate the communication between the designer, programmer and end user, but also to consider implementation of the data on the computers. It will tell how the data are represented and manipulated in the database system [10]. For this reasons, the data modeling is divided into three phases: Conceptual data model, logical (relational) data model and physical data model.

The conceptual and logical data models identify entities, their characteristics, and clarify the relationships between one another. They encompass different modeling technique that defines the data structure and relationships. The two crucial modeling techniques used in the conceptual and logical data model are the E-R model and the relational model. The E-R model represents entities and relationships between them. While the relational model displays how the data will appear in the database system in the form of database tables [11].

The final phase of data modeling involves combining the E-R and the logical models into one model (called the physical data model). The Microsoft Access database can then take physical data model and converted it into a graphical user interface during system implementation.

The physical data model is presented below in Figure 1. It shows the fabric data model of the textile manufacturing process with entities, the associated relationships, and database tables. These are explained below in Subsection 2.2.1 and 2.2.2.

The relationship lines are represented according to Crow's notation [4]. There are two lines: a solid line indicates that the relationship is identified, while a dashed line refers to a non-identified or optional relationship.

2.2.1. Entities and relationships:

The text below will describe the entities and their relationships developed in the database:

- Lot number identifies the yarn, and yarn is identified by one or more lot number.
- Lot number identifies the supplier, and each supplier is identified by one or more lot Number.
- Supplier produces many yarns type, but each yarn type is produced by only one supplier.
- Beam gathers yarn together, or many yarns are gathered or wrapped into one beam.
- Knitted fabric uses many beams, or many beams are used for knitting only one fabric.
- Fabric master identifies many knitted fabric, or many fabrics are identified by a fabric master.
- An operator monitors many knitted fabric, or many knitted fabric is monitored by an operator.
- A machine knits many fabrics, or many fabrics are knitted by one machine.
- Operator may control many machines, or many machines may be controlled by an operator.
- The dyeing machine colors many fabric batches. Many fabric batches are colored by a dyeing machine.

- Operator monitors many dyeing batches, or many dyeing batches may be monitored by an operator.
- A primary inspection process identifies many defects, or many defects are identified by a primary inspection process.
- The stentering machine adjusts many dyed fabrics, or many dyed fabric may be adjusted by a stentering machine.

2.2.2. Tables definition: The tables shown in the physical data model (Figure (1)) explains the type of data that will be stored in the database system. The tables are designed based on the requirements and the data that need to be collected. It constitutes 13 tables. It is clear that each entity (table) contains a primary key (PK) to uniquely identify one row from another. The primary key is unique for each entity, its value must not be equal to null, and should not be changed once recorded. In addition to the primary key, some entities (tables) might contain a foreign key, i.e. a foreign key is a field (or fields) that points to the primary key of another table. The purpose of which is to ensure referential integrity of the data. All key fields are underlined and placed at the top of table.

In tables shown in Figure (1), the required attributes are indicated by boldface, while the optional ones are left in standard form as follows:

Supplier table: This table is created to store all data concerning the supplier such as; name, company, phone, email, etc. All supplier data is stored in the database, and every supplier is given an identification number (Supplier ID).

Yarn table: This table stores the yarn data, and Yarn ID is a primary key given for each new yarn entry in the database, which uniquely identifies yarn characteristics, such as yarn type, number of count, filament number, plies, mixing ratio, and yarn color and count system.

LotNo table: This table is designed to link the supplier with yarn table from one side, and beam table from the other side. Every new Lot is given a new LotNoID, which identifies the supplier and yarn.

Beam table: This table stores the data of the wrapping process, it contains beam ID which is given for each beam to be considered an identifier, with yarn ends indicating the number of yarn bobbin used in the process, beam length, net weight, gross weights, and beam manufacturing date.

Fabric Beam table: This table relates the fabric table with the beam table. It is created to facilitate the relation between the fabric and beam, by creating a one-to-many relationship instead of many-to-many.

Fabric Master table: This table stores data about all the produced fabric. Each fabric type is given a fabric code that describes the fabric type and width. Each time a new fabric type is produced, a new code is set.

Fabric table: This table stores the data related to the knitting process. A fabric ID is a primary key. Once a new fabric is knitted, it is given a new ID. All the knitting data is stored in this table such as, fabric code, fabric length, weight, knitting date, machine ID, operator ID, shift, and the primary inspection data.

Dyeing table: This table refers to the dyeing process; a dyeing batch ID is given for each new batch, machine ID, color ID, operator ID, and dyeing comments.

Dyeing Fabric table: This table is concerned with the stentering and finishing process and contains dyeing batch ID, fabric ID, stentering date, stentering comments, first and second grade data, and final inspection details.

Dyeing Color table: This table stores all data about the dyeing colors. It contains Color ID, color name, and color number

Defect table: This table stores all defect types; a defect ID is used to refer to each type.

Operator table: This table stores operator names, with each one given an ID.

Machines table: This table stores all machines data. It contains Machine ID, machine type, department name, machine width, machine gauge, and source (origin) of machine.

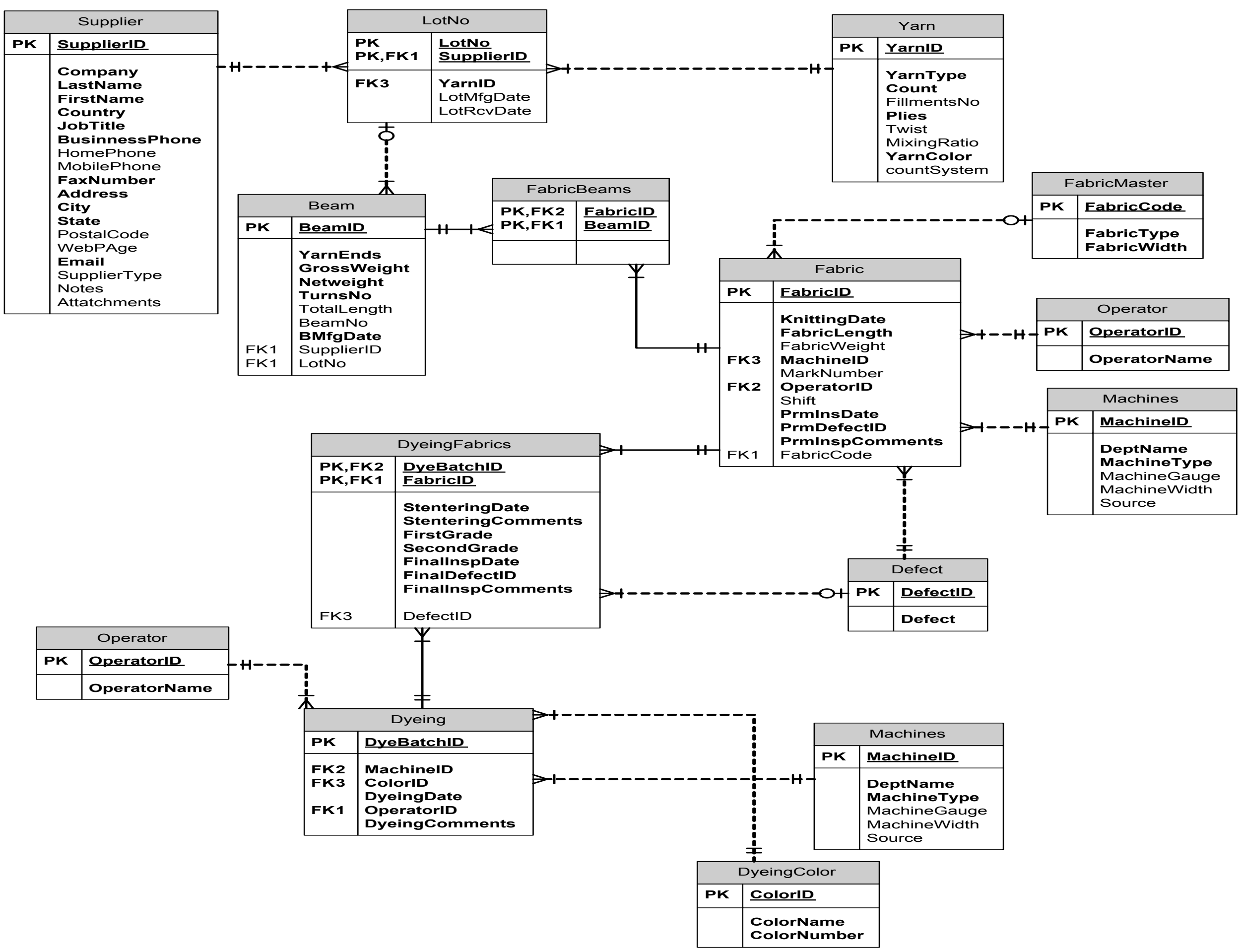


Figure 1. Physical data model

2.3 System implementation

This is the step of converting the physical data model into a graphical user interface program. Microsoft Access was chosen to design and develop the database, which is simple enough to trace the fabric roll and develop the required data analysis.

Once the physical data model is established, and all relationships are tested and approved by the system designer and user, a graphical user interface will be created to facilitate the storage of data. In the database, the user first sees a main menu as shown in Figure 2(a). This main menu contains 5 main buttons: the basic (master) data, transaction data, reports, charts, and fabric roll barcode label. Mainly, basic and transaction data are created for storing data, whereas the reports, charts, and fabric roll labels are used for retrieving and analyzing data. They will be discussed in more detail in the use of database for quality improvements (Section 3).

The basic data menu contains forms for permanent data, as shown in Figure 2(b) about: yarn, supplier, fabric master file, dyeing color, defects, machines and operators. These tables are created only once and are updated as new items or units are used. They are used as reference tables, where each table contains an identifier. In this way, just using the ID, all details referring for supplier ID, yarn ID and others IDs can be retrieved. The transaction data shown in Figure 2(c), contains forms for wrapping, knitting, primary inspections, dyeing, stentering, and the final inspection. It usually describes a day to day process. Figure 2(d) and Figure 2 (e) shows the reports and the charts that can be used to retrieve data from the database.

The use of the above database starts when the company (responsible for producing fabric) lists their requirements of different yarn types (raw material). For tracing purposes, once the yarn is received by the company, the following steps must be done:

- The yarn data is stored in the yarn form and the supplier data recorded in supplier form.
- The received Yarn LotNo must be uniquely identified every time the company receives new yarn shipments. The LotNo table is a crucial table; it is designed to identify each yarn lot uniquely. This is initial step for achieving traceability. LotNo must remain traceable from the receiving point and throughout production. The identification of both the supplier and the yarn must be recorded in the LotNo table, thus LotNo creates a relationship between the Supplier ID, and Yarn ID.
- The next step is the wrapping process where a number of yarn bobbins (ranging from 300 to 600 bobbins) having the same lot number are used in the wrapping process such that one lot number creates a number of beams. In wrapping form, a beam sub form was created, so that all the beams created from the same lot number are recorded. Once a beam of yarn is wrapped, the knitting process starts, each knitted fabric is made up of many beams and is a unique fabric ID, using an invisible barcode label. The fabric beams sub form found in the knitting form provides the data of the beams used each in each fabric. To link the knitted fabric with the LotNo table, a FabricBeam table contains two attributes: a Beam ID and Fabric ID, which links the fabric table with beam table is created. These enable the traceability of fabric back to the yarn type.

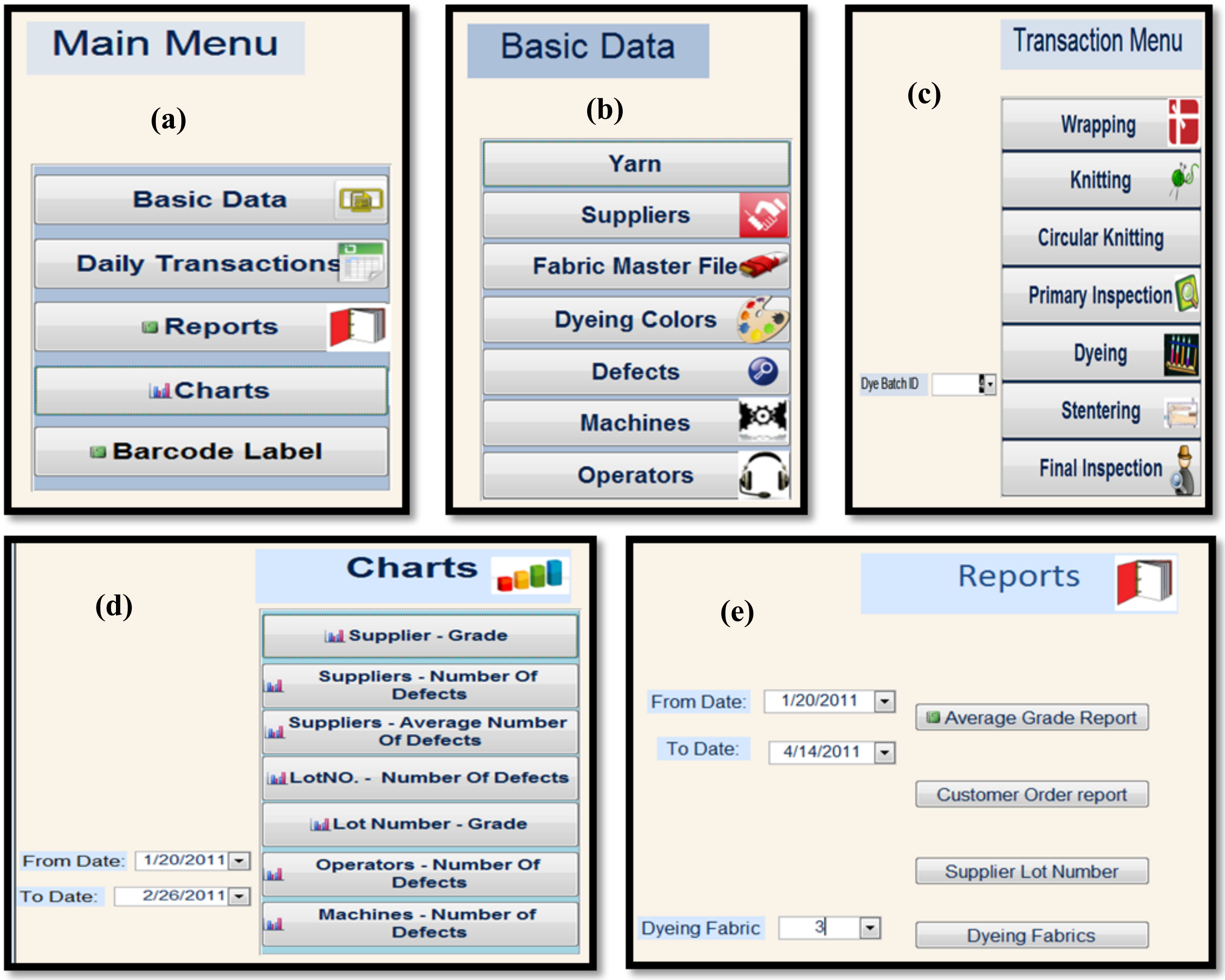


Figure 2. Database menus

- A very important process, following the knitting process is the primary inspection where the inspector has to scan the fabric's invisible barcode (using a florescent light scanner). All knitting data concerning this fabric will be automatically displayed on the computer terminal. The inspector then has to enter the primary inspection date, primary defect type, and primary inspection comment.
- After the primary inspection, the fabrics pass through the dyeing process where a number of fabrics are placed in a batch. The identification of dyeing batches including the dyeing data must be recorded. A fabric sub form is created in the dyeing form, such that for every Dyeing Batch ID, the database user will be allowed to select and enter the fabric ID that belongs to the dyeing batch.
- Once dyed, each batch is sent to stentering and final inspection one at a time; first, the user needs to identify the dyeing batch ID, then the fabric belonging to these batches will appear in the stentering screen and the final inspection screen so the user can enter the results obtained from the processes. If

the user forgets to choose the dyeing batch ID, no data will be displayed in the stentering screen.

- Packaging and labeling: The final stage after the final inspection is performed on the fabric is the packaging and labeling. Once the invisible barcode on the fabric is scanned using a fluorescent light, using the database the fabric information is displayed on the screen that just requires printing in the form of a label and attach it to the package.

3. Using the database for quality improvement

The principle reasons for implementing a traceability system were to better manage and control the textile manufacturing processes. A large number of usages were observed from constructing a traceability system in an industrial company. The use of traceability data can be categorized into: material flow management, segregation, measurements and analysis of processes. It enables the company to identify the details and retrieve the history of the fabric rolls owned by an individual customer. It can be used by the company to provide customers with full data on the status of the fabric being manufactured, including details data on the raw material used, all the operations that the fabric was involved in, primary inspection data, data concerning the dyeing and finishing processes, and an indication of the quality of the fabric roll in the final inspection sections.

Traceability data enables the company to produce a fabric label, which can be used to route or trace the shipments from the manufacturer throughout the supply chain to the customer. Segregation application mainly identifies traced items with given characteristics.

In case of quality problems, traceability data provides precise data concerning a damaged fabric. This application enables the company to identify all fabric rolls gathered in one batch during the dyeing process. In case a need to identify fabric rolls in a single batch arises the manufacturer uses the dyeing batch serial number to directly retrieve (recall) all fabrics rolls. Queries were implemented in the database to create the combination of multiple linkages in order to perform the desired analysis and results.

Moreover, traceability data collected enables the company to analyze the manufacturing processes, including the performance of the machines and operators and the number of defects associated with each lot number and suppliers.

In the quality control department, traceability data enables the company to better manage, control and trace the source of defects. Using the database, charts can be created to graphically represent the number of defects resulting from each process. There are 6 options to choose from to provide statistical evaluations of the number of defects, and two combo boxes that enable the user to identify the desired date (from: and to: date), as shown in Figure 2(d).

The traceability data enables the company to relate the number of defects with each yarn lot number. Figure 3 graphically displays the number of defects contributed from each lot number. The lot number F780 supplied by CSA has the highest number of defects 80, which can provide an indication of the root cause of the fabric defects. This allows the company to better analyze the number of defects contributed from each lot number.

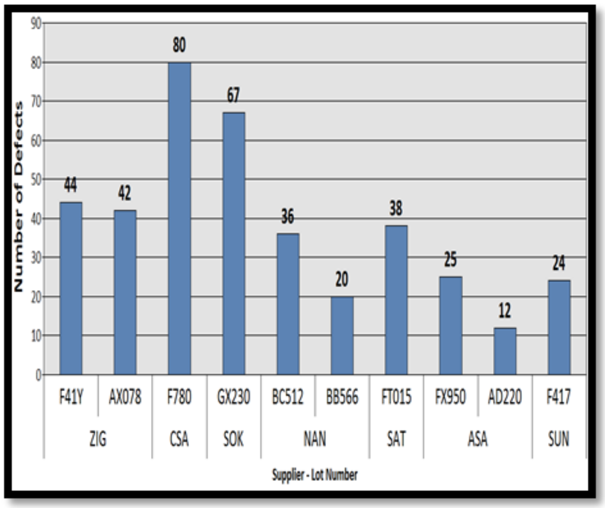


Figure 3. Number of defects by lot number

Moreover, using traceability data, the company was able to evaluate the quality of each supplier by presenting information about the average number of defects associated with each supplier. Figure 4 provides a graphical display of the number of defect from each supplier. Using analysis from this graph enables the company to differentiate the good suppliers from the suppliers that requires developments.

The analysis of variance for the data of the average number of defects per lot by each supplier revealed that the difference between suppliers is significant (P-Value = 0.0001). All residual plots revealed no violation to the ANOVA assumptions. Some suppliers' quality is significantly better than others. SOK and CSA were found to have quality of submitted batches that are significantly lower than others. These are the suppliers that need attention from the management to improve their quality.

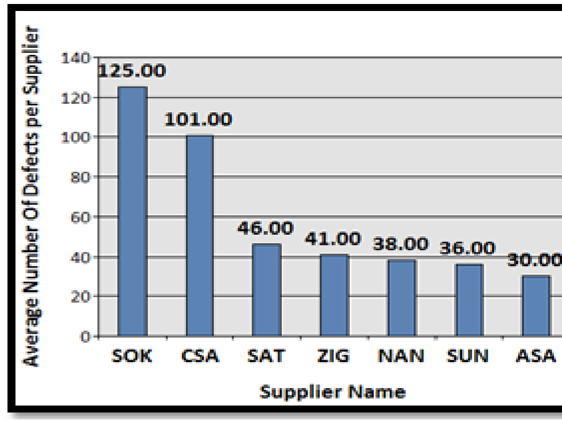


Figure 4. Average number of defects per lot by each supplier

Furthermore, the company was able to relate the fabric quality with supplier data. Figure 5 graphically displays the supplier raw material with the quality (first grade vs. second grade) of the fabric roll.

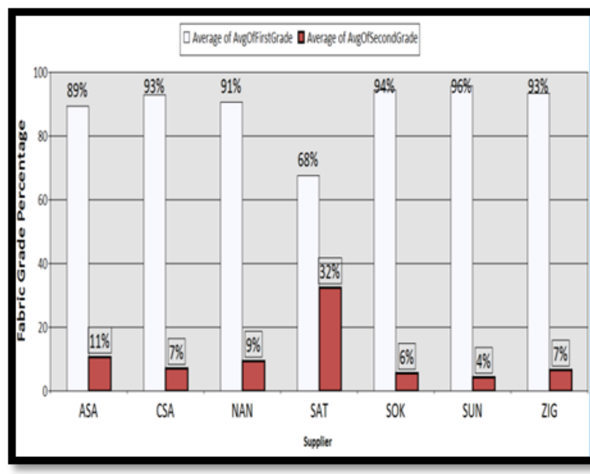


Figure 5. Average fabric grade by supplier

Figure 6 presents a graphical display of the number of defects made by each operator. A Pareto chart was used to visualize the operator performance on different time intervals (weekly, monthly or even yearly). This chart allows the company to relate number of defects by operator, which can be further analyzed to manage the operator performance. The operators in the manufacturing line can be given a reward or penalty based on their individual performance. In the chart below, the operator name Emad Menam and four other operators have 4 defects in this pre-specified period of time, which is the highest among their peers.

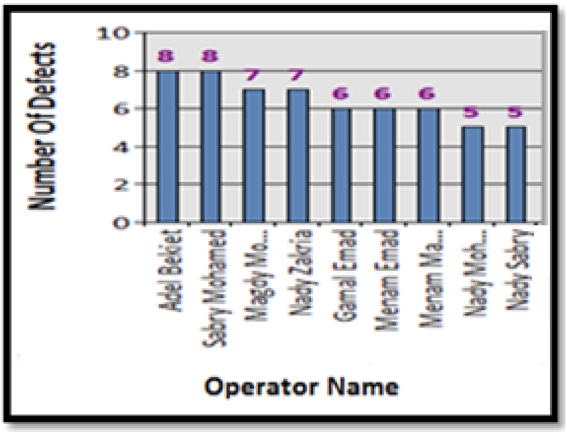


Figure 6. Numbers of defects by operator

Although the Pareto diagram (Figure 6) shows difference in the quality of the output among operators, an analysis of variance was performed for the defects data coming from each operator and revealed no significant difference (P-value = 0.92) which means that all operators perform to the same level of quality.

Similarly, traceability data can be used to analyze a machine's performance. Figure 7 presents a graphical display of the number of defects resulted from each machine. The analysis of machines would provide a clear indication of the machine performance. For example, too much defects made from a single machine, indicates that machine needs maintenance, or an alarm that such machine needs inspection.

The analysis of variance for the data of the number of defects made by each machine revealed that the difference between the machines is significant (P-Value = 0.0186). All residual plots revealed no violation to the ANOVA assumptions. Machine 19 and 15 were found to be the worst machines with respect to number of defects produced. They produce statistically significant higher number of defects than the rest of the machines. These are the machines that require immediate production intervention.

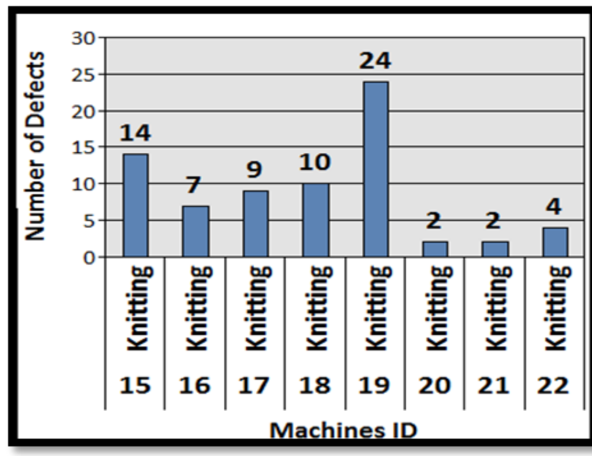


Figure 7. Numbers of defects by machines

4. The impact of traceability system implementation

Implementing the traceability system enables the company to manage and trace the manufacturing processes. This provides the ability to retrieve data associated with the manufacturing process of the fabric rolls. Moreover, traceability data minimizes the effort exerted in tracing the fabric rolls, and reduces the negative impacts of product recall by allowing the company to easily and quickly identify and locate the fabric rolls that need recall.

Traceability data allows the company to produce a fabric label to quickly identify products. In case of shipment routing, the fabric label reduces the time of fabric recognition and manual effort. Also, the fabric identification label utilizes the scanning process in the supply chain and shipment phase. Providing the customer limited access to the company's traceability system can save the customer money and time in shipment process. Furthermore, traceability enables the segregation of the fabric rolls after being gathered in the dyeing batch, which helps the company to precisely trace fabric rolls. It also allows the company to identify and trace individual defective fabric rolls.

The impact of using traceability data for measurements and analysis is to evaluate the supplier and analyze quality of manufactured fabric rolls. The lot number analysis allows the company to recognize the number of defects attributed to each lot number and to identify the percentage of first- and second-rate quality produced from each lot. This would enable the company to better evaluate the suppliers and reduces the higher cost raw material. The company can benefit from the analysis of the number of defects contributed from each lot by drawing conclusions about which suppliers supplies low quality lots and adjust their purchasing accordingly.

5. Conclusions and recommendations

In conclusion, from this research we have successfully designed and implemented a tracebility system in the textile manufacturing processes. This was through formalizing the current system's specific tracing requirments, and accordingly designing a data model, which was then implemented into a database. The integration of the database with the invisbile barcode led to the development of a traceability system. That was able to trace the textile manufacturing processes from initial raw material to finished fabric. We examined the impact of implementing the traceability system which facilitated the process of identifying and locating the manufactured product, improved the visibility of the manufactured fabric rolls, and reduces the impact of manual work in the shipment processes.

The development of a traceability system for textile manufacturing is not over. In this respect three crucial areas still need further work. The first area is using the traceability data for further developing quality control charts. This would enable the company to better control, manage, and increase the fabric's quality. It could also provide statistical representation of whether the manuafctured product is fullfuling the quality specifications or not. The second area in need of further work is providing the customers with limited accsses to the traceability database, which would lead to improved customer service, and help in reducing the manual entry during the shipment process. Last, but not least, much reaserach should be performed to automate the printing of the invisible ink on the fabric.

References

1. V. Andersen, How to Do Everything with Microsoft Office Access 2007, (1st ed.), McGraw-Hill, United States, 2006.
2. A. Bjork, M. Erlandsson, J. Hakli, K. Jaakkola, A. Nilsson, K. Nummila, V. Puntanen, A. Sirkka, "Monitoring Environmental Performance of the Forestry Supply Chain using RFID", Computers in Industry, 62, 2011, pp. 830-841.
3. H. Bulut, and J. Lawrence, "Meat Slaughter and Processing Plants' Traceability Levels Evidence From Iowa", Proceedings of the NCCC-134 Conference on Applied Commodity Price Analysis, Forecasting, and Market Risk Management, Chicago, Illinois, 2007, pp-1-22.
4. C. Coronel, S. Morris, and P. Rob, Database Systems: Design, Implementation and Management. 9th edition, Joe Sabatino, 2010.
5. E. Ilie-Zudor, Z. Kemeny, F.V. Blommestein, L. Monostori, A. V. Meulen, "A Survey of Applications and Requirements of Unique Identification Systems and RFID Techniques", Computers in Industry, 62, 2011, pp. 227-252.
6. J. Dejonckheere, S.M. Disney, M.R. Lambrecht, D.R. Towill, "Measuring and Avoiding the Bullwhip Effect: A Control Theoretic Approach", European Journal of Operational Research, 147(3), 2003, pp.567–590.
7. M. Khabbazi, M. Ismail, N. Ismail, and S. Mousavi, "Modeling of Traceability Information System for Material Flow Control Data", Australian Journal of Basic and Applied Sciences, 4(2), 2010, pp. 208-216.
8. V. Leino, Documenting Requirements Traceability Information, Master of Science Thesis, Helsinki University of Technology, Finland, 2001.
9. D. Leipziger, and E. Epema, "CSR, Part 3: Improving Traceability Requires Training and Capacity Building", CBI News Bulletin, 2006 pp. 8-11.
10. A. Oppel, Databases: A Beginner's Guide. (3rd ed.), McGraw-Hill, United States of America, 2009.
11. P. Ponniah, Data Modeling Fundamentals: A Practical Guide For IT Professionals, John Wiley & Sons, United States of America, 2007
12. R.E. Spekman, I.I. Sweeney, "RFID: From Concept to Implementation", International Journal of Physical Distribution and Logistics Management, 36 (10), 2005, pp. 736–754.
13. D. Ranasinghe, Q. Sheng, and S. Zeadally, Unique Radio Innovation for the 21st Century: Building Scalable and Global RFID Network (1st Ed.), Springer, 2010.
14. M. Rönkkö, A Model for Item Centric Material Control in Manufacturing, Master of Science Thesis. Helsinki University of Technology, Finland, 2006.
15. I. Töyrylä, Realising the Potential of Traceability: A Case Study Research on Usage and Impacts of Product Traceability, Masters of Science Thesis, Helsinki University of Technology, Finland, 1999.
16. M. Xu, Managing Strategic Intelligence: Techniques and Technologies, IGI Global, United States, 2007, retrieved from ebook3000.com.

SpyNot: A Framework for Vetting Android Apps for Security Flaws

Andrew Cordar and Dia Ali
The University of Southern Mississippi, Computer Science Department, Hattiesburg, MS 39402, USA
Andrew.Cordar@eagles.usm.edu; Dia.Ali@usm.edu

Abstract

In this paper, we discuss the possible threat of malware applications on the Android operating system. We describe the Android OS and the general structure of Android applications. We present the current state of virus protection for Android as well as different approaches used in protecting Android from malicious applications. We propose SpyNot, a framework for vetting Android apps for security flaws. This framework relies on data gathered from the Android Market including the category of the application as well as the permissions it is granted. This framework also uses Hadoop, an open source MapReduce tool. SpyNot could be used as part of a tool to support Defense Advanced Research Projects Agency's (DARPA) Transformative Apps [19] to scan Android apps to expose potential security flaws. We present the results, and discuss the implications of our findings.

1. Introduction

With the increased prevalence of smart phones, people are essentially able to carry a small computer in their pocket. They can check their email, browse the Web, and most recently, purchase and install applications onto their device. While this certainly enhances the user experience, it also puts the user at risk of installing malicious software onto their mobile device. Some could argue that there is no reason for malicious applications to exist on mobile devices; however, the information accessible on a user's mobile device could be extremely valuable. Another reason there is potential for an emergence of malicious applications is the massive growth of the smart phone market. The fourth quarter of 2010 saw 101 million smartphones sold to consumers [1]. In fact, a recent study shows that in the fourth quarter of 2010, more smartphones were shipped than PCs [1]. Obviously, protection of some sort will be necessary to curb the potential threat of malware infecting millions of smartphones. Another potential problem is not necessarily malicious applications but personal data security. Applications could be completely legitimate; however, they could be accessing personal information to sell to advertisers. While not necessarily malicious, there are many ethical and moral issues related to this problem, which makes the task of detecting malicious applications on mobile operating systems such as Android extremely difficult. Our approach relies less on analyzing an application in extreme detail, but more on analyzing the state of the Android Market and permissions used by applications. The idea is to detect applications that are using permissions that they don't really need. For example, a Solitaire card game shouldn't require permissions for accessing the user's phone number or GPS location. The approach is simple; however, can be very effective in finding possible malicious applications that exist on the Android Market.

In this paper, we present a framework for vetting Android apps from the Android Market for security flaws. We discuss the background information necessary to understand the Android OS as well as existing approaches to malware detection for Android. We then explain our approach of using Hadoop to analyze the Android Market for potential malicious applications. We present this information, as well as further improvements that could make the detection more robust and effective.

2. Background

In this section, we provide background information about the Android OS, the Android Market, basic application structure, as well as existing anti-virus applications for Android. We also discuss Hadoop and MapReduce.

2.1 Android Operating System

According to the Android Developer Guide, "Android is a software stack for mobile devices that includes an operating system, middleware and key applications" [2]. Android is supplemented with an SDK that can be used with IDEs such as Eclipse to easily create Android applications. The Android OS is composed of 4 levels: Applications, Application Framework, Libraries and Android Runtime, and the Linux Kernel [2]. Applications are programs either provided by the OS itself such as the web browser, or applications from the Android Market. The Applications Framework essentially provides services to the developer to help create applications. Some of these services include the Activity Manager which helps control applications lifecycles, i.e., it manages what happens when the application is paused, what happens when the user reopens the application, etc [2]. The Libraries are lower level C/C++ libraries such as OpenGL ES, a version of OpenGL optimized for mobile devices, and SQLite, a lightweight database engine [2]. The Android Runtime is essentially composed of a virtual machine to execute Java code. In this case, instead of the Java VM, Android uses what is known as the Dalvik Virtual Machine. Finally, the Linux Kernel provides crucial services to manage the OS. This includes security, memory management, as well as interfacing between the hardware layer and software layer [2]. Figure 1 provides a diagram of the Android architecture. The Android software is an open source package and is part of the Open Handset Alliance, which was created to provide smartphone manufacturers with an opportunity to release smartphones with the Android operating system [3]. Obviously, the main advantage of such an alliance means that manufacturers no longer have to build an operating system from scratch and can just add on to the already built Android OS; adding other features/applications that fits their product. Since Android's release, many manufactures have completely abandoned creating their own OSes and are just using Android. Motorola almost exclusively sells Android smartphones including the popular DROID series of phones [4]. Other manufacturers include HTC who manufactured the first Android phone, the G1 [5], as well as Google's first flagship phone, the Nexus One [6], and Samsung who manufacturer the Nexus S, Google's latest flagship smartphone [7]. With such growth, the Android OS has become one of the giants in the mobile operating system market. In fact, a recent report by Gartner states that the Android OS is now the number 2 smartphone OS with 22.7% of the market share in 2010, second to Symbian, Nokia's smartphone platform [8]. The Android OS has seen an 888.8% growth in sales in 2010 which shows just how dominant it is becoming [8].

2.2 Android Application Structure

Applications in Android are written using Java and are bundled into what are known as APK (Android Package) files [9]. APK files are much like JAR files or Zip files in which the code is archived into the APK file. When applications are executed in the Android environment, they are run in their own Linux process and have their own VM; however, applications can use other parts of applications given that it is permitted [9]. For example, if an application requires the need for a camera application, the application can just use the OS's stock Camera app, rather than its own. Each APK file is structured the same way, and Figure 2 shows this general structure. Important files/folders include the res folder, the classes.dex file, and the AndroidManifest.xml file. The res folder contains resources that the application uses for look and feel. This includes a XML based layout file, and any image files that are used in the application. The AndroidManifest.xml file is a very important file that details any libraries the application needs as well as detailing any permissions the application needs to execute properly [9]. Another important aspect of the manifest file is to declare the components of an application. This includes Activity, Receiver, Provider, etc [9]. The activity component is one of the most important as it usually provides much of the functionality of an application. For example, a contacts application could have an activity for viewing all contacts and an activity for adding and removing contacts from the contacts list. Figure 3 provides an example of an Android Manifest file. Another important aspect of Android applications is the permission based system. Essentially, if an application wants permission to do something, developers must declare this that the application wants a certain permission. For example, an application that needs internet must declare that it is using the Internet permission. Table 1 gives examples of some of these permissions a developer can grant. Permissions cannot be added after a user installs an application, and users are made known of what permissions an application is granted. The classes.dex file is essentially the Dalvik executable file in which all of the classes of an application are compiled and stored [2]. DEX files by themselves are fairly difficult to read however, a disassembler has been created known as baksmali which disassembles DEX files into a readable format [11].

2.3 Android Market

The Android Market is essentially a large digital store in which users can browse, download, and purchase hundreds of thousands of applications. The Market is essentially the same regardless of which phone carrier or device is being used. Differences occur between carriers because there is a section in which carriers like Sprint or T-Mobile can recommend certain applications for users to download. Other differences can arise with which version of Android is installed on the device. Applications that require the latest version of Android will not be displayed on the Market for users of older versions of Android such as Donut (Android 1.6). Figure 4 displays the Android Market running on the HTC EVO 4G with Froyo (Android 2.2). Applications are divided into two broad categories: Apps and Games. Apps include categories such as Business, Finance, and Lifestyle. Games include categories such as Arcade & Action, Casual, and Racing. Users have the ability to rate and comment on applications as well as report any bugs. Paid applications are authenticated using Google Checkout and users are given a 15 minute window in which they can get a refund. When users download an application, they are given a list of every permission an application is granted. Figures 5 and 6 give examples of an application on the Market as well as the screen providing information on permissions.

2.4 Hadoop and MapReduce

Hadoop is a project by Apache providing a framework to run data intensive applications in parallel over a large cluster of computers being able to handle petabytes of data [12]. Hadoop processes this data with what is known as MapReduce. Hadoop is an open source Java based implementation. MapReduce is a paradigm developed by Google in which large sets of data are broken into smaller key/value pairs (map), and then merges these pairs together (reduce) [13]. A simple example is counting the occurrences of words in a book. MapReduce would initially read every word in the book and create a pair for each word: <word,1>. The "1" indicates that it is one occurrence of the word. After all of the data is processed, reduce is then called and will merge all of the similar key/value pairs. For example, if one of the occurrences was <"Dog",1>, and there were 20 occurrences of this pair, reduce would end with the result <"Dog",20>. The advantage of such a system is how simple it is to use, and less reliance on worrying how to parallelize or optimize as an implementation can handle partitioning the data, handling failures, and communication between the clusters [13].

2.5 Related Work

The approach to anti-virus protection and detection on the Android platform is a fairly new topic, and there is not necessarily one perfect solution. One of the most popular and successful anti-virus Android applications is known as Lookout. The Lookout application grew out of a bigger project known as the App Genome Project, which the founders of Lookout claim to be the "largest-ever mobile app dataset" with about 300,000 apps from both iOS and Android [14]. To gather all of this information on Android applications, the developers created a distributed crawler to gather application metadata and binaries and then perform static analysis on this information including an application's DEX file and even string data [14]. They have a heuristic approach, for example, if they know an application is granted the READ_PHONE_STATE permission then they look for references in the DEX files for a function that requires that permission, e.g., getLine1Number, which gets the cell phone's number [14]. The Lookout Android application has been very successful in the Market as well as finding potentially dangerous viruses. The most recent is known as the Geinimi Trojan which is the most sophisticated piece of malware to date. Geinimi repackages itself inside of real applications and uses techniques like code obfuscation to prevent detection [15]. Another study conducted by SMobile Systems considered combinations of permissions for finding potential threats [16]. In their study, released in June 2010, they collected metadata on 48,694 applications which at the time was about 68% of the Android Market; and according to their study, 1 in every 5 applications requested permissions that could provide developers with users' personal information [16]. By initially identifying applications that were known to be spyware, they based further searches for other malicious applications by analyzing the Market for applications that contained the exact same set of permissions. For example, SMobile Systems identified SMS Message Spy Pro as a spyware app and then compared its permissions (INTERNET, READ_SMS, RECEIVE_SMS, READ_CONTACTS, etc) to other applications in the Market [16]. Table 2 shows some of SMobile's findings. While this approach can identify applications as potentially malicious, the study fails to consider the category of applications. An SMS messenger replacement would require the same permissions that they identified as possibly being spyware. The study; however, was enlightening, and showed just how many applications have access to personal data. The most robust and ambitious approach to malware detection is a project known as TaintDroid. TaintDroid is a project developed by Intel Labs, Penn State, and Duke University in which they propose a modification to the Android OS adding dynamic taint tracking [17]. Dynamic taint tracking essentially adds taint markings to sensitive information processed in an application and tracks what is happening to the data [17]. Basically, if a program takes a user's cell phone number and sends it to a server, the taint tracker would report this event, because a potentially dangerous method was called on tainted data. This project is the most sophisticated of existing malware detection on Android because it can detect potentially malicious actions in real time, rather than with static code analysis such as Lookout's approach. The other main advantage of TaintDroid is that it accomplishes all of this with little performance overhead, only 14% [17]. While this seems like the most logical solution for a more secure operating system, for a user to use TaintDroid they would be required to root their phone and install the custom OS. This potentially can be very risky if not done carefully, and in many cases, would void the user's warranty. For a system like this to be used by smartphone users, Google would have to integrate this framework into an official version of Android. While there are many other anti-virus applications on the Market, some could actually argue that Google already offers an effective security model. The argument is that users are warned before they install an application exactly what permissions an application is going to be granted. It is the user's responsibility to read this information carefully and make an educated decision on whether an application legitimately requires the permissions it requests. Unfortunately, the warning of this permission screen may not be enough for protection, as the less technical savvy could care less about what permissions the application needs and really just want the application. The reward of downloading and using the application is much greater than the consequences of what the application has access to, especially if the user really wants the application. The permission screen literally warns the user of everything the application will have access to; however, Lookout's paid premium subscription provides a service in which *Lookout* will present information on what secure information users' applications have access to. Rather than just warning users what permissions an application has, it seems it might be more effective to just let users install the application, and detect after the fact whether the application is malware or not. The other potential problem associated with security on Android is the fact that Google has a very lenient app approval process, unlike Apple who has been known for its strict approval process. It's a Catch 22 for Google who is potentially sacrificing some security in order to provide a more open product. A potential reason that iOS has not been known for many viruses is because of their strict approval process which would most likely weed out any potentially malicious apps before they could make it to Apple's App Store.

3. SpyNot

While there is no actual SpyNot Android application, our approach to analyzing the Market for potentially malicious applications could easily be integrated into an Android application that relied on a database of known malware detected by our approach. One of the challenges associated with analyzing the Market is that Google does not provide any public API to easily query the Market. Fortunately, an unofficial open source

API has been developed which provides a simple an easy way to query the Market for application information [18]. This approach; however, is not completely fool proof as Google will deny service if too many requests are made. Since authentication is done by a Gmail account, the account can be temporarily banned from getting any more results. To get around this issue, multiple email accounts were used as well as temporarily backing off after so many requests. Figure 7 represents the pseudo-code of metadata collection on the Android Market. The only metadata collected in this project was the application name, category, and permissions requested. The format of the output generated by the program is fairly simple. The general structure is as follows, the app name is printed, followed by the category, and then by a list of permissions. It would have benefited greatly to add another line indicating how many permissions an application requested; however, it was easier just to stick with this format than request each application's details again. Figure 8 is an excerpt generated by the program. Our approach was able to get about 90,000 applications from the Market, which now is only about half the Market, but at the time this project this was a larger percentage. It is however, almost double the amount that SMobile presented in their study. The next step was to actually process the data with Hadoop. For simplicity's sake, we just used a virtual machine running Hadoop. The initial step in analyzing the data was just to get statistics on what permissions are being used. Table 3 gives an excerpt of this data. It's interesting to note that there are still five applications still requesting the BRICK permission; however, the number has declined since SMobile's study. The power of Hadoop is that the possibilities of queries on the Market are limitless. Rather than just look at the entire Market as a whole, we can drill down and look at what permissions are being used by specific categories of Applications. By getting more specific information, we can make better decisions on what categories of applications are requesting more potentially dangerous permissions. Tables 4 and 5 are examples of permissions used by Brain and Puzzle games, and Arcade and Action games respectively. Rather than just finding information on what permissions are being used, with Hadoop, we can find information on applications in a specific category using permissions that seem strange for such a category of application. Figure 9 represents the pseudo-code of such an approach using Hadoop. In this case, reduce most likely does not merge anything as applications names are usually unique, but processing the data is very simple using MapReduce. Any combination of rule can be generated to find results in the Market. For example, we can query the data for all applications that are of category "Entertainment" and use permissions like SEND_SMS, ACCESS_COARSE_LOCATION, and READ_PHONE_STATE. The idea being an entertainment application requesting such permissions is fairly strange. One publisher "Addicting SMS," has about 450 applications that are essentially the same thing. Almost every application has the same description with a minor difference depending on the name of the application. Figures 10 and 11 are an example of an application from publisher "Addicting SMS" and its permission screen. The basic functionality behind this application is to pop up with a picture every time a user receives a text messages, which is practically spam to begin with. It makes sense that the application requires permission to receive SMS messages; however, the need for the application to access contact information as well as have access to location, both fine and coarse, is highly unnecessary for an application like this.

While it might not necessarily be malicious, it seems that the developer is just spamming the Market with applications that are strange in nature, and request way too many permissions than it really needs. It is also interesting to note that the Market is flooded with other developers that are obviously aliases of each other. The developers "SMS Mos" and "Smiley Sun" both publish applications that do the same thing as "Ham Sandwich SMSCup," and even include the same generic description. It's obviously just spam; however, these applications still remain in the Market. The overall goal for these applications is most likely to get "ad clicks" to make money while distributing really simple applications. Google might have done some cleaning up of the Market as some developers which we found to be publishing possibly suspicious applications have since been removed from the Market. Some of these developers include "Playstation", "GameBox," and "Blue Tomato." This has not eliminated the problem as these types of applications are still present in the Market. For example, the game "Crystal Faces" was found by our approach under the developer Playstation; however, is now under the developer "funweaver." Figure 12 shows these applications in the Market. These games request permission for READ_PHONE_STATE as well as "ACCESS_COURSE_LOCATION" meaning they wanted permission to access coarse location; however, failed to spell it correctly. Other examples of suspicious applications include "Hoiio," which allows users to makes international calls using their service. This application gets permission to send text messages, directly call phone numbers, record audio, read contact data, and internet access. Some of these permissions make sense; however, reading the comments users have posted about this application give more insight on what the application is doing. A few comments noted that their friends were getting spammed with SMS Ads. Now it makes more sense why this application has permission to send text messages, and it's obvious they are using it for unethical purposes. Despite comments by users, this application still exists in the Market and companies like Lookout have not released any information on this application. In fact, Lookout's virus scan application says that Hoiio is safe. It might be possible that these incidences are coincidental; however, given the permissions this application is granted, it is definitely possible that this application could be spamming users' contacts with text messages.

4. Conclusion and Future Work

By using MapReduce and a heuristic approach for detecting possibly suspicious applications on the Market, we were able to give some insight on the current state of the Market as well as current techniques that possible spammers and malicious developers are using. While there are other popular solutions to malware detection on Android, our solution is fairly simple, and only relies on applying rules to metadata collected from the Market. The result is an interesting and insightful approach to detecting potential malware on Android devices.

In terms of future work on this project, improvements could be made on the heuristic approach by considering more metadata gathering from the Market. This includes the rating of applications, as well as user comments on applications. With this information, we could analyze comments with keywords such as "virus", "spam", "scam", etc in addition to considering combinations of permissions. With this approach, we could develop a much more robust system for correctly identifying potential malware applications. Another future work would be to create an Android application that uses our approach to malware detection. It would most likely be backed by a database of possible malicious applications, and updates in the database could easily be pushed to the user. As a part of DARPA's plan to create an Android military app marketplace [20], DARPA is looking to develop a software tool to test Android apps for security flaws. SpyNot could be used as part of such a tool to support DARPA's Transformative Apps to scan Android apps to expose potential security flaws.

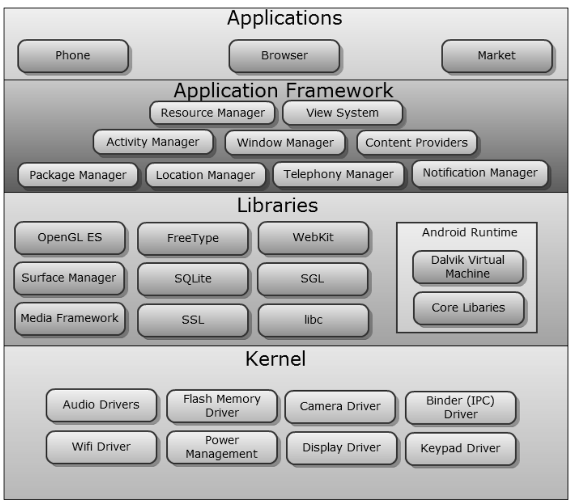


Figure 1: Android Architecture Diagram adapted from [2]

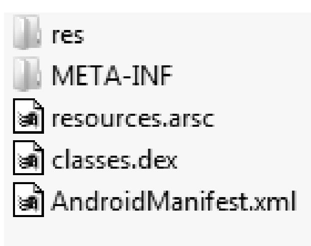


Figure 2: Structure of APK file

```
<?xml version = "1.0" encoding="utf-8"?>
<manifest xmlns:android="http://schemas.android.com/apk/res/android"
    package="com.example.app"
    android:versionCode="1"
    android:versionName="1.0">
    <application android:icon="@drawable/icon android:label="@string/app_name">
        <activity android:name=".DoSomething"
                  android:label="@string/app_name">
                  ...
                  ...
        </activity>
    </application>
    ...
    ...
</manifest>
```

Figure 3: Example AndroidManifest.xml file

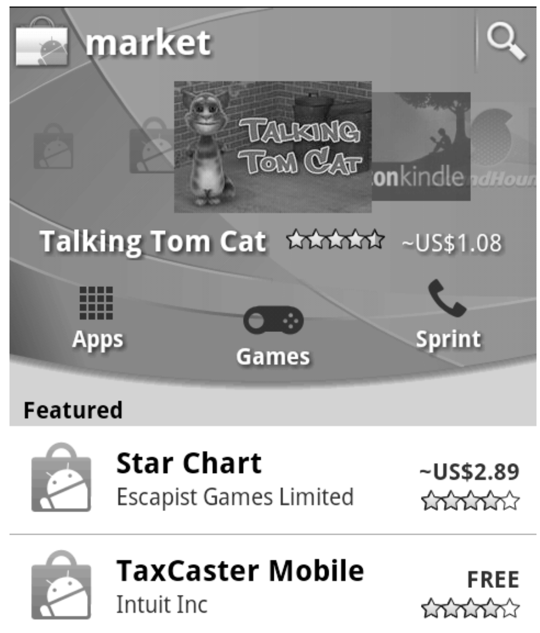


Figure 4: Market running on HTC EVO 4G

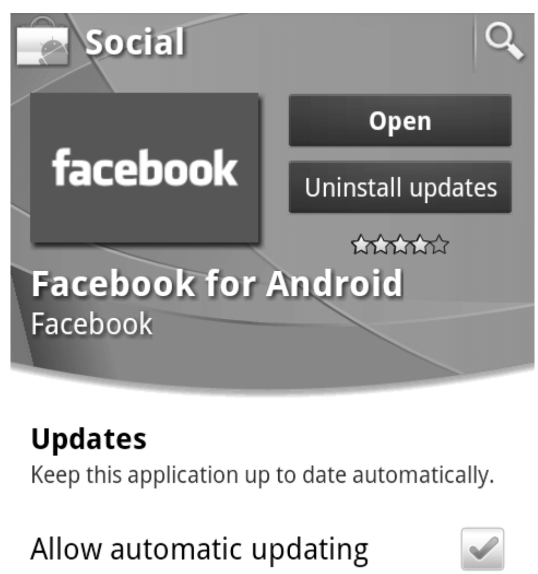


Figure 5: Application on Market

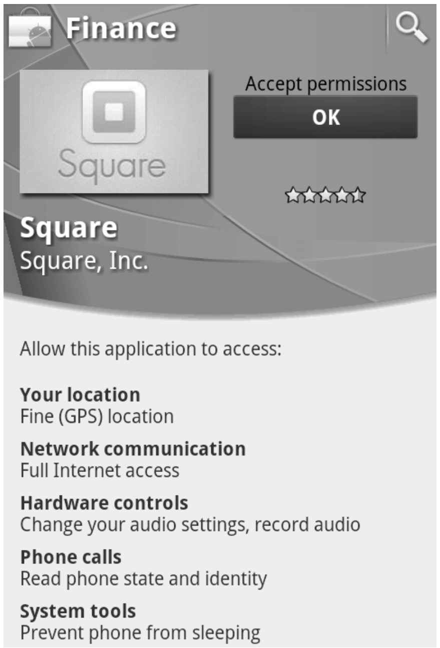


Figure 6: Permission screen

```
Array:packageNames
String:credentials

void getData(File file)
{
   MarketSession session = new MarketSession
   session.login(credentials)
   foreach(packageName in packageNames)
   {
      AppRequest request
      request = AppRequest.search(packageName)
      file.println(request.appTitle() + ":")
      file.println("Category:" + request.category())
      file.println(request.getPermissions())
   }

   file.save()
}
```

Figure 7: Pseudo-code of app data retrieval

```
DailyHoroscope:,Lifestyle,android.permission.INTERNET,
Zillow Real Estate:,Lifestyle,android.permission.INTERNET,android.permission.ACCESS_FI
Layar Reality Browser:,Lifestyle,android.permission.ACCESS_NETWORK_STATE,android.permi
My Days - Period & Ovulation:,Lifestyle,
?? ?? ??? ????(Korea NextBus!):,Lifestyle,android.permission.INTERNET,android.permissi
????-?? ?? ??? ???? ?? ?:,Lifestyle,android.permission.READ_PHONE_STATE,android.permis
Bible King James Version:,Reference,android.permission.INTERNET,android.permission.ACC
10001 Cocktails:,Lifestyle,android.permission.INTERNET,
My Tracks:,Lifestyle,android.permission.RECEIVE_BOOT_COMPLETED,android.permission.ACCE
Bartender:,Lifestyle,android.permission.INTERNET,
HistoryEraser:,Lifestyle,android.permission.READ_CONTACTS,android.permission.WRITE_CON
Sherpa - Discover your world:,Lifestyle,android.permission.INTERNET,android.permission
SeoulBus (????):,Lifestyle,android.permission.INTERNET,android.permission.ACCESS_COARS
aFlashlight:,Lifestyle,android.permission.WAKE_LOCK,android.permission.INTERNET,androi
Love Poems:,Social,android.permission.INTERNET,android.permission.ACCESS_NETWORK_STATE
Epicurious Recipe App:,Lifestyle,android.permission.INTERNET,android.permission.WRITE_
```

Figure 8: Portion of output generated

```
void map(Data data, String category, Array
permissions)
{
   Info = data.parse()
   If(Info.category = category)
   {
      If(Info.permissions.contains(permissions)
         emit(Info.appName,1)
   }
}

void reduce(Data data)
{
   merge(data)
}
```

Figure 9: Pseudo code of our map and reduce

Figure 10: Ham Sandwich SMSCup Application

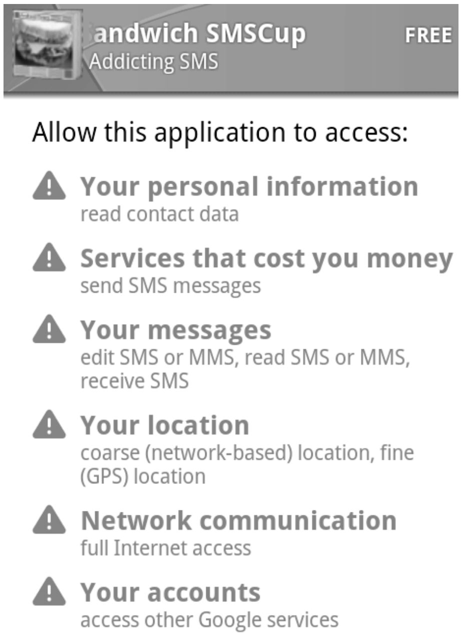


Figure 11: Permission screen for Ham Sandwich SMSCup

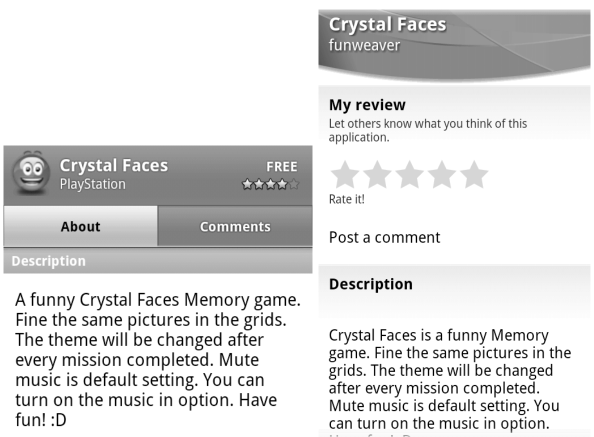


Figure 12: Crystal Face game

ACCESS_FINE_LOCATION	Grants location using GPS
INTERNET	Grants connection to the internet
BRICK	Gives application permission to render device disabled
RECEIVE_SMS	Application can process incoming SMS messages

Table 1: Example of permissions [10]

Permission	Numbers of Applications
ACCESS_COARSE_LOCATION	12,062
ACCESS_FINE_LOCATION	7,533
BRICK	9
INTERNET	34,636

Table 2: **Statistical Information gathered by SMobile Systems [15]**

Permission	Number of Applications
INTERNET	58,365
ACCESS_FINE_LOCATION	16,629
ACCESS_COARSE_LOCATION	20,720
BRICK	5

Table 3: Excerpt of Permissions

Permission	Number of Applications
READ_PHONE_STATE	1080
ACCESS_COARSE_LOCATION	888
SEND_SMS	70
READ_CONTACTS	46

Table 4: Permissions used by Brain and Puzzle games

Permission	Number of Applications
READ_PHONE_STATE	765
SEND_SMS	89
ACCESS_FINE_LOCATION	228
WRITE_SMS	73

Table 5: Permissions used by Arcade and Action games

Acknowledgements

We appreciate the input from Lashonda Bell, Jeremy Blakeney, Devin Lucius, and Robert Merkosky.

References

[1] Menn, Joseph, "Smartphone shipments surpass PCs," Financial Times. 8 February 2011. http://www.ft.com/cms/s/2/d96e3bd8-33ca-11e0-b1ed-00144feabdc0.html. Last Visited On 2/11/2011.

[2] Google, "What is Android?" Android Dev Guide. http://developer.android.com/guide/basics/what-is-android.html. Last Visited On 2/11/2011.

[3] Open Handset Alliance, "Overview," http://www.openhandsetalliance.com/oha_overview.html. Last Visited On 2/11/2011.

[4] Motorola, "Mobile Phones," http://www.motorola.com/Consumers/US-EN/Consumer-Product-and-Services/Mobile-Phones/. Last Visited On 2/11/2011

[5] T-Mobile, "T-Mobile Unveils the T-Mobile G1 – the First Phone Powered by Android," 23 September 2008. http://www.t-mobile.com/company/PressReleases_Article.aspx?assetName=Prs_Prs_20080923&title=T-Mobile%20Unveils%20the%20T-Mobile%20G1%20%E2%80%93%20the%20First%20Phone%20Powered%20by%20Android. Last Visited On 2/11/2011.

[6] Google, "Nexus One," http://www.google.com/phone/detail/nexus-one. Last Visited On 2/11/2011.

[7] Google, "Nexus S," http://www.google.com/nexus. Last Visited On 2/11/2011.

[8] Rao, Leena, "Gartner: Android OS Sales Trump iOS And RIM, Grew 888 Percent In 2010," TechCrunch. 9 February 2011. http://techcrunch.com/2011/02/09/gartner-android-os-sales-trumps-ios-and-rim-grew-888-percent-in-2010. Last Visited On 2/11/2011.

[9] Google, "Application Fundamentals," Android Dev Guide. http://developer.android.com/guide/topics/fundamentals.html. Last Visited On 2/11/2011.

[10] Google, "Manifest.permission," Android Reference. http://developer.android.com/reference/android/Manifest.permission.html. Last Visited On 2/11/2011.

[11] JesusFreke, "smali – An assembler/disassemble for Android's dex format," http://code.google.com/p/smali. Last Visited On 2/11/2011.

[12] Apache Software Foundation, "Apache Hadoop," http://wiki.apache.org/hadoop. Last Visited On 2/11/2011.

[13] Dean, Jeffrey and Sanjay Ghemawat, "MapReduce: Simplified Data Processing On Large Clusters." In OSDI'04: Sixth Symposium on Operating System Design and Implementation, San Francisco, CA, December, 2004.

[14] Mahaffey, Kevin and John Hering, "App Attack: Surviving the explosive growth of mobile apps." As Presented In Black Hat USA 2010, Las Vegas, NV, July 2010.

[15] Strazzere, Timothy, and Timothy Wyatt. "Geinimi Trojan Technical Teardown." 6 January 2011. http://blog.mylookout.com/_media/Geinimi_Trojan_Teardown.pdf. Last Visited On 2/11/2011.

[16] Vennon, Troy and David Stroop, "Threat Analysis of the Android Market," 22 June 2011 http://threatcenter.smobilesystems.com. Last Visited On 2/11/2011.

[17] Enck, William, et al, "TaintDroid: An Information-Flow Tracking System for Realtime Privacy Monitoring on Smartphones." In OSDI '10: 9th Symposium on Operating Systems Design and Implementation, Vancouver, BC October, 2010.

[18] "android-market-api: An open-source API for the Android Market,"

http://code.google.com/p/android-market-api. Last Visited On 2/11/2011.

[19] DARPA, "Transformative Apps", https://www.fbo.gov/index?s=opportunity&mode=form&tab=core&id=5db2b9ccbed8edc27d7e1df20a0e2f39&_cview=0. Last Visited On 9/27/2012.

[20] Rausnitz, Zach, "DARPA, NIST seek Android app security tool", http://www.fiercemobilegovernment.com/story/darpa-nist-seek-android-app-security-tool/2012-08-21, Last Visited On 9/27/2012