Continuous improvement of occupational safety performance in aerospace production systems through collaborative automation

by

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B.S. Mechanical Engineering, Instituto Tecnológico y de estudios superiores de Monterrey, 2010

Submitted to the Department of Mechanical Engineering and the MIT Sloan School of Management in partial fulfillment of the requirements for the degrees of Master of Science in Mechanical Engineering and Master of Business Administration in conjunction with the Leaders for Global Operations Program at the

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Abstract

Employee health and safety are a top priority in aerospace manufacturing. As companies increase their production systems capacity in preparation for upcoming rate targets, new opportunities for continuous improvement start becoming evident and time critical. A strong collaboration of Health and Safety, Quality, Manufacturing and Research and Technology groups is paramount to ensure that adequate technologies are developed and deployed in the right stages of the manufacturing system in a way that is compliant with both technology readiness and the business needs.

The integration of collaborative automation on ergo-motivated continuous improvement projects pose two major challenges in this aerospace manufacturing process. Firstly, the availability of resources to measure the current state, i.e. the identification and prioritization of the sub-steps and specific tasks in the process that require technological intervention. Secondly, the potential incompatibility of production systems, continuous improvement and technology development road maps that limit the speed at which new technologies flow to the shop floor.

By leveraging the existence of historical safety performance and labor-tracking data, the proposed methodology offers an immediate approximation of occupational risk of the current state. This allows a "first gate" deliverable for any given continuous improvement project for the Occupational Health and Safety group with minimal use of resources, a framework for the R&D organizations to create and prioritize ergonomically-driven projects and ultimately complement business cases to propel technologies towards final deployment.

The methodology results in a statistical risk profile that highlights the manual sub-steps of a product line that show better candidacy for collaborative automation. Continuous improvement and conventional Lean/Six Sigma tools where furthermore applied to demonstrate process capability and move a collaborative robot through the production system implementation roadmap in record timing.

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I would also like to take this opportunity to dedicate this work to my family: Maricela I. Castillo, Guillermo E. Pámanes and Natalia Pámanes, for their unconditional love and support throughout my life.

Table of contents

Abstract..3

Acknowledgments..5

Table of contents..6

Chapter 1: Introduction..11
1.1 A brief walk through the history of airplane manufacturing..11
1.2 Airframe manufacturing forecasts and strategies in the 21st Century..14
1.3 Boeing Aerostructures Australia..16
1.4 Productivity and Safety in the Workplace..19
1.5 Identifying the problem: safety performance baseline..22
1.6 Overview of Hypotheses, Approach and Methodology..23
1.7 Summary..25
1.8 Chapter 1 references..26

Chapter 2: Literature review on economics, ergonomics and risk assessment tools..29
2.1 Occupational health and safety in the aerospace industry..29
2.2 Finding the economic optimal point and the importance of risk assessments..31
2.3 Human body as a machine-biomechanical models..36
2.4 Risk assessment forms..37
2.5 Chapter 2 summary..41
2.6 Chapter 2 appendix..43
2.7 Chapter 2 references..44

Chapter 3: Rough order of magnitude risk profile for manual tasks in wingbox assembly..46
3.1 Epidemiological study approach..46
3.2 Composite wingbox manufacturing for flight control elements..48
3.3 Benchmarking the Rough Order of Magnitude Budget Estimate for model acceptability..55
3.4 Rough Order of Magnitude Risk Profile..56
3.5 Creation and evolution of the model..61
3.6 Data analysis..65
3.7 Confidence intervals by production line and by activity..75
3.8 Conclusions..81
3.9 Recommendations..84
3.10 Chapter 3 references..84

Chapter 4: Continuous improvement and collaborative robots 86
4.1 The history of automation and collaborative robots 86
4.2 Capabilities and limitations of collaborative robots 89
4.3 The importance of continuous improvement for commercial aerospace manufacturers.... 91
4.4 Penetration of robotics in aircraft manufacturing 93
4.5 Continuous improvement........ 96
4.6 Summary 97
4.7 Chapter 4 references 97

Chapter 5: PDCA using a collaborative robot........ 101
5.1 Continuous improvement in aerospace........ 101
5.2 Continuous improvement roadmaps in the aerospace industry 103
5.3 Identifying the problem and studying the current situation 106
5.4 Finding the root causes and choosing the solution 108
5.5 Developing the action plan 108
5.6 Fundamentals of stem machining analysis and requirements development (Step 1) 109
5.7 Blind fastener input height variability 113
5.8 Input-Process-Output energy diagram for machining with a collaborative robot (Step 3) 115
5.9 Design of experiments (Step 4) 116
5.10 Experiment........ 119
5.11 Experiment results 120
5.12 Process model (Step 5)........ 124
5.13 Parameter optimization (Step 6) 125
5.14 Parameter optimization and Cpk Calculation (Step 7)........ 126
5.15 Checking results........ 133
5.16 Chapter 5 appendix 135
5.17 Chapter 5 references 136

Chapter 6: Implementation and sustaining performance for collaborative robot........ 139
6.1 Establishing reliable methods 139
6.2 Continuously improving products and processes 140
6.3 Further continuous improvement on ergonomics 143
6.4 Conclusions........ 145
6.5 Chapter 6 references 146

List of figures

Figure 1-1: Commercial aviation demand forecast [15] ... 15
Figure 1-2: Market-share by company [16] [17] ... 15
Figure 1-3: Price summary [18], [19] ... 15
Figure 1-4: Orders by company [17] [16] ... 16
Figure 1-5 787 moveable trailing edge ... 17
Figure 1-6: 777 elevator and rudder ... 18
Figure 1-7: 737 ailerons ... 18
Figure 1-8: 747 moveable leading edge ... 18
Figure 1-9: Boeing deliveries and employment forecasted for 2022[16] [24] ... 19
Figure 1-10: Estimated productivity to maintain market share ... 19
Figure 1-11 [25]: TCR Aerospace vs. Manufacturing sector ... 20
Figure 2-1: Comparison of TCR for aircraft assembly companies and aircraft parts fabrication [1] ... 30
Figure 2-2: TCR comparison of the commercial aircraft supply chain and the manufacturing sector in the US [1]. ... 30
Figure 2-3: Optimal level of automation [10] ... 33
Figure 2-4: OSHA worskite analysis plan ... 39
Figure 2-5: Probability and severity ranks [23] ... 40
Figure 2-6: European OSHA Risk Assessment [23] ... 41
Figure 3-1: Cohort study [2] ... 47
Figure 3-2: Risk factors classification in epidemiological studies [4] ... 47
Figure 3-3: Ailerons ... 49
Figure 3-4: Rudder location ... 49
Figure 3-5: Elevator location ... 50
Figure 3-6: Flaps [9] ... 50
Figure 3-7: Wingbox elements [10] ... 51
Figure 3-8: Planned labor-hours for flight control elements assembly ... 51
Figure 3-9: Lockheed L-1011 [11] ... 52
Figure 3-10 [12] Aileron assembly ... 53
Figure 3-11: Process flow diagram ... 53
Figure 3-12 Composite aileron cost summary [12] ... 55
Figure 3-13: Incidents by root-cause ... 56
Figure 3-14 NCR vs incident reports ... 57
Figure 3-15: Labor data extract ... 58
Figure 3-16: Equation 3.1 applied across employee IDs. ... 59
Figure 3-17: TAR calculated across activities ... 60
Figure 3-18: Linear regression ... 60
Figure 3-19 Non-linear model regression ... 61
Figure 3-20: Employee labor tracking variability ... 62
Figure 3-21: Daily average of labor-hours reported per employee ... 63
Figure 3-22: Normal probability plot for daily averages ... 64

Figure 3-23: Confidence interval for daily average ... 64
Figure 3-24: Labor-hours extract ... 65
Figure 3-25: Venn diagram ... 66
Figure 3-26 Activity category allocation ... 67
Figure 3-27: Model regression input array ... 67
Figure 3-28: First model (*m=11, i=133, l=2*) ... 69
Figure 3-29: Parameter screening ... 70
Figure 3-30: Regression model (*m=11, i=30, l=1*) ... 70
Figure 3-31: Regression model after screening non-significant parameters ... 71
Figure 3-32: Regression model with screened parameters ... 71
Figure 3-33: Multilinear regression with 85 samples (*j=85, l=4, m=17*) ... 72
Figure 3-34: Model test ... 73
Figure 3-35: 85-sample model comparison ... 74
Figure 3-36: Multi-linear regression using 96 samples. ... 74
Figure 3-37: Confidence interval for TRR ... 75
Figure 3-38: ROM risk profile for production line A ... 76
Figure 3-39: Nominal ROM for production line A ... 77
Figure 3-40: Activities raked by risk rate ... 77
Figure 3-41: Nominal ROM for production line B ... 78
Figure 3-42: Production Line D risk profile ... 79
Figure 3-43: Nominal ROM risk profile for production line D ... 80
Figure 3-44: Activities raked by risk rate ... 81
Figure 3-45: Example of ROM risk assessment for current state applied to the workstation level ... 82
Figure 3-46: ROM reduction of TRR ... 83
Figure 3-47: Confidence intervals for each category ... 84
Figure 4-1: Worldwide sales of industrial robots[33] ... 94
Figure 4-2: Industrial robots: estimated operational stock by continent ... 94
Figure 4-3 : Estimated annual supply of industrial robots ... 95
Figure 5-1: Theoretical breakthrough improvement ... 102
Figure 5-2: Real trend after a breakthrough improvement [... 103
Figure 5-3: The PDCA Cycle ... 103
Figure 5-4 [4]: Figure 1.0.1 from D1-9000 ... 104
Figure 5-5: Figure 1.0.1.2 from D1-9000 Basic Problem-Solving Flow ... 105
Figure 5-6: ROM statistical risk profile for Production Line A ... 106
Figure 5-7: Stage 3 ROM ... 107
Figure 5-8:: Future state ... 107
Figure 5-9: Figure 1.0.2.3 from D1-9000 ... 109
Figure 5-10: Flush fasteners ... 110
Figure 5-11: Blind fasteners ... 110
Figure 5-12: Installation of blind fasteners ... 111
Figure 5-13: Steam break ... 111
Figure 5-14: Horizontal slab milling ... 111
Figure 5-15: Stem height run chart ... 113
Figure 5-16: Normal probability plot ... 114
Figure 5-17: X-bar chart for stem heights with sample size 4 ... 114
Figure 5-18: IPO diagram ... 115

Figure 5-19: IPO diagram for stem machining........116
Figure 5-20: Design of Experiments........116
Figure 5-21: Test coupon........117
Figure 5-22: Stem height comparison between production part and coupon........117
Figure 5-23: Distribution of stem heights........118
Figure 5-24: Distribution of stem heights........118
Figure 5-25: Test sequence........120
Figure 5-26: Flushness results........120
Figure 5-27: Histograms for Test Blocks 1.1 and 1.2........122
Figure 5-28: Median test for tool shift........122
Figure 5-29: Median test........123
Figure 5-30: Regression model 1........124
Figure 5-31: Regression model for linear material removal........125
Figure 5-32: Regression model for variance........126
Figure 5-33: First simulation........127
Figure 5-34: Cutting tool analysis........128
Fig 5-35: Tool wear........129
Fig 5-36: Cut time vs chip thickness........129
Fig 5-37: Cumulative sums for 144 runs........131
Fig 5-38: Material removal trend (effect) per test setting........131
Fig 5-39: Simulation 2........132
Fig 5-40: Simulation run 3........133
Figure 5-41: Final simulation........133
Figure 6-1: Accuracy to tolerance ratio for inspection tools........139
Figure 6-2: Defect concentration diagram........140
Figure 6-3: Risk Analysis template........141
Figure 6-4: Risk rating........142

Chapter 1: Introduction

The following thesis has the objective of helping to improve ergonomics with the use of collaborative automation. A brief walk through the main checkpoints in the history of airplane manufacturing will reveal the political, social, technological antecedents that gave birth to the current state of commercial aircraft factory architecture and operation modes. Reviewing this history is also crucial to understand the challenges regarding occupational safety and deployment of automation faced by the airplane manufacturers. This thesis proposes an innovative approach to identify ergonomic risks and implement collaborative automation. In a broader sense, it helps to demonstrate how breakthrough technologies can be implemented using continuous improvement roadmaps to sustain performance in a world-class production system.

1.1 A brief walk through the history of airplane manufacturing

The Machine that Changed the World outlines how the assembly lines designed by Henry Ford achieved the standardization of work and implementation of moving lines resulting in unprecedented productivity performance[1]. However, as it will be described in Chapter 2 of this thesis, standard work and task dilution may increase ergonomic risk due to repetitive motions performed in extended periods of time. Although standard work helps to unveil root causes for quality defects, it also causes ergonomically risky tasks to worsen because of the increase in repetition. While quality defects can be reworked, injuries shall not be tolerated and must be prevented.

Airplanes and automobiles are common in that the first concepts were not engineered to be mass produced. Most of the funding for the earliest models was consumed to build functional prototypes that only intended to meet functional requirements. Such was the case for the first piloted unit assembled by the Wright Brothers in 1903 [1] and all automobiles before the Model T. The Wright Brothers Company provided the first Model A to the army at a price of $25,000 for several years. At that time, the Wright Brothers only faced competition from Curtiss Aeroplane Company who were capable of offering an airplane that traveled at a speed record of 47 miles per hour. The price-tag for this aircraft was only $5,000, which lead Curtis to become the largest aircraft producer in the US by 1914 [2].

Aircraft design and production soared to above 200,000 units for the first time in WWI [3]. It was not until then when in California, under the name of the Glenn A. Martin Company, a third major competitor emerged. Although the primary focus in airplane development was targeted to military applications including fighting scouts, night bombing, night fighting and ground attack, non-military applications existed as well and the public had the possibility of buying the airplanes they saw at racing events [2].

While there is limited information that describes the detailed conditions the employees worked in at these 3 companies, it should not be hard to imagine that although very limited amount of technologies were in place to make the production systems more efficient, there must have been extraordinary efforts to put assembly lines in place to transit from the 49 total airplanes delivered in 1914 in the United States, to the 20,000 in the subsequent 4 years during the war [4].

By 1917 the demand for aircraft produced in the US was already of the order of thousands. Evidence of that is provided in in the cable received during the war by President Wilson Woodrow, where tens of thousands of units were being requested by the French Government [4]. In these times the aerospace industry was just emerging and airplane designs were not yet suited for mass production, it is easy to picture that building airplanes was craftsmanship-reliant. To mitigate the craftsmanship dependency Britain introduced a system of "dilution" as the war itself demanded for growing production volumes. This marks the beginning of the simplification of tasks that were more suitable for unskilled workers [4].

Another example of early attempts to ramp up aircraft production is the Aeronautical Mission led by Major Raynal in 1917. The main objective was to study European airplane designs to see which ones could be adopted and produced in the US in cooperation with the European manufacturers, since the European air forces counted for only a few hundred units at that time [5]. The final recommendation made by Raynal was to support the Allied manufacturers with raw materials, instead of launching a huge program in the US which would have been costly to ramp up. The recommendation also included a handful of specific European aircraft designs that could have been built in the US. The only model that was successfully delivered by the US following this premise was the DH-4 [5]. An important note is that the objectives of this program drove President Wilson Woodrow's administration to question if planes could be mass produced as cars or bicycles. A big caveat was that the mass production systems pioneered by Hendry Ford relied on standardized product configurations [4].

During WWI, the airframe production in Europe was already outnumbering the engine manufacturing, mainly because airframe production emerged before the need of improved reconnaissance operations during WWI. The Rumpler Taube Monoplane was the first military aircraft that was mass produced [6] and was equipped with a piston power plant ranging from 70 to 120 hp, 2 seats and steel frame fuselage; about 500 units of this model were produced in Germany[6].

Towards WWII the US engaged in one of the biggest industrial efforts in history. Aircraft manufacturing passed from being in the 41st place to lead the chart of industries in the US in less than 5 years. By 1939, the total of military aircraft production barely reached 3,000 units, by the end of the war the US had produced 300,000 [7].

The P51 Mustang is a valuable case study from WWII for the purpose of this thesis. The Royal Airforce (RAF) approached to Curtis, that had merged in 1929 with the Wright Company, with the request to build 300 P-40 Warhawks. Curtis originally turned the request down because of the lack of factory capacity. The British turned to North American Aviation, whose company president made an innovative counter-proposal: to design and deliver an entirely new airplane using cutting edge technologies, since they knew that the P-40 fell short in maneuverability. This came with the implication of putting a whole new production system in place. Astonishingly North America Aviation provided the first prototype in less than 120 days [8].

Another example to consider is the B-24 heavy bomber program for which the Ford Motor Company had created a production line that closely resembled those used for cars. The Willow Run Plant in Michigan launched with early quality problems, mainly due to the workforce adaptation from an automotive environment to airframe assembly operations, but it was always remarkable for their high production rates [9].

To satisfy the demand of aircraft during WWII, factories were running 24 hours 7 days a week, employing a total of 2.1 million workers, female representation was in order of tens of thousands. The Ford Motor Company delivered more than 5,400 B-24 bombers produced in their Michigan factory. The Douglass Aircraft company was producing C-47s every 5 hours. In total by 1944 there were 15 airframe manufacturers producing 23 different types of combat airplanes in the US. To achieve this, automobile manufacturers were brought into play through licenses and sub-contracts. The most innovative stage of airframe manufacturing happened in this period of time where "job shops" were transformed into full production lines requiring less skilled workforce. This demanded a great standardization of parts and processes to overcome the complexity of the products. To provide an example, the nose section of the Boeing B-29 by itself bomber required more than 50,000 rivets and 8,000 different parts brought in from more than 1500 suppliers [10]. The war defined the basis of the 21st century major aircraft manufacturers, that would be focusing primarily on airplane development, major assemblies and systems integration [10].

The military technologies developed during WWII permeated the aircraft developed and built on the eve of the Cold War era, built in lower volumes, but unprecedented complexity of systems integration. Boeing focused its resources on building long-range strategic bombers such as the B-47 (produced 2,000 units) and large commercial aircraft, such as the B-52 and the 707 (total of 878 units produced) on a tight competition with the DC-8. These technologies also prompted the specialization of companies on specific technologies such as the turbojet engine. Aircraft manufacturers focused on developing airframes for higher speeds and altitudes to be coupled with major advancements such as turbojet propulsion [11].

Airbus was born in the late 1960s and thrived to become a competitor to the major US commercial manufacturers: Boeing, McDonell Douglass and LockheedThe 1950s and 1960s set a foundation to the product portfolio that exists nowadays, giving birth to the 737, DC-9 and the new wide bodies like the 747, the DC-10 and L-1011 Tristar [11].

The beginning of the decade of the 1970s witnessed a substantial decrease in demand caused in great part by the Gulf oil crisis. The total volume of aircraft production did not surpass 400 units per annum. In fact, the average units shipped per years according to the Bureau of Labor Statistics struggled to surpass the 1500 units within the period of 1972 to 1991 [12]. However, this is a long term average that hides years where orders peaked.

By the beginning of the 1980s air travel was forecasted to grow at a rate of 6.6% per year and record orders for commercial air carriers was achieved in 1978 [12]. Boeing approached the Japanese manufacturing systems on a study mission performed by John Black in an effort to streamline their manufacturing capabilities and ensure that these order records would be fulfilled on time and on budget [13].

John Black describes the aerospace industry to be in an upward-slope, while Boeing was beginning the longstanding efforts to improve the quality of their products, productivity and quality of work life. A result of this effort were the innovative employee involvement initiatives implemented in 1978, referred to as "Productivity Circles", which set the foundations and the means to ensure a successful journey towards a just-in-time production system. The 757 program is evidence of the benefits that resulted from these Productivity Circles that Black describes in Lean Production "Implementing a World Class System". The 757 not only achieved its maiden flight on time and on budget during in 1982, but furthermore pioneered the introduction of statistical process control, lean manufacturing and continuous improvement. [12].

A study made by the Bureau of Labor Statistics shows that the aircraft production productivity in the US increased 3.8 percent annually from 1973 to 1979 and just 0.3 percent annually from 1979 to 1990 [14]. The study itself describes the conditions of aircraft factories during these years being not so different from what can be seen today: *"power drills, wrenches, flashlights, screwdrivers...workers standing on scaffolds, crouching under, sitting inside the aircraft...etc."* The decrease in productivity of the later period was mainly because demand decreased unexpectedly while labour in this industry posed risks to be downsized. This report also remarks: *"One of the ironies about the aircraft industry is that while it makes a high-tech product, it does not rely heavily on high technology for aircraft assembly"*[14].

Attempts to invest in automation can be found since the early 1980s, but even for the most repetitive tasks, the business cases were hindered by the low volumes, uncertainty of demand, complexity and the levels of customization the customers demanded on top of the high costs of automation. In consequence, the technological options to reduce labor in aircraft assembly were limited world-wide. Since 1990, wing drilling and riveting, and milling in some fabricated components were some of the applications that benefited from certain levels of automation, such as numerically controlled machines [13]. Nevertheless, manual tools operated by highly skilled workforce has been an on-going element of the aerospace production systems.

In summary, the most evident periods of productivity increase in the aircraft industry are the war years and the 1980s, and the main takeaways regarding airframe production systems design and performance improvement are:

1) There were consistent efforts to approach the American automobile industry to facilitate capacity increase in aircraft assembly factories during the war periods

2) The Japanese manufacturing cultures were consulted to benchmark methodologies for productivity improvement

3) The search for opportunities to use robots to reduce labour began during the 1980s and 1990s.

1.2 Airframe manufacturing forecasts and strategies in the 21st Century

Section 1.1 provided general information on production volumes and workforce throughout the history of airframe manufacturing. This section summarizes the same information for the commercial aviation segment in the upcoming decades.

The passenger airlines are split into four categories according to the US department of Transportation. The biggest airplane category in revenue is the "international" category that employs small, medium and large wide body airplanes with more than 130 seats. Companies in this category have annual revenues in the ballpark of 1 billion USD. The second biggest category is then "national", utilizing small single aisle airplanes that can accommodate between 100 and 150 passengers providing revenues that range from 100 million to 1 billion USD. Thirdly the "regional" segment that cover short-haul flights with regional jets with less than $100 million of revenue per year.

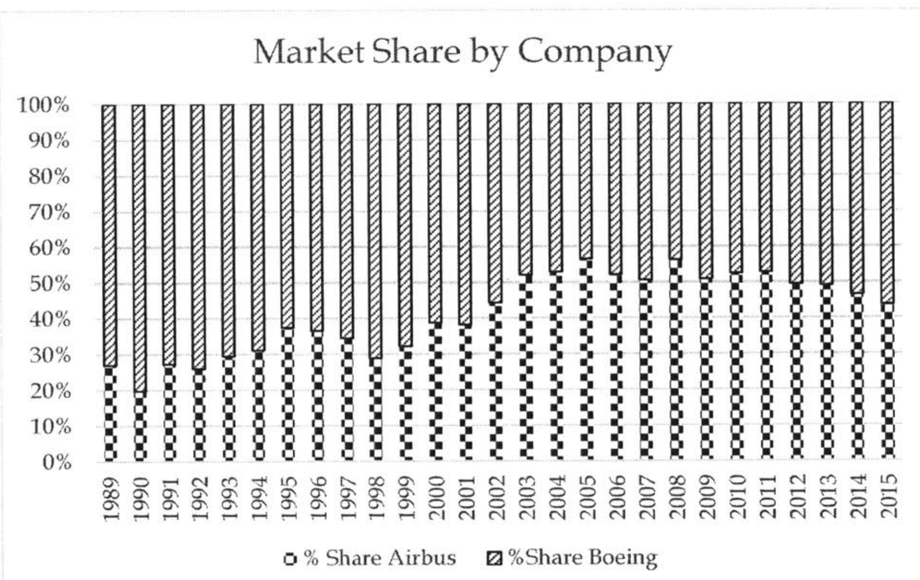
In line with these classifications, the forecasted demand for new airplanes is provided by size for the next 20 years in Figure 1-1.

Figure 1-1: Commercial aviation demand forecast [15]

Demand by size 2015 to 2034	New Airplanes	Value ($B)
Large widebody	540	230
Medium widebody	3,520	1,220
Small widebody	4,770	1,250
Single aisle	26,730	2,770
Regional jets	2,490	100
Total	**38,050**	**5,570**

Figure 1-2 depicts the panorama of the competition of the two companies dominating the market, Boeing and Airbus.

Figure 1-2: Market-share by company [16] [17]



Although Airbus market share has been declining and Boeing has been leading deliveries in the last few years, the commercial airliners price summary (Fig. 1-3) reveals that Airbus prices are more competitive than Boeing in comparable models. The differences in list prices and current order backlog orders (Figure 1-4) creates incentives for Boeing to reduce its cost structure.

Figure 1-3: Price summary [15], [16]

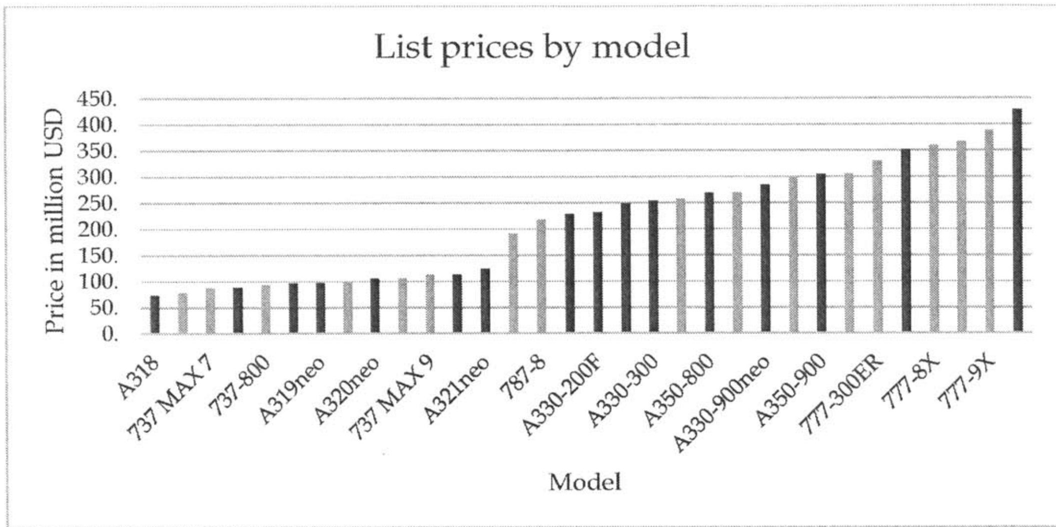
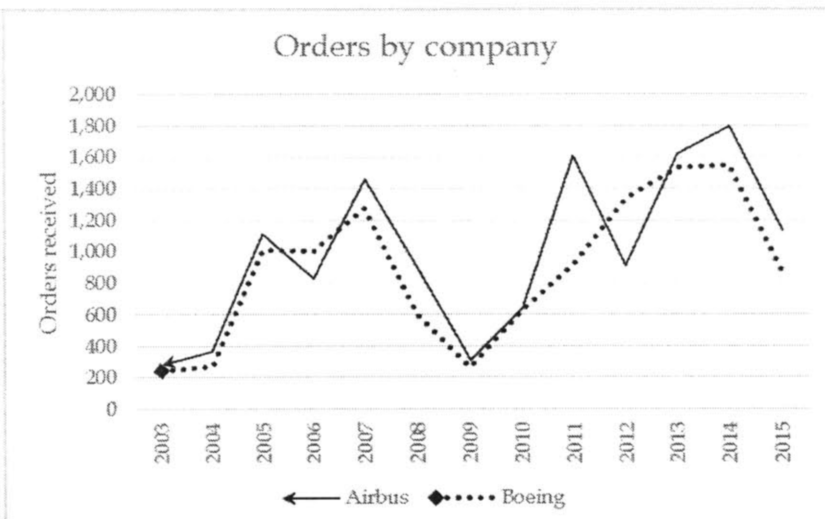


Figure 1-4: Orders by company [17] [18]



A common strategy for both companies is the transition to become more vertically integrated[19]. The National Bureau of Economic Research explains that the relationship between downstream producers and suppliers is more likely to be vertically integrated when the industry is technologically intensive, and the effect is stronger when the suppliers represent large fractions of the producer's costs. This is the business environment under which Boeing Aerostructures Australia existed and where the research activities for this thesis took place.

1.3 Boeing Aerostructures Australia

Australia has played a key role in aerospace manufacturing since the early 20th century. In 1936 the Commonwealth Aircraft Corporation (CAC) was created to focus on the first mass produced aircraft in Australia, the NA-16 general purpose and trainer. This airplane was engineered by

North American Aviation and shared with CAC through a license agreement for 755 units to support the allied fleets. The agreement permitted CAC to modify the engineering design of the NA-16 to meet RAF requirements but furthermore conceived the aerospace industry first industrial establishment in Australia. This aircraft was named the Wirraway, which translates to "challenge" in aboriginal language. The airplane was used for tactical reconnaissance, target marking, supply dropping, dive bombing, army support and, on occasions, as an interceptor fighter [20].

Commonwealth Aircraft Corporation (CAC), which had been in partnership with North American Aviation since the years following the Second World War, was acquired in 1986 by Hawker de Havilland Australia.

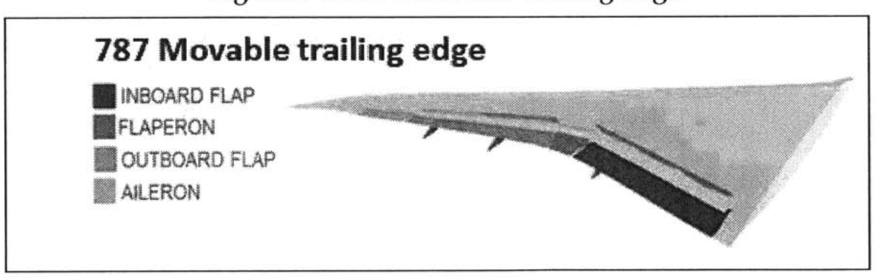
Also, Government Aircraft Factories (GAF) established operations during the Second World War (originally as the Department of Aircraft Production) to assemble Bristol Beauforts and Beaufighters. GAF eventually became AeroSpace Technologies of Australia (ASTA) in 1987; this event marks an acknowledgeable root of Boeing's footprint in Australia [20].

In 1996 Boeing acquired North American and ASTA. In 2000 Boeing also acquired Hawker de Havilland and merged Australian entities under this name. Boeing renamed this subsidiary to Boeing Aerostructures Australia to emphasize the importance of its role in Boeing's Vertical Integration strategy in 2009. Up until then, BAA was a major exporter of components for Boeing, Airbus, Lockheed Martin, Bombardier and other Airplane manufacturers [20].

Boeing Aerostructures Australia (BAA) became the largest manufacturing footprint of The Boeing Company outside of the United States and specializes in designing, developing, testing and manufacturing flight control surfaces [22]. As for 2015, BAA has in-house capabilities of design and analysis, materials and process technology, testing, structural bonding, resin infusion, non-destructive testing, automated assembly and paint [21] to deliver the following set of products to Boeing Commercial Airplane Programs:

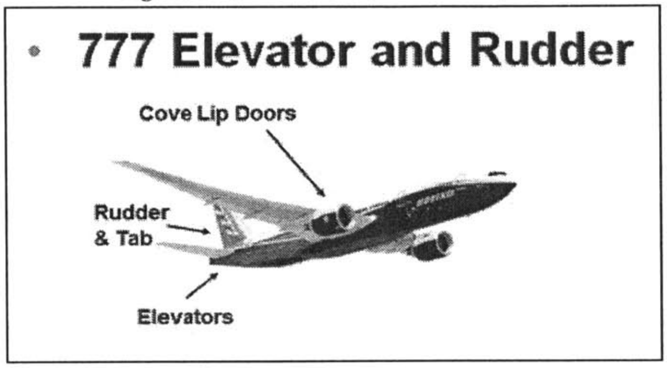
- 787 Moveable trailing edge components (Inboard Flap, Flaperon, Outboard Flap and Ailerons):

Figure 1-5: 787 Moveable trailing edge



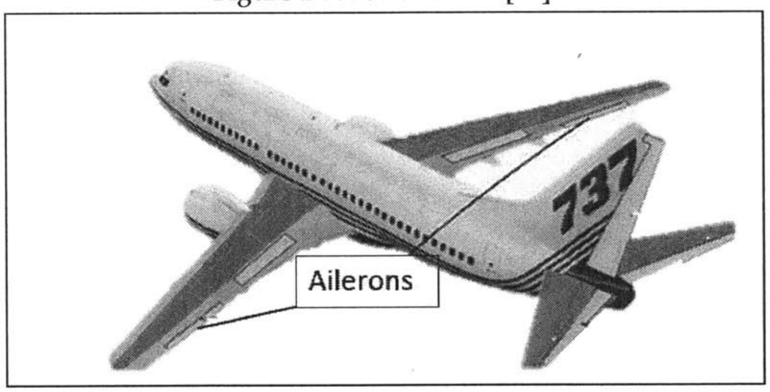
- 777 Rudders, elevators and cove lip doors:

Figure 1-6: 777 elevator and rudder



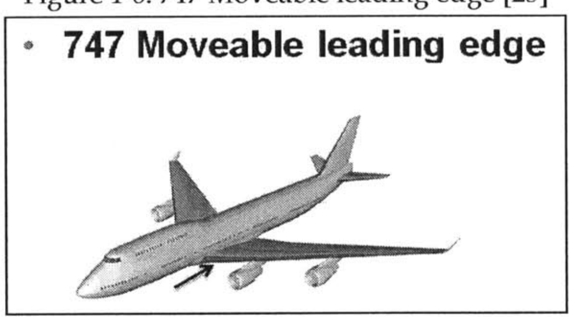
- 737 Ailerons

Figure 1-7: 737 ailerons [22]



- 747 Moveable leading edges

Figure 1-8: 747 Moveable leading edge [23]



The site employs approximately 1200 people and has received significant investments in the last few years to increase capacity to meet production targets for the 787 Dreamliner and will remain playing an important role as a subsidiary for sustaining the 777, 747 and 737 programs with their upcoming delivery targets.

BAA has demonstrated both organizational and operational capabilities to support the rate targets established by Commercial Airplanes, their main internal customer. Starting from delivering 5 ship sets of moveable trailing edges per month for the Dreamliner program, they have successfully reached the 12 ship sets per month line and expect to continue doing so to deliver 14 a month by 2020 [24]. In addition, the 737 line will be ramping up production from delivering 42 airplanes per month to 52 by 2018.[24]

BAA combines design engineering, research and manufacturing to provide an exceptional environment for continuous improvement. Here researchers, engineers and front line workforce contribute organically to help place the Australian manufacturing industry to play key strategic roles in Boeing's global supply chain.

1.4 Productivity and Safety in the Workplace

Considering the increasing demand for new airplanes in the next 20 years (Figure 1-1) and assuming that Boeing's market share of 56% is kept (as of November-2015), a forecast for deliveries can be plotted as shown in Figure 1-5. Additionally, assuming an 11% decrease in employment for aerospace technicians as projected by US Bureau of Labor Statistics in 2022 [25], a theoretical productivity ratio can be calculated for the upcoming years as shown in Fig 1-9.

Figure 1-9: Boeing deliveries and employment forecasted for 2022[18] [25]

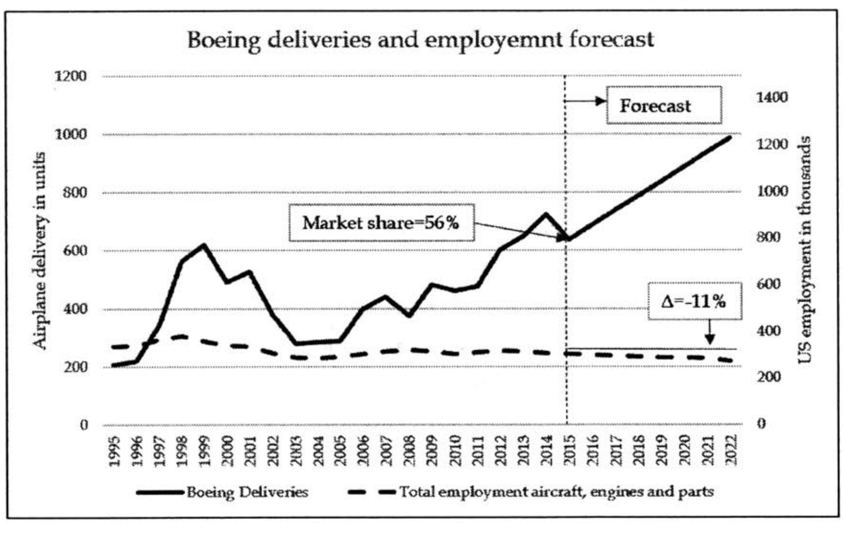
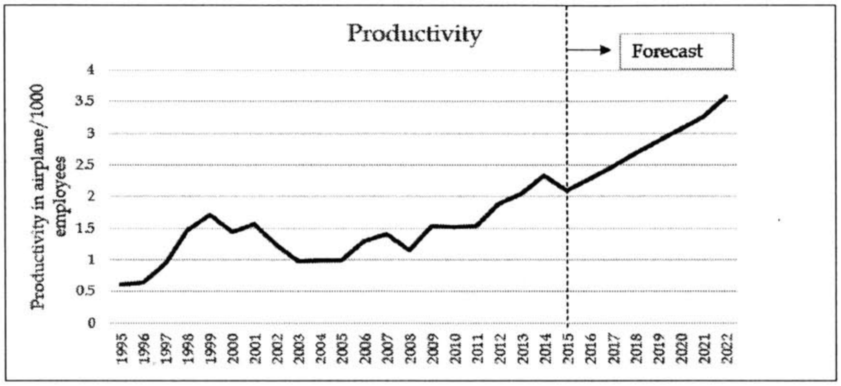


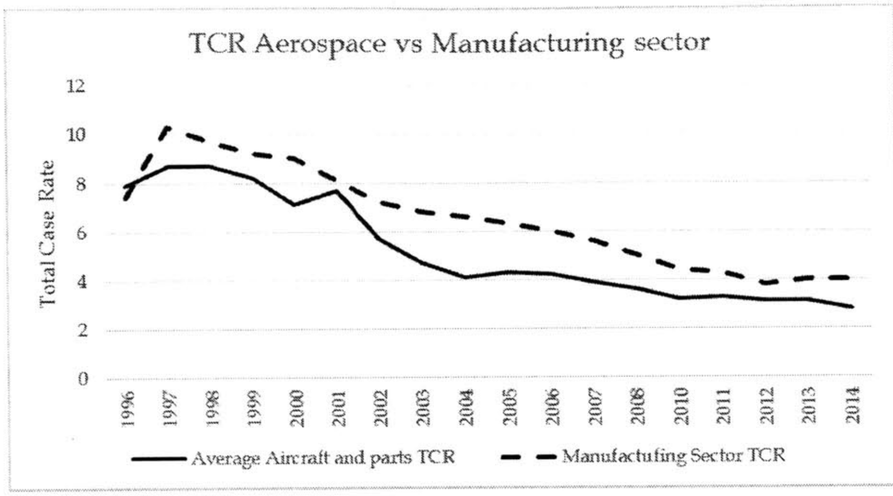
Figure 1-10: Estimated productivity to maintain market share



The productivity estimations based on the current forecasts suggest that all companies in the supply chain will have to produce more with the same workforce. As mentioned earlier, this need for productivity increase should signal the companies to mobilize industrial engineering innovation, automation and reinforce safety and ergonomic improvement programs.

With respect to safety and ergonomics Fig 1- 7 compares the performance of occupational health and safety in aerospace manufacturing in the US with the broader manufacturing sector. The Total Case Rate refers to the total injury reports of a given site, company or industry standardized in a basis of 100 full time employees. According to the reports from the Occupational Health and Safety Administration the TCR decreased by approximately 50% in the last 10 years for airframe manufacturers who have been also performing better than the manufacturing sector overall. Opportunities for improvement will have to be fostered as airframe manufacturers push the current threshold to a 0 case rate [26] while simultaneously increasing the size of production schedules. Improvements have to be made to bring the current production systems from the current occupational health and safety performance metrics to lower values while increasing productivity. Ergonomics and Productivity could become inversely proportional with inadequate implementation of standard work and moving lines.

Figure 1-11: TCR Aerospace vs. Manufacturing sector [26]:



The 757 productivity program is an example of the early efforts to increase production rates [13] and reduce cycle times though the design and implementation of moving lines. These manufacturing improvements are characterized by standardizing the statement of work for employees in the shop floor, moving them from performing several different tasks in parallel, to perform less tasks in a series of workstations. The tasks are designed based on the fundamental principle of standard work: performing simpler tasks, and mastering them with repetition to increase productivity.

One of the immediate benefits of moving and pulsing lines is that quality defects become evident. As an employee performs the task more times in a day, problems become evident faster since more defects will be produced. Action teams are created and improvement plans are defined to tackle the root cause of defects.

Quality is not the only aspect impacted by moving lines. As mentioned previously occupational health and safety metrics are also affected the same way. If an employee on the previous example performs a task that is risky or that poses some degree of discomfort, there should be a concern that the increased repetition of the same tasks will yield more injuries in the moving line than in the previous manufacturing cells operating mode.

Every continuous improvement effort, for productivity, quality, or ergonomics starts with a quantitative measure of performance of the current state as recommended by the PDCA (Plan-Do-Check-Act cycle) methodology suggested from William E. Deming as the foundation of the *kaizen* culture [27]. Similarly, and according to experts in ergonomics, the first step for a comprehensive ergonomic improvement program is to identify and measure ergonomic risk across the operation and then to prioritize the channelling of resources towards safety improvement projects [28], [29], [30]. Having a prioritization method ensures that resources for improvement are applied efficiently.

1.5 Identifying the problem: safety performance baseline

As it will be described in Chapter 2 of this thesis, the study of the human body itself is a vast topic of research, not only for the industry sector but also for athletes and consumer goods [31] [32]. Different tools are used to study the dynamic behaviour of the human body under different load conditions and postures. For example, using biomechanical modelling approaches using muscle fatigue models, musculoskeletal fatigue formulas would require vast expertise At the other end, simplified risk assessment forms and surveys, while easy to use for non-ergonomists, are prone to subjectivity and extensive and detailed observation of the entire manufacturing processes, tools and tasks [33].

To comply with company strategies that foster cost reduction, projects are created to increase productivity by standardizing statements of work, simplifying work schedules, implementing automation and pushing manufacturability into the airframe design. The Occupational Health and Safety departments hold a crucial stake in these project portfolios since they represent the interests of the shop floor employees. In order to make ergonomic improvements in the manufacturing environment, resources have to be prioritized to improve tools and processes. The most common framework to prioritize ergonomic improvement projects is observational risk assessments. These workplace risk assessments require exhaustive observation of the manufacturing process and often times are requested to be delivered with tight lead times. While biomechanical models could be perceived as better option against observational risk assessments, they require to bring in highly specialized professionals. Two main needs are identified therefore for a quick prioritization of ergonomic improvements in the workplace:

1) A methodology for calculating a risk baseline to prioritize ergonomic improvement projects
2) A quantitative evaluation framework that facilitates the quick measurement of risk at early stages of projects that are not targeted to improve ergonomics, but that would impact the statement of work of the technicians.

With limited resources to map out the current state of an entire manufacturing process, the proposed approach then is to measure risk on an aggregated and historical basis. This means providing a statistical approximation of risk, leveraging the similitudes of product architectures and hence the commonality of the assembly process for flight control elements, labor tracking datasets and injury/incident reports. This methodology would not only be helpful to prioritize ergonomic improvement projects, but would also serve to evaluate the ergonomic benefit of any change to the production system, as a function of labor .

Once opportunities are identified and prioritized, the PDCA methodology will be suggested to engage in continuous improvement. A continuous improvement project will be executed with the use of collaborative automation as the pivotal point for the second part of this thesis.

With statements of work transiting from craftsmanship to standard work, motion repetition increases, creating more automation-inclusive environments. Collaborative robotics is a novel category of robotics that emerged in the last decade [34]. This type of technology has been approached by several industries, but has not found an easy way into aerospace assembly, mainly due to the disadvantageous precision capabilities compared to the robotic technologies in place nowadays for airframe assembly operations like match-drilling.

An additional hurdle that is commonplace for technology intervention is economies of scale. Due to the relatively low volumes of aircraft shipments, the investments are hard to justify financially. Examples throughout this thesis will show that there is a significant amount of repetition in assembly and verification operations that, if measured at the appropriate level, create a sound business case for technology intervention. It is difficult to envision automation in an industry that barely delivered above 500 units a year in peak production year (Figure 1-1), but it is easier to envision automation when considering that a single airplane is composed of more than 3 million individual parts [35].

Although many airframe assembly tasks require a high degree of handcraft expertise or high precision automation, this project reveals opportunities for collaborative robotics where repetition and time of exposure represent a risk for the operators and that do not require the level of precision that is mistakenly associated with all operations in the aerospace environment.

1.6 Overview of Hypotheses, Approach and Methodology

Chapter 2 addresses the need for an immediate and practical risk profile to help prioritize occupational-safety motivated projects. It provides an extensive overview of standardized risk assessments from different countries where the main aerospace manufacturers and stakeholders of this project are based in. The main takeaways from this chapter are:

1) In order to make a comprehensive identification and quantification of risk for prioritization purposes, all activities need to be risk-assessed
2) Timeliness and resource planning required to effectively utilize these risk assessment forms across a factory slows down implementation of projects that are critical not only for safety motivated projects, but for productivity and competitiveness driven improvements
3) Risk assessment forms and alternative methods are always prone to subjectivity, especially if the fact that both the assessments and surveys are performed by different individuals.

Based on this analysis, Chapter 3 develops the hypothesis that the risk of injury increases with the increase of labour for a particular task in airframe manufacturing in proportion to historical injury and incidents reported for that and or similar tasks within the same factory. By leveraging the positive correlation of labor and injuries, a risk profile can be obtained with shorter lead time than an observational risk assessment by using currently available datasets of labour per task and injuries per employee. The methodology for creating the data sets, defining the translation of tasks into effect variables and construction of the model through linear regression is presented. The benefits and potential applications of the resulting risk profile are also discussed, as well as its limitations. Chapter 3 finalizes with the recommended next steps for complementing and maintaining the model accuracy and thus to ensure its utility for further continuous improvement projects and new production system design.

Chapter 4 leaps into the overview of collaborative automation, its current availability, capabilities and limitations as well as their applicability for continuous improvement. This results in the identification of the intersection of total automation cost and total industrial safety costs. A blind fastener stem machining was then selected to be a pilot for implementing a collaborative robot following the PDCA methodology.

This chapter describes the time, scope and resource differences between conducting a full production system design and a continuous improvement project, as well as the surrounding productive environment to which the robot will be coupled, in order for the reader to understand the requirements and the constraints within which the development of this solution has to land.

Chapter 4 touches also on the challenges of integrating these technologies for continuous improvement driven projects that are prioritized and decided upon tighter budgets and timelines than the ones characterizing new airplanes and new production systems development.

Chapter 4 continues with proposing a methodology for the implementation of the collaborative robot following a continuous improvement roadmap, rather than a full technology development project.

To support this objective, Chapter 5 begins with describing the foundations and history of continuous improvement and how it should be executed according to aerospace standards. Following existing continuous improvement roadmaps in the aerospace context, the execution of a continuous improvement project using a collaborative robot coupled with the Plan-Do-Check-Act (PDCA) methodology is described.

As indicated by the PDCA basic problem solving flow, the first step was to identify the problem. The Rough Order of Magnitude Risk Profile developed in Chapter 3 was used to evaluate a flight control element assembly line and find the tasks that seem prone to ergonomic risk.

Once a blind fastener stem machining process in the assembly line was selected for improvement, the manufacturing requirements were gathered and cross matched with the available collaborative robot capabilities. The "current situation assessment" was done by summarizing cycle time, conformance requirements, quality performance and ergonomic risk level for the current condition.

After the problem was identified and assessed to establish a baseline for improvement, an action plan was developed to cover the "Do" portion of the problem solving flow chart:

1) Study the fundamental physics of the machining process to understand the deterministic sources of variation
2) Measure the input variability, i.e. state of the parts flowing into the process
3) Hypothesize effects of the process control variables in the collaborative robot
4) Design and conduct experiment to test the effect of the control variables
5) Model the process based on the significant effects of the control variables
6) Determine optimal process settings
7) Simulate process with optimal settings
8) Calculate theoretical process capability

In the first step of the action plan, the blind fastener stem machining process is described and studied to understand the manufacturing tools and deterministic factors that may affect the process output. The study was made to understand the condition of the material entering to the blind fastener machining station, the output of the process and the variables to perform hypothesis testing on.

In the second step, a variability study was done for the blind fastener stem conditions prior to machining. Non-random effects were suspected to be present due to the architecture of the flight control element and the effect of this deterministic offsets on the flight control element final surface flushness is discussed.

To assess the robot capability of taking over the machining task, and based on the outcome of the first step, force, speed and cutting tool shift were defined as the study variables, as defined by the third step of the action plan. The experimental hypotheses is presented as: "The effects of TCP down-force and TCP speed in a collaborative robot are significant to the process capability (Cpk) for stem machining of blind fasteners". An initial approximation is provided using deterministic approaches (Material Removal Rate formulas) for the control variables (force and speed) to be used in the preliminary experimental runs.

To understand the effect of these three variables, a full factorial experiment was designed and conducted using a collaborative robot and a coupon. Robot, hardware, test setting and measuring instruments are also addressed in this step.

For step five, surface flushness measurements were taken from the coupon. Step six describes the data post-processing methodology that lead to the construction of a linear optimization model and furthermore simulate the robot process capability in steps seven and eight. This optimization exercise was performed to determine the optimal settings for the control variables needed to estimate the robot process capability Cpk through a simulation of the stem machining process using observed variability of the key parameters

Chapter 6 finally discusses the last steps of the PDCA problem solving roadmap (establish reliable methods and continuously improve processes) as well as the main observations and key learnings from the process capability simulations. The key topics discussed in this chapter

1) The effect of different inspection devices
2) The effect of uncontrolled variables
3) Other sources of variability that are significant to meeting key product characteristics
4) Recommended next steps for further benefits that could be gained by establishing a statistical process control as suggested per ARP9013 (aerospace recommended practice).

1.7 Summary

Application of kaizen and lean/six sigma to airframe production systems is not new, history shows that many successful attempts have been made from implementing lean principles, to building airplanes in automobile factories to meet ambitious production rates. What is different today, is the width of the gaps in the production systems and the good fit of currently available technologies in terms of cost and capability to fill those gaps along with the objective of becoming an injury-free industry.

Improving ergonomic conditions of the workstations must start with the prioritization of projects based in a standard risk measurement tool. The conventional risk assessment methodologies while adept for non-specialized ergonomist to produce acceptable data is both time and resource consuming and prone to subjectivity. The end result demonstrates that it is possible to measure risk using existing data.

Considering the aforementioned incentives that exist to reduce costs, investment in continuous improvement becomes both non-trivial and time critical. The channels that are in place for technology to be integrated from the lab to the shopfloor are not flexible enough to fit different levels of complexity. This results in unnecessarily exhaustive roadmaps for off-the-shelf technologies to be integrated and implemented. Through the adequate coupling of experimentation and PDCA roadmaps, it is provable that new technologies can flow to the shopfloor in matter of months and not years.

Continuous improvement using cutting edge technology needs to and can be achieved at a fast pace even in an arduously regulated environment such as the aerospace industry. This project demonstrates that through the strong collaboration of the of EHS (Environment, Health and Safety), Quality, Production Systems Engineering and Research and Technology the adequate technologies can be developed and deployed in the right stages of the manufacturing systems in a way that is compliant with both technology readiness and the business needs. For the success of this project, strong involvement was required from every stakeholder from the front line employees to top management levels.

1.8 Chapter 1 references

[1] J. P. Womack, D. T. Jones, and D. Roos, *The machine that changed the world : how Japan's secret weapon in the global auto wars will revolutionize Western industry.* New York, NY : HarperPerennial, 1991., 1991.

[2] "How The Wright Brothers Blew It - Forbes." [Online]. Available: http://www.forbes.com/2003/11/19/1119aviation.html. [Accessed: 06-Feb-2016].

[3] "Flying Wings : An Anthology : Igo Etrich (1879 - 1967)." [Online]. Available: http://www.ctie.monash.edu.au/hargrave/etrich_taube.htm. [Accessed: 07-Feb-2016].

[4] "The Great War Society: Relevance Archive." [Online]. Available: http://www.worldwar1.com/tgws/relairprod.htm. [Accessed: 07-Feb-2016].

[5] "World War I: The Definitive Encyclopedia and Document Collection," *Ref. User Serv. Q.*, vol. 54, no. 4, pp. 85–85, Summer 2015.

[6] "Flying Wings : An Anthology : Igo Etrich (1879 - 1967)." [Online]. Available: http://www.ctie.monash.edu.au/hargrave/etrich_taube.htm. [Accessed: 07-Feb-2016].

[7] B. & Noble, "Freedom's Forge: How American Business Produced Victory in World War II," *Barnes & Noble*. [Online]. Available: http://www.barnesandnoble.com/w/freedoms-forge-arthur-herman/1106725548. [Accessed: 07-Feb-2016].

[8] A. Haggerty and R. Wood, "The P-51 Mustang: A Case Study in Defense Acquisition," *Def. AR J.*, vol. 17, no. 4, pp. 508–519, Oct. 2010.

[9] Willow Run Bomber Plant., "Willow Run reference book," 1945.

[10] "The History of the Aerospace Industry." [Online]. Available: https://eh.net/encyclopedia/the-history-of-the-aerospace-industry/. [Accessed: 06-Feb-2016].
[11] H. W. Lawrence, *Aviation and the Role of Government*. Kendall Hunt, 2004.
[12] "Aerospace Engineering and Operations Technicians : Occupational Outlook Handbook: : U.S. Bureau of Labor Statistics." [Online]. Available: http://www.bls.gov/ooh/architecture-and-engineering/aerospace-engineering-and-operations-technicians.htm#tab-6. [Accessed: 27-Nov-2015].
[13] J. R. Black, *Lean Production: Implementing a World-class System*. Industrial Press Inc., 2008.
[14] *A BLS reader on productivity*. U.S. Department of Labor, Bureau of Labor Statistics, 1996.
[15] "Airbus aircraft - prices 2015 | Statistic," *Statista*. [Online]. Available: http://www.statista.com/statistics/273962/prices-of-airbus-aircraft-by-type/. [Accessed: 07-Feb-2016].
[16] "Boeing aircraft - average prices 2015 | Statistic," *Statista*. [Online]. Available: http://www.statista.com/statistics/273941/prices-of-boeing-aircraft-by-type/. [Accessed: 07-Feb-2016].
[17] "Orders & deliveries | Airbus, a leading aircraft manufacturer," *airbus*. [Online]. Available: http://www.airbus.com/company/market/orders-deliveries/. [Accessed: 07-Feb-2016].
[18] "Boeing 737 Orders and Deliveries," *The Boeing 737 Technical Site*. [Online]. Available: http://www.b737.org.uk/sales.htm. [Accessed: 26-Nov-2015].
[19] "The Industry Handbook: The Airline Industry," *Investopedia*. [Online]. Available: http://www.investopedia.com/features/industryhandbook/airline.asp. [Accessed: 26-Nov-2015].
[20] "Boeing: history." [Online]. Available: http://www.boeing.com.au/boeing-in-australia/history.page. [Accessed: 07-Feb-2016].
[21] "Boeing: Boeing Australia - Boeing Aerostructures Australia (BAA)." [Online]. Available: http://www.boeing.com.au/boeing-in-australia/subsidiaries/boeing-aerostructures-australia.page. [Accessed: 07-Feb-2016].
[22] "Boeing 737 Primary Flight Controls - DutchOps.com powered..." [Online]. Available: http://www.dutchops.com/Portfolio_Marcel/Articles/Flight%20Controls/B737_Flight_Controls/B737_Primary_Flight_Controls.html. [Accessed: 02-May-2016].
[23] "Boeing 747-400 3D Model Download | 3D CAD Browser." [Online]. Available: http://www.3dcadbrowser.com/download.aspx?3dmodel=3631. [Accessed: 02-May-2016].
[24] "Boeing strengthens commitment to Australian manufacturing." [Online]. Available: http://www.smh.com.au/business/boeing-strengthens-commitment-to-australian-manufacturing-20150616-ghpb6d.html. [Accessed: 07-Feb-2016].
[25] "Databases, Tables & Calculators by Subject." [Online]. Available: http://www.bls.gov/data/#employment. [Accessed: 07-Feb-2016].
[26] "Establishment Specific Injury and Illness Data (OSHA Data Initiative)." [Online]. Available: https://www.osha.gov/pls/odi/establishment_search.html. [Accessed: 01-Dec-2015].
[27] "THE PLAN, DO, STUDY, ACT (PDSA) CYCLE." [Online]. Available: https://www.deming.org/theman/theories/pdsacycle. [Accessed: 07-Feb-2016].
[28] "How to Develop an Ergonomic Opportunity List & Prioritize Jobs for Improvement," *Ergonomics Plus*, 21-May-2014. .

[29] "Safety and Health Topics | Ergonomics - Identify Problems." [Online]. Available: https://www.osha.gov/SLTC/ergonomics/identifyprobs.html. [Accessed: 07-Feb-2016].
[30] C. C. for O. H. and S. Government of Canada, "Job Safety Analysis : OSH Answers," 05-Feb-2016. [Online]. Available: https://www.ccohs.ca/oshanswers/hsprograms/job-haz.html. [Accessed: 07-Feb-2016].
[31] "Ergonomics in Sport and Physical Activity - Thomas Reilly," *human-kinetics*, 18-Aug-2009. [Online]. Available: http://www.humankinetics.com/products/all-products/ergonomics-in-sport-and-physical-activity. [Accessed: 07-Feb-2016].
[32] D. O. N. Diban and L. A. Gontijo, "The Complexity of Ergonomic in Product Design Requirements," *Procedia Manuf.*, vol. 3, pp. 6169–6174, Jan. 2015.
[33] F. Redmill and T. Anderson, *Developments in risk-based approaches to safety : proceedings of the fourteenth Safety-critical Systems Symposium, Bristol, UK, 7-9 February 2006*. London : Springer, c2006., 2006.
[34] M. Bélanger-Barrette, "What Does Collaborative Robot Mean ?" [Online]. Available: http://blog.robotiq.com/what-does-collaborative-robot-mean. [Accessed: 07-Feb-2016].
[35] "How Many Fasteners in a Boeing 777? - Global Fastener News." [Online]. Available: http://globalfastenernews.com/main.asp?SectionID=26&SubSectionID=39&ArticleID=10822. [Accessed: 07-Feb-2016].

Chapter 2: Literature review on economics, ergonomics and risk assessment tools

This chapter describes the fundamental relationship of workplace safety with ergonomics and economics, as well as the intersection of these two sciences. Establishing a risk baseline is described as the first recommended step for every occupational health and safety improvement program. Biomechanical models are reviewed first to understand their temporal incompatibility with continuous improvement programs. Conventional risk assessment forms are also discussed as a more convenient option for identifying and measuring risk in the workplace without specialized biomechanical expertise. Both alternatives come, however, with the restriction of being observation-dependent and thus resource-consuming. A common trade-off, accuracy vs. complexity, is found when deciding between these 2 alternatives for gaging risk in the workplace. The more robust or accurate a model or a risk assessment form is, the more data it requires, and thus more observation and resources generally need to be allocated.

2.1 Occupational health and safety in the aerospace industry

OHSA provides data collected since 1996 to measure and compare companies' safety performance. One of the indicators used for this matter is the Incident Rate, which provides the number of recordable incidents that resulted in "days away from work". This figure is standardized per 100 full-time employees in a given time frame. The datasets were gathered through the OSHA Data Initiative [36].

The formula through which OSHA computes incident rates is then:

Incident rate= Number of injuries and illnesses X 200,000 / employee hours worked [1]

The 200,000 labor-hours base rate comes from assuming 100 employees, working 40 hours per week, 50 weeks per year.

The Total Case Rate (TCR) is a similar indicator that includes all cases recorded on the OSHA Form 300, including those that did not result in "days away from work".

The summary of the TCR for the aerospace industry, the entire manufacturing sector and the aerospace component fabrication companies is summarized in Fig 2-1. The TCR for airframe manufacturers and the aerospace component manufacturers (including suppliers) decrease very similarly.

Figure 2-1: Comparison of TCR for aircraft assembly companies and aircraft parts fabrication [1]

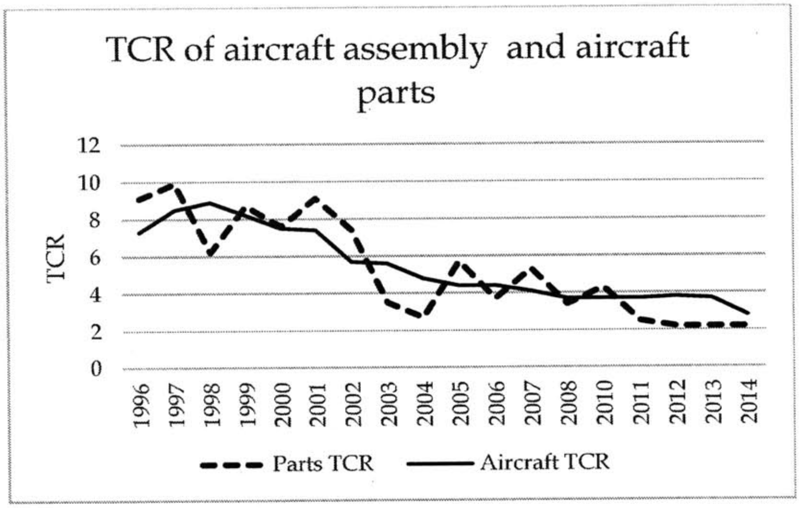
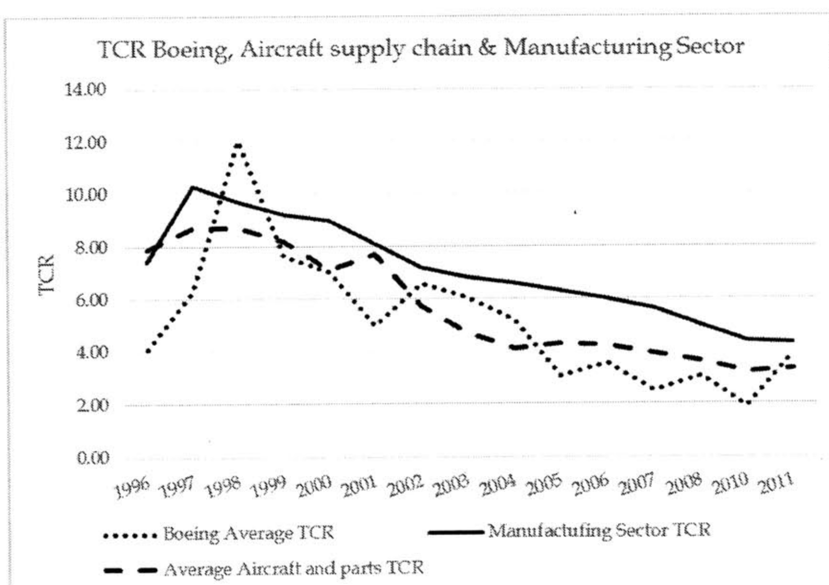


Figure 2-2 shows how The Boeing Company TCR has been similar to the commercial aircraft production sector in the US, including parts suppliers, and generally better than the entire manufacturing sector in the US as mentioned in Chapter 1.

Figure 2-2: TCR comparison of the commercial aircraft supply chain and the manufacturing sector in the US [1].



Companies from all sectors are currently pushing the envelope to reduce the number of incidents, pursuing incident-free production systems. Such is the case with "Nobody Gets Hurt" from Exxon and "Go4Zero" at Boeing [37] [38]. These culture reinforcing programs fall within the second level of safety improvement mechanisms: administrative controls. The caveat with administrative controls is that they are not as effective as the first level of improvements such as engineering controls. Additionally, incentives to not report incidents in a detailed manner are a common reaction to administrative controls resulting in poor investigations [39]. This project proposes a methodology to go from incident investigation to incident prevention using a statistical approach.

2.2 Finding the economic optimal point and the importance of risk assessments

Ergonomics is the applied science that studies the fit of the human body to the work environment and conditions. It defines the physical stressors that act on the mechanical joints of the body as well as the environments factors that can affect hearing, vision and comfort [40]. Ergonomists pursue to promoting the design of jobs and workstations that are safe and productive.

The American Society of Safety Engineers (ASSE) and many scholars in Environment, Health and Safety converge on the fact that the benefits of investing in industrial safety improvement programs are difficult to quantify. Civil liability damages, benefit claims, litigation expenses are some examples of costs that companies incur in when safety-management systems are overlooked.

Costs of poor workplace safety might as well extend beyond the immediate consequences. Increase in psychological stress, loss of skilled workers, and damaged reputation affect companies in their efforts to attract talent while finding themselves pushed to offer wages above the market average for doing so [41].

According to ASSE about $40 billion is paid each year by employers and insurance companies. ASSE also claims that there is a positive correlation between investments in health and safety and subsequent ROI [41].

Companies typically address workplace safety thorough interventions as mentioned in the previous section. Literature on health and safety management systems nests these workspace interventions into three different clusters: engineering controls, administrative controls and personal protective equipment [42]. This project relates to the engineering controls including all changes to statements of work, processes and tools to reduce the exposure of the body to hazards.

Economics is the study of the optimal and efficient allocation of resources (land, labor and capital) to maximize welfare [43]. Cost-benefit analysis techniques used in operations management result from interpolating this definition of economics to make decisions on budget allocation and expenditure channels based upon information summarized business cases. Generally these business cases include estimated cash-flow projections expected to be perceived as a result of making such investment. The information and assumptions made to construct business cases is then of great importance for the efficient allocation of resources.

As described by Ray K. Tapas [44], ergonomics and economics find common ground when the workforce is deployed to safe work conditions and technological interventions are performed in the right places to ensure that these conditions are sustained.

Oftentimes the benefits of ergonomics are difficult to quantify in terms of cash flow; especially when jobs are performed in poor ergonomic conditions and there are no documented injuries or incidents that could be directly associated with them. The financial justification of ergonomically driven programs is composed of injuries and incidents that might or might not take place in the future. Hence, constructing a cost-benefit analysis for purely ergonomics- improving motivated projects is usually painstaking [9].

A common hurdle in the process of constructing a business case manifests when the total cost of presenteesim (employees present and working but in a non-optimal physical state) and absenteeism (lost days of work because employees are injured) cannot be traced back to the particular jobs or workstation, since only the raw and discrete record of an injury is kept. To address this issue, Tapas K Ray[44] proposes 3 ways to construct business cases when this data is not available:

1) Cost-analysis
2) Cost-benefit analysis and c
3) Cost-efficiency ratio.

The cost-analysis starts with identifying the opportunity cost, which implies calculating the production output that could have been achieved if an entirely healthy employee would have been in place. The opportunity cost is calculable when ergonomic risks have been identified and quantified or injuries have already been recorded. While this approach could justify the need for administrative controls, it does not provide a prioritization methodology for tasks in a manual-labor intensive manufacturing process.

The costs of safety can be categorized into direct costs and indirect costs. Direct costs refer to medical expense costs and insurance administrative costs, which could be covered by the employees or the employers. Direct costs are easy to trace and calculate whereas indirect costs relate to those (monetary or non-monetary) in which the employer, employee and/or society incurs and that are not work-compensation related. These costs are often referred to as "hidden" but could be exemplified by loss of efficiency, idle capital and labor due to absenteesim, worsened employee morale, low productivity, additional resources that have to be allocated to train new employees, investigation, counseling...etc. This information is not easy to gather and integrate into a sound business case. According to Leigh et al [45], indirect costs can add up to almost 80% of the total illness costs. Because of this, performing risk assessments to quantify risk might not capture altogether the real indirect costs of an injury that might be caused in the future.

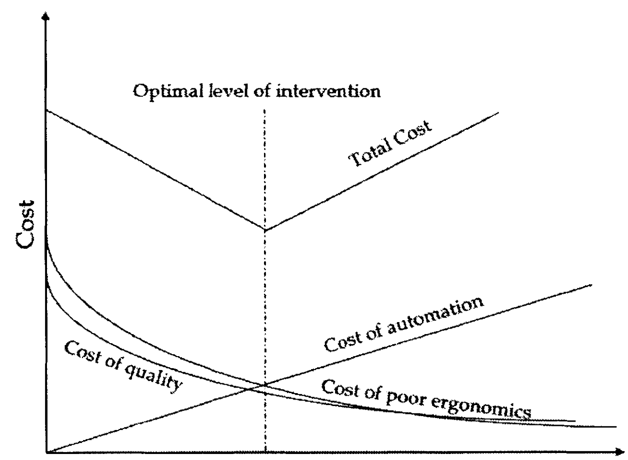
There are documented cases of companies that have been successful at justifying safety improvement initiatives. Avery Deninnson reported savings of $1.7 million over 2.5 years in compensation costs and an increase in productivity. Nintendo was able to observe savings of $1 million annually after an initial investment of $400,000, representing a 40% reduction in labor costs and Hewlett-Packard recovered investment plus 5% in a year[46].

Tapas also emphasizes that "hazard exposures that result in cumulative trauma and injuries/illnesses take time to become acute and to lead to workplace absences"[9]. So even before the hazard brings measurable consequences, like a traceable injury report, it might have already incurred in loss of efficiency and productivity.

In general, approaching occupational safety by using cost analysis can immediately reveal the need for technological intervention and improvements to processes and tools, but it does not indicate what is the most optimal way to intervene; in other words, a cost analysis will only point out to the decision makers that the company would be simply better off by improving economics, without providing guidance towards specific workstations nor the most adequate technological interventions to mitigate risks. Tapas then suggests a Cost-Benefit Analysis as a secondary option [10].

A cost-benefits analysis allows to factor in the cost of the technological solution depending on the level of technological intervention and the availability of the options. While performing a cost-benefit analysis, the savings due to improved quality can be factored in to gage the profitability of any technological intervention. By applying this rationale proposed by Tapas to justify automation [10] the optimal level of intervention can be understood as follows:

Figure 2-3: Optimal level of automation [10]



A total cost function, as shown in Figure 2-3, could be constructed if the following information was available and accurate:

1) Detailed records of injuries/incidents
2) Re-work and scrap records to calculate cost of quality
3) The net effect automation, or any type of technological intervention, would have in the process.

With a total cost function constructed, it would be easy to find that minimum where total cost of the technological intervention equates the cost avoidance associated with poor ergonomics and poor quality.

In a cost analysis, a decision on capital investment can be made upon a net present value that is greater than zero or determined by a benefit-cost ratio that is greater than one [10].

(2.1)

$$\text{Net present value (NPV)} = \sum_{t=0}^{N} \frac{Benefit(B) - Cost(C)}{[1+r]^t}$$

t=time interval length
N=total time in which the benefits are perceived
r= interest rate or cost of capital

(2.2)

$$\text{BCR} = \sum_{t=0}^{N} \frac{Benefit}{(1+r)^t} \Big/ \sum_{t=0}^{N} \frac{Cost}{(1+r)^t}$$

t=time interval length
N=total time in which the benefits are perceived
r= interest rate or cost of capital

The second approach suggested by Tapas is the Cost-Effectiveness Analysis. This method allows the decision maker to consider the effectiveness of different alternatives of intervention on reducing the likelihood of injuries and/or incidents. This method does not rely on monetary value of the benefits from technological interventions, but rather proposes health associated variables like "reduced absenteeism" or "injuries prevented".

A cost/efficiency (CE) ratio is proposed then as:

(2.3)

$$\left(\frac{C}{E}\right)_A = \frac{(\text{intervention cost}_A - \text{injury/illness cost averted}_A)}{\text{total injuries/illnesses prevented}_A}$$

In this formula injury/illness cost adverted refers to the health associated variables, the smaller the ratio the better a technology for the job that is being considered for improvement or intervention.

Similar to the cost-only analysis mentioned previously, cost-benefit and cost/efficiency analyses work under the assumption that particular tasks and workstations have already been selected and prioritized for improvements. It is of great usefulness to gage the level of automation that is needed to address ergonomics, quality and productivity; there, however, a preliminary step that must be taken to prioritize workstations that need improvement. While these 3 methodologies allow some degree of comparison between different intervention options, they do not provide a prioritization framework for the current condition of a production system.

Across industries the decision making process for engineering projects is not only subject to cost-based analysis. There are other factors such as time to implementation, performance requirements, and complexity, among other factors, that influence the technology development decisions process. This is covered in more depth in Chapter 4.

Selecting the right level of intervention is a "second step" in an ergonomic improvement project, but the first step should be to identify which jobs are hazardous and how hazardous they are compared to each other. Cost analysis could be applied to a macroscopic level where comprehensive administrative controls for ergonomic improvement are evaluated to be implemented by high management layers. Here, at a corporate level, the cost of occupational health and safety could be easily considered as the aggregated costs recorded by Occupational Health departments. Alternatively, the cost analyses can be applied to a microscopic level where a particular step or particular workstation has been identified and selected for improvement.

Thus, when a company has already decided to commit resources to ergonomic- improvement projects, a preliminary and yet timely step is necessary to map-out where those resources need to be allocated, where the interventions are needed the most; as addressed by Tapas (page 14): "Uncertainty may arise due to the presence of imperfect information and/or incomplete information" [10].

In this matter, "$afety Pays", offered since 2009 by OSHA [47], is a free and interactive tool that helps estimating the cost of occupational health using a national average cost of injury and the company profit margin. Similarly the productivity assessment tool proposed by Oxenburgh and Marlow [48] is used to measure the cost-effectiveness of an employee after an improvement has been made to the work conditions.

Companies are often reactive to incidents [49]. They trigger improvement projects and investigations immediately after an injury/incident is reported. Usually a risk quantification is made, but very seldom the same risk measure will be available for the remainder of the jobs in the manufacturing process. The resulting measure will be only used to gage the benefits of an improvement project for that particular task. This leaves aside other tasks that might be already more risky or even hiding indirect costs, but that have not manifested their severity because an injury has not happened yet elsewhere. If a factory is understood as a system, that has certain probability of failing and we want to estimate that probability in the most accurate way, one would have to experiment as dictated by the basics of scientific method. In this case, when people are the subject matter, experimenting is never an option.

The only way to prioritize quantifiable workplace improvement is first measuring the ergonomic risk factors for every task that compose a manufacturing system, and the most common way of doing this effectively is by applying the appropriate ergonomic assessment tools. Being aware of fatigue/discomfort on the shop floor is an easy task, and employees can always be proactive in raising hazards observed day after day in the workplace. Without standardized risk quantification techniques, the difficulties arise when deciding whose voice to listen to first.

2.3 Human body as a machine-biomechanical models

The human body can be pictured as a fascinating and complex machine. It has 244 degrees of freedom, controlled by 630 muscles. Analyzing causes and treatments for its' (still unquantifiable) failure modes is covered by vast and diverse medical disciplines.

As far as the industry is concerned, the most typical injuries in the workplace are musculoskeletal disorders (WMSDs), such as low-back pain (LBP) and distal upper-extremity musculoskeletal disorders (MSDs) [50]. The main sections of the body suggested to study MSDs are neck, shoulders, wrists, back (upper and lower), hips, legs, knees, feet which are the areas that constitute the musculoskeletal system according to the American Academy of Orthopedic Surgeons. The most common disorders are: low back pain, fibromyalgia, gout, osteoarthritis, rheumatoid arthritis, tendinitis [15].

Damage to bones, ligaments and muscles is a result from collisions, excessive strain and stress and repeated use under moderately large cyclic stresses, such as any other machine that is built of materials with certain properties and strengths.

The objective of biomechanical models is to describe the stressors to the musculoskeletal structure of the human body. These models can be applied to analyze workstations and gain understanding of how the human body would react or fail to a given set of task conditions. One of the benefits of biomechanical modeling is the quantitative nature of the results and provides deterministic values for the critical loads and exposure times that could be acceptable for the human joints, and furthermore provide predictive insight for injuries.

A biomechanical model is then a "mathematical representation of the musculoskeletal system" [51]. A biomechanical model is useful to calculate the resulting forces (external and internal) on joints based on exertion parameters such as angles, velocities, load magnitude and impacts for complex load condition and motions. With a further comparison to the tolerances and strengths of these joints, a prediction of failure or injury can be obtained. The most available models are for back and wrist but models can be found for almost any joint of the body [16].

One disadvantage of biomechanical modelling is the complexity of the human body and the load conditions that are in question. There are for instance static 2D models with stick figures, where motion is neglected and anatomical elements that can result of structural importance are oversimplified [52]. In order for the model to gain accuracy, it needs to become more complex. Building or buying an existing model might be a recommended solution for preventing poor ergonomics since early stages of future production systems, but not for continuous improvement purposes.

Because of the sensibility to the assumptions made by the analyst, another disadvantage faced by even the most simplified biomechanical models is the dependency on highly specialized and scarce professionals; just like any other type of mechanical simulation such as FEA, CFD where the software tools though being effective to deliver a numeric result, it may vary significantly depending on how the loads, constraints and meshing where treated and how reports are interpreted.

The study performed by Marras and associates is of relevance for the purposes of this project. More than 400 manual material handling tasks were studied in almost 50 different industries. Based on observation, above 100 job characteristics such as weights, distances, heights and cycles where identified and recorded. The study required workers to use tri-axial goniometer for measuring angles and positions. Then a multiple logistic regression was used to identify the combination of factors that seemed to better predict an increase of the likelihood of an LBD (low-back disorder). This study demonstrates quantitatively that by considering the magnitudes of the aforementioned factors is possible to predict an increase of risk [53].

Although these models are evolving and useful in early stages of workstation design, there is no evidence that these models are of optimal utility in continuous improvement environments when time-to-action is critical. The most important limitation is the needed level of realism to accurately describe pain and discomfort, especially in industries where the employees' statement of work are changing rapidly with new lay-out of processes as mentioned in Chapter 1 such as industrial engineering improvements, integration of new tools, technologies and constant evolution of the workstations in a broader sense. The accurate application of these models require extensive measurements and observation of the workstation to measure tasks and gather the needed inputs for the models to work properly.

2.4 Risk assessment forms

Risk assessment forms are an interface for unspecialized analysts to address ergonomic evaluations. These type of tools are convenient for fast evaluation of workstations, tools, processes and conditions with a very pragmatic approach to rapidly identify opportunities for improvements and justify investment.

There is not a perfect tool to be applied to aerospace manufacturing systems, but some of them might be better suited than others in providing a standardized measure of risk among manual tasks within the manufacturing layout.

According to [19] a good field (risk) assessment tool should be;

1) Predictive: it shall have the ability to provide a quantitative measure of the likelihood of injury
2) Robust: meaning that it shall be useful in different tasks
3) Inexpensive: should be available at minimum cost
4) Noninvasive: it should not interfere with the normal execution of the task
5) Quick
6) Easy to use with minimal training

A common trade-off identified across risk assessment tools is complexity vs accuracy. The more robust an assessment form is, the more inputs it needs and the more complex it gets. After considering several risk assessment forms, MANTRA, WSPS (formerly IAPA) and the OSHA Job Hazard Analysis forms where selected as the most adequate for risk assessing manual tasks.

The "Manual Task Risk Assessment" better known as MANTRA is an Australian risk measurement tool whose intent is to be used by health and safety inspectors. This tool relies in a semi-quantitative scale and requires the inspector to describe tasks in terms of the following variables: cycle time, force, speed, awkwardness and vibration. This tool also allows to analyze the body by breaking it down into regions. Then, by combining duration and cycle time, the measure of "repetition" is derived. Similarly, the "exertion" value is derived by combining force and speed [54]. Later, all scores added up linearly and with an equivalent weight for each of the stressors. The MANTRA provides the inspectors with guidance, based on the results obtained, for when to create improvement projects. MANTRA is known to be unnecessarily complex for usual workstation evaluations [19]. PERFORM, on the other hand, provides a much simpler interface especially when analyzing manual tasks. Again PERFORM suggests to breakdown the tasks in terms of duration, exertion, posture, vibration, repetition for different zones of the body. This risk assessment tool summarizes the results using a "risk profile". Nevertheless, PERFORM does not suggest any mathematical way of combining scores for each one of the factors neither does it provide guidance in how to compare different risk profiles. According to AS/NZS ISO31000:2009, risk evaluation is a fundamental component of risk assessment [19].

Another MSD risk assessment tool, provided originally by IAPA (Industrial Accident Prevention Association) is now offered by Workplace Safety & Prevention Services (WSPS) [55]. The tool suggests beforehand to find potential risks of repetitive strain before performing a detailed risk assessment. The stressors suggested by WSPS are: contact stress, repetition, grip force, lift/lower force, awkward posture and vibration. This ergonomic risk assessment tool furthermore analyzes different segments of the body like hands and knees for contact stress. For calculating risk coming from repetition, the tool suggests to focus on the neck, shoulders, elbows, wrists, hands. The physical risk factors are described as repetition of the same or very similar motion with very limited variation every few seconds. The assessment forms asks the evaluator to identify if the duration for the repetitive motions are of more than 6 hours per day. For wrists and hands in combination on the other hand, the threshold to consider repetition to be critical is 2 hours per day, where a combination of wrist and hands with wrist bending is considered more critical. Awkward postures and keying are considered critical if performed in a repetitive fashion for more than 4 hours per day. For the stressor labeled as Gripping Force, the physical risk factor suggested to be captured by the evaluator is gripping unsupported objects weighting 1 kg or more per hand. This is considered to be risky if exerted for more than 3 hours a day.

MANTRA and IAPA-WSPS converge in the fact that a prioritization of tasks is done before applying the risk assessment forms. According to [56] "The first step was to develop a prioritized list of departments and jobs to evaluate". Prioritizing the processes, tools, tasks and conditions is not an easy job when a complex process, such as aerospace structures assembly, is composed of hundreds of different manual tasks. This source for example recommends Initial Ergonomic Audits and even performing surveys which are also subject to some degree of subjectivity.

OSHA recommends a job hazard analysis to identify hazards before injuries or incidents occur. To select the most appropriate jobs for hazard analysis, OSHA points out to filter the list of jobs according to the illness or injury rates, severity or likelihood to cause disabling injuries, jobs in which human error would lead to a severe injury or incident, new jobs or tasks in the operation and jobs that are complex enough that require written instructions [29].

Furthermore, because the frontline workforce owns the best understating of the job hazards, OSHA points out that the best starting point is employee engagement. The second step is reviewing the accident history. Everything from "near misses" to "lost days" or even events in which an incident did not happen, but could have happened. This type of events indicate that the current controls in place might not be adequate or deserve careful re-evaluation. The next step on performing job hazards is performing job reviews, which is receiving input from the front line employees about the current hazards in the current state and brainstorm on the potential solutions [21].

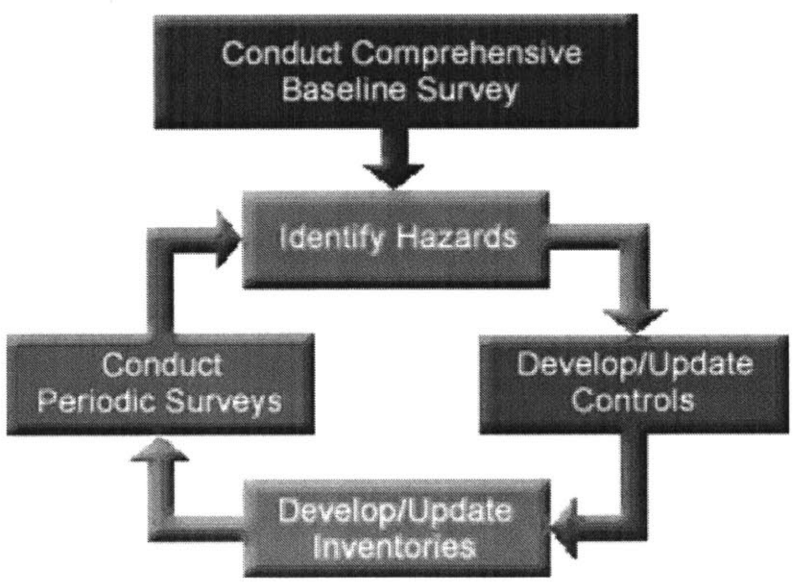
OSHA suggests that "any hazards exist that pose an immediate danger to an employee's life or health, take immediate action to protect the worker" [21]. They indicate that problems that could be easily corrected do not need to wait to be put through the job hazard analysis. As number 4, OSHA indicates to list, rank and prioritize hazardous jobs. The final instruction in the job hazard analysis is to break down the job into sub steps or sub tasks without being too detailed, but without being too broad.

To identify hazards within the workplace the preliminary questions to be answered are:

- What can go wrong?
- What are the consequences?
- How could it arise?
- What are other contributing factors?
- How likely is it that the hazard will occur?

A complementary framework proposed by OSHA is the Worksite Analysis which suggest companies to follow this plan:

Figure 2-4: OSHA worskite analysis plan



A final recommended action for the Worksite Analysis plan is to identify trends over time in a way that common causes of injuries or incidents could be prevented. The recommended sources of data are inspection records and employee hazard reporting records. For small sites, OSHA suggests a review of 3-5 years of records while suggesting yearly or even quarterly reviews for trend identification. Illness and injury records are mere evidence of lack of controls and variables like the type of work that was being performed, time of the day and equipment are suggested to be scrutinized [21].

According to the European OSHA, the main goal of an occupational risk assessment should be to protect worker's health and safety. Risk assessment allow to reduce the probability of workers or the environment being harmed because of work-related activities. The proposed steps to carry out a risk assessment are:

1) Collect information
2) Identify hazards
3) Assessing risk from hazards, which means quantifying the probability and the severity of the consequence along with the tolerance of this risk.
4) Plan actions to minimize risk
5) Documenting risk assessment.

For step 1 the information suggested to be collected is specifics on materials equipment and procedures used, hazards that have been identified, lists of people, accidents, diseases and occurrences of ill-health that have been reported. The sources of information should be technical data on equipment, technological procedures and work manuals, records of work accidents, scientific and technical literature.

For step number 2, the European OSHA makes available a General Checklist (Fig 2-5) and also provides specific checklists depending on the nature of the industry (food processing, automobile repairs…etc.). Once a list of identified hazards has been created, the next step is to risk-assess them. Each identified hazard has to be ranked on small, medium or high depending on the probability and severity of harm that can be caused. Probability and severity should be calculated using Figure 2-5.

Figure 2-5: Probability and severity ranks [23]

	Severity of consequences		
Probability	Moderate harm	Medium harm	Extreme harm
Highly improbable	Small (1)	Small (1)	Medium (2)
Probable	Small (1)	Medium (2)	High (3)
Highly probable	Medium (2)	High (3)	High (3)

Figure 2-6: European OSHA Risk Assessment [23]

| Checklist – General

No.	Hazard	YES	NO	Do not know: go to this hazard-specific checklist:
1	2	3	4	5
1.	Uneven or slippery surfaces (which can cause slips, trips, falls, etc.)	O	O	Part III - 1
2.	Moving vehicles and machines	O	O	Part III - 2
3.	Moving parts of machines	O	O	Part III - 3
4.	Objects and parts with dangerous surfaces (sharp, rough, etc.)	O	O	
5.	Hot or could surfaces, materials, etc.	O	O	
6.	High workplaces and climbing points (which can cause falls from a height)	O	O	
7.	Hand tools	O	O	
8.	High pressure	O	O	
9.	Electrical installations and equipment	O	O	Part III - 4
10.	Fire	O	O	Part III - 5
11.	Explosion	O	O	Part III - 6
12.	Chemical substances (including dust) in the air	O	O	Part III - 7
13.	Noise	O	O	Part III - 8
14.	Hand-arm vibration	O	O	Part III - 9
15.	Whole-body vibration	O	O	Part III - 9
16.	Lighting	O	O	Part III - 10
17.	UV, IR, laser, and microwave radiation	O	O	
18.	Electromagnetic fields	O	O	
19.	Hot or cold climate	O	O	
20.	Lifting and carrying loads	O	O	
21.	Work involving poor posture	O	O	
22.	Biological hazards (viruses, parasites, moulds, bacteria)	O	O	
23.	Stress, violence, harassment (mobbing)	O	O	
24.	Others: please specify below and tick "YES":			
		O	O	
		O	O	

2.5 Chapter 2 summary

Analytical and observational methodologies, such as risk assessment forms, are not optimal in terms of time and money for calculating risk. Although risk assessment forms provide a simplified method to quantify ergonomic risk, they also involve direct observation of the entire manufacturing process in order to build a comprehensive risk mapping. One alternative to these methodologies are biomechanical models, for which a team of experts, coupled with sophisticated monitoring equipment, will most likely be required to get to results. A statistical approach, that would work similar to an epidemiologic study from the data processing perspective, will be proposed in the next chapter as a fast-paced alternative to map risk across an operations environment. When a company has already committed to the strategy of minimizing ergonomic risk as a response to employees communicating the need for improvement, workstation and process flow- redesign is happening faster every time and list of continuous improvement projects and technologies are standing by waiting to be prioritized. This proposed approach shall comply better with one of the main characteristics for risk assessement forms described in the beginning of this chapter, namely that it should be quick.

Standardized risk assessment forms can find better application when making a final assessment of implemented improvements to the worksite. Next chapter will discuss where in the product lifecycle the best opportunities for biomechanical models, statistical risk profiling and risk assessment forms are encourntered.

2.6 Chapter 2 appendix

MaANTRA [19]

Physical Stressor Assessment

Appendix C

Manual Tasks Risk Assessment tool (ManTRA) Scoring Matrix

			Task Codes							
Body Region	Total time	Duration	Cycle time	Repetition Risk	Force	Speed	Exertion Risk	Awkwardness	Vibration	CumulativeRisk
Lower Limbs										
Back										
Neck										
Shoulder/ Arm										
Wrist / Hand										

Cumulative risk is the sum of unshaded cells.

Codes

	1	2	3	4	5
Total time	0-2 hours/day	2-4 hours/day	4-6 hours/day	6-8 hours/day	> 8 hours/day
Duration of continuous performance	< 10 minutes	10 min - 30 min	30 min - 1 hr	1 hr - 2 hr	> 2 hr
Cycle time	> 5 minutes	1 – 5 minute	30 s - 1 min	10 s - 30 s	< 10 s
Force	Minimal force		Moderate force		Maximal force
Speed	Slow movements	Moderately paced	Little or no movement – static posture	Fast and smooth movements	Fast, jerky movements
Awkwardness	All postures close to neutral	Moderate deviations from neutral in one direction only	Moderate deviations in more than one direction	Near end range of motion posture in one direction	Near end range of motion in more than one direction
Vibration (Whole body or Peripheral)	None	Minimal	Moderate	Large amplitude	Severe amplitude

Scoring Keys for Repetition & Exertion

Scoring key for Repetition

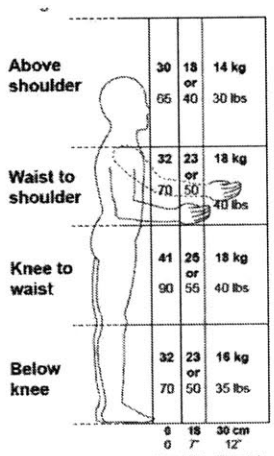
			Duration		
Cycle Time	*1*	*2*	*3*	*4*	*5*
1	1	1	2	3	4
2	1	2	3	4	4
3	2	3	3	4	4
4	3	3	4	4	5
5	3	4	4	5	5

Scoring key for Exertion

			Force		
Speed	*1*	*2*	*3*	*4*	*5*
1	1	1	2	3	4
2	1	2	3	4	4
3	2	3	4	4	5
4	2	3	4	5	5
5	3	4	5	5	5

IAPA-WSPS MSD [20] evaluation form

IAPA



How Many Lifts per Minute	For How Many Hours per Day?		
	1 hr or less	1 hr to 2 hrs	2 hrs or more
1 lift every 2-5 min.	1.0	0.95	0.85
1 lift every minute	0.95	0.9	0.75
2-3 lifts every minute	0.9	0.85	0.65
4-5 lifts every minute	0.85	0.7	0.45
6-7 lifts every minute	0.75	0.5	0.25
8-9 lifts every minute	0.6	0.35	0.15
10+ lifts every minute	0.3	0.2	0.0

Note: For lifting performed less than once every five minutes, use 1.0

Risk Factor	"Potential Risk"	"High Risk"
Contact Stress	☐	☐
Repetition	☐	☐
Grip Force	☐	☐
Lift/Lower Force	☐	☐
Awkward Posture	☐	☐
Vibration	☐	☐

2.7 Chapter 2 references

[1] "Establishment Specific Injury and Illness Data (OSHA Data Initiative)." [Online]. Available: https://www.osha.gov/pls/odi/establishment_search.html. [Accessed: 07-Feb-2016].

[2] "Boeing: Employee Safety Guiding Principles." [Online]. Available: http://www.boeing.com/principles/employee-safety.page. [Accessed: 08-Feb-2016].

[3] "'Nobody gets hurt': A safety journey." [Online]. Available: http://www.safetyandhealthmagazine.com/articles/-nobody-gets-hurt-a-safety-journey. [Accessed: 08-Feb-2016].

[4] "Zero injuries - goal or vision?" [Online]. Available: http://www.ishn.com/blogs/16-thought-leadership/post/98932-zero-injuries---goal-or-vision. [Accessed: 08-Feb-2016].

[5] "Defining Ergonomics." [Online]. Available: https://ehs.okstate.edu/kopykit/ergo.htm. [Accessed: 08-Feb-2016].

[6] "bosc article 6 | American Society of Safety Engineers." [Online]. Available: http://www.asse.org/bosc-article-6/. [Accessed: 01-Dec-2015].

[7] "Safety and Health Management Systems eTool | Module 2 - Overview of System Components: Hazard Prevention and Control." [Online]. Available: https://www.osha.gov/SLTC/etools/safetyhealth/comp3.html. [Accessed: 08-Feb-2016].

[8] P. A. Samuelson and W. D. Nordhaus, *Macroeconomics*. Boston : McGraw-Hill Irwin, c2010., 2010.

[9] TapasK Ray, ThomasR Waters, and Steve Hudock, "Economics of Ergonomics," in *Occupational Ergonomics*, 0 vols., CRC Press, 2012, pp. 1013–1039.

[10] J. P. Leigh, *Costs of occupational injuries and illnesses*. Ann Arbor : University of Michigan Press, c2000., 2000.

[11] "Making A Business Case: Selling Ergonomics." [Online]. Available: http://www.ishn.com/articles/82685-making-a-business-case-selling-ergonomics. [Accessed: 08-Feb-2016].

[12] "Safety Pays." [Online]. Available: https://www.osha.gov/Region7/fallprotection/safetypays.html. [Accessed: 08-Feb-2016].

[13] A. M. Dore and E. K. Lo, "Economic evaluation of robot-based assembly systems," *Int. J. Prod. Res.*, vol. 29, no. 2, p. 267, Feb. 1991.

[14] elementalergonomics, "Reactive and Proactive Ergonomic Evaluations," *Elemental Ergonomics's Blog*, 09-Feb-2011. .

[15] "Musculoskeletal Disorders," *Healthline*. [Online]. Available: http://www.healthline.com/health/musculoskeletal-disorders. [Accessed: 08-Feb-2016].

[16] J. J. Yue, *Motion Preservation Surgery of the Spine: Advanced Techniques and Controversies*. Elsevier Health Sciences, 2008.

[17] KevinP Granata, KermitG Davis, and WilliamS Marras, "Biomechanical Models in Ergonomics," in *Occupational Ergonomics*, 0 vols., CRC Press, 2012, pp. 145–171.

[18] W. S. Marras, S. A. Lavender, S. E. Leurgans, S. L. Rajulu, W. G. Allread, F. A. Fathallah, and S. A. Ferguson, "The role of dynamic three-dimensional trunk motion in occupationally-related low back disorders. The effects of workplace factors, trunk position, and trunk motion characteristics on risk of injury," *Spine*, vol. 18, no. 5, pp. 617–628, Apr. 1993.

[19] "Cornell University Ergonomics Web: ManTRA V2.0." [Online]. Available: http://ergo.human.cornell.edu/cumantra2.htm. [Accessed: 09-Feb-2016].
[20] "RESOURCES DOWNLOADS." [Online]. Available: http://www.iapa.ca/Main/resources/resources_downloads.aspx. [Accessed: 09-Feb-2016].
[21] "A Systematic Approach to An Ergonomics Improvement Process," *Ergonomics Plus*, 21-Sep-2012. .
[22] "Safety and Health Topics | Ergonomics - Identify Problems." [Online]. Available: https://www.osha.gov/SLTC/ergonomics/identifyprobs.html. [Accessed: 07-Feb-2016].

Chapter 3: Rough Order of Magnitude Risk Profile for manual tasks in wingbox assembly

Chapter 2 describes the need for a quantitative methodology for the rapid assessment of ergonomic risk of manual tasks. This chapter presents and develops the hypothesis that ergonomic risk can be identified and quantified in the workplace by calculating the correlation of incident and labor reports. Literature on composite assembly processes and epidemiological studies is included in addition to the early findings regarding the positive correlation between incidents and labor. A statistical risk profile is proposed to gauge ergonomic risk, similarly to how epidemiological studies approach the causes of diseases. The following chapter presents the details of the statistical profile construction, evolution, applicability and limitations.

3.1 Epidemiological study approach

The main objective of an epidemiological study is to explain causes and patterns of disease occurrence. Epidemiological studies aim to quantify exposures, confounders and outcomes to evaluate the association of these 3 variables. A good epidemiological study should be able to identify causal effect of diseases with minimum margin of error. [1] In a comparable manner, the proposed statistical risk profile should be able to relate times of exertion of manual tasks to incidents in the workplace.

There is a wide range of classifications for study designs, but they all have in common the starting point of defining a particular population in a particular period of time, also referred to as cohort[1]. The population of interest in this study are the shop floor employees assigned to assembly tasks for flight control elements.

Epidemiological studies can be divided into two major classifications: *descriptive studies* and *analytic studies*. Analytic studies are "designed to examine etiology and causal associations" [2]. Within the analytic classification, the sub-class of *observational-studies* refers to those where intervention is not involved, i.e. the investigator is merely dedicated to record, count and analyze the results. Given the necessity a short-term risk measurement method, this type of study aligns with the resources and time available to create a risk profile. Within the *observational-study* the *cohort-study* allows to define variables to quantify exposure as shown in Figure 3-1:

Figure 3-1: Cohort study [2]

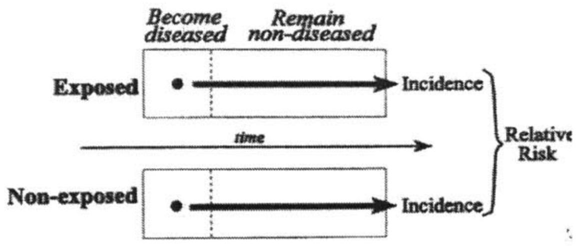
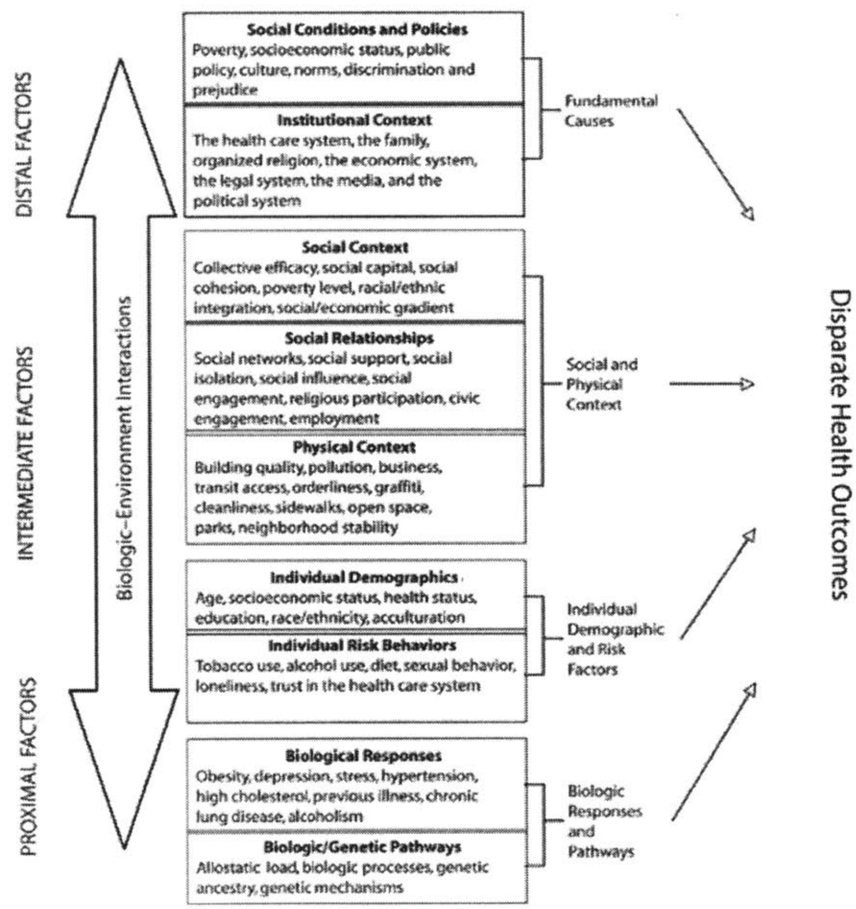


Figure 1-14 Basic analytical approach in a cohort study.

Furthermore, a retrospective cohort study allows to measure a relative risk of incidence (or injury) for different levels of exposure to the risk factors. With the use of historical records of exposed and non-exposed individuals, a current case/non-case status can be determined [3].

According to Warnecke et al., the risk factors in an epidemiological study can be classified as proximal, intermediate and distal as shown in Figure 3-2:

Figure 3-2: Risk factors classification in epidemiological studies [4]



If manufacturing workstations are defined as the physical context and intermediate factors as suggested by Warnecke [4], a cohort-study can be performed. The manual tasks performed for flight control elements assembling would then be defined as the theoretical risk factors. The measure of exposure can consequently be considered as the total of labor-hours reported by the employees for each one of those tasks.

By considering the manual tasks as individual risk factors, pain and discomfort might be treated as the symptoms of a potential incident. From the biomechanical perspective, pain and discomfort are symptoms of excessive loads exerted on the human body. As an analogy, machine elements such as beams, shafts and motors have a predictable life based on the loads and conditions under which they function. As an example, a shaft can be subject to high to static loads and not fail, but when combined sets of high torsion and high shear loads are applied cyclically, material failure will eventually happen when a finite level of cycles is reached. This means that for elements of machinery under critical cyclic loads, mechanical failure becomes a function of time. The human musculoskeletal structure works reacts very similarly to loads and stressors. While these loads in the workplace sometimes fall within the static mechanical strengths of bones, muscles, tendons and joints, the that fact there is repetition during extended intervals in a standard shift (7.5 hours) might lead to muscle, tendon or bone fatigue, causing an injury. Pain is the signal of these loads being harmful in magnitude and form and pose significant risk for the human structure. When pain arises while executing repetitive task, an injury (failure) becomes also a function of time.

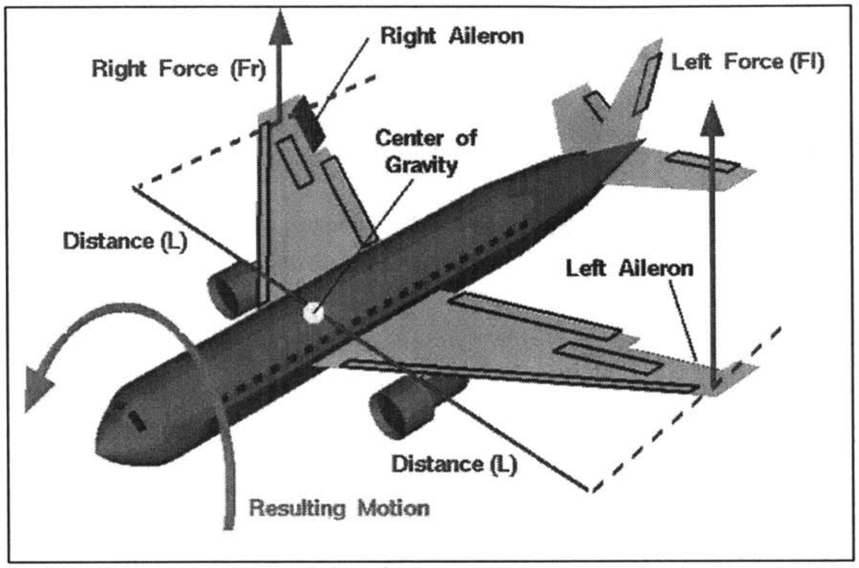
In order to conceive the inherent risk and stressors from manual tasks in flight control elements assembly, it is worthwhile to be familiar with the characteristics of manufacturing processes for composite structures. A pilot process developed by NASA as part of the Aircraft Energy Efficiency (ACEE) in the 1980s will be used to exemplify the basic operations involved in composite wingbox manufacturing.

3.2 Composite wingbox manufacturing for flight control elements

Aircraft flight controls are categorized into primary and secondary systems. Ailerons, elevators and rudders constitute the primary control systems which are essential to keep control of an aircraft during flight. Wing flaps, leading edge devices, spoilers and trim systems constitute secondary control systems and are used to improve the performance characteristics of the airplane [5].

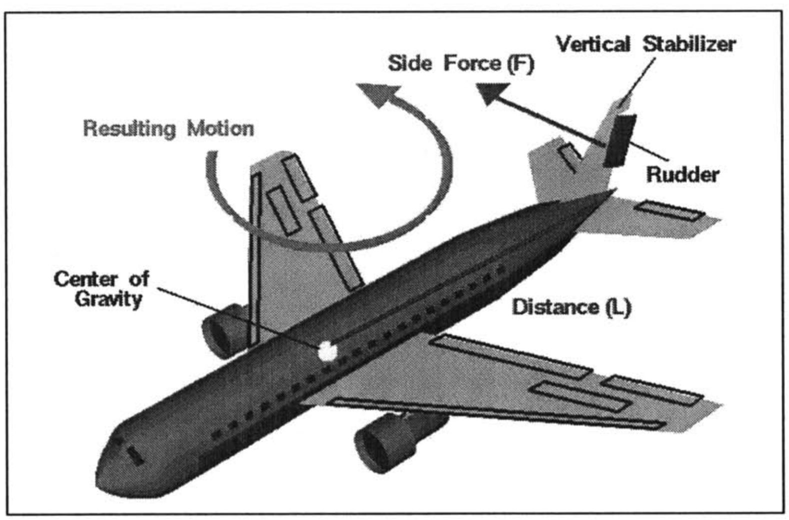
Ailerons are responsible for the rolling motion of the aircraft during flight. They are hinged to the outboard segment of the wing as shown in Figure 3-3[6]:

Figure 3-3: Ailerons



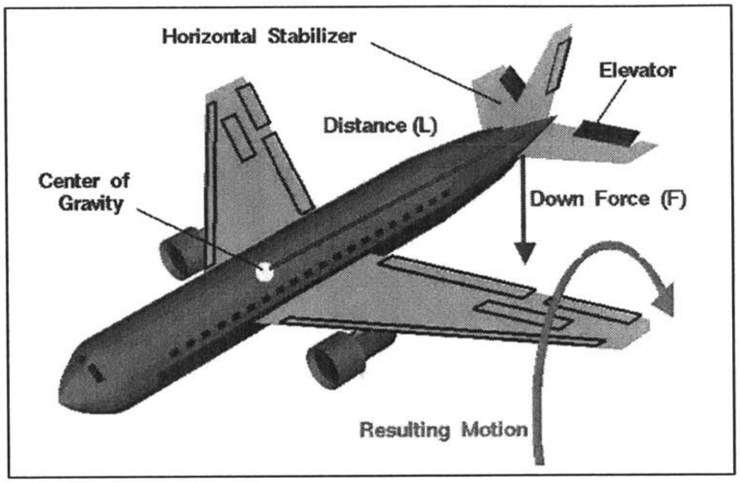
The rudder, coupled with the vertical stabilizer, generates the yawing motion that in combination with the rolling effect of the ailerons, provides direction control for the aircraft. The rudder location is shown in Figure 3-4 [7]:

Figure 3-4: Rudder location



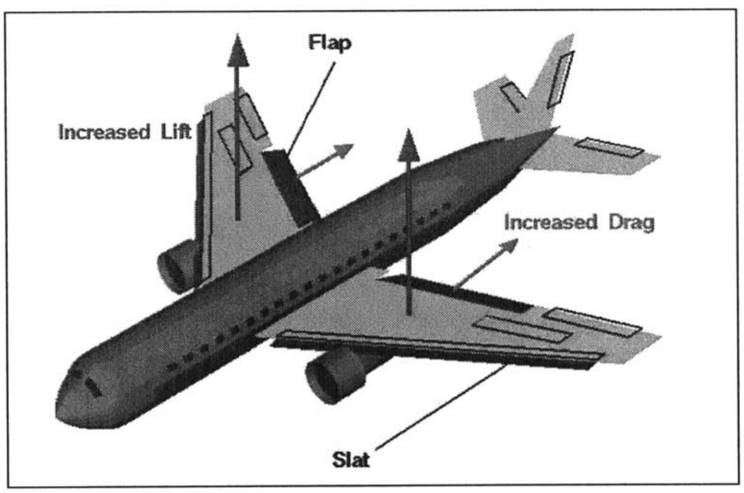
Similar to the rudder, the elevator is coupled to the horizontal stabilizer and generates the pitching motion of the aircraft as shown in Figure 3-5 [8]:

Figure 3-5: Elevator location



Flaps and slats are the flight control elements used during takeoff and landing to increase lift and therefore the minimum stall speed of an airplane. Flaps are located on the trailing edge of the wings whereas slats are installed on the leading edge as shown in Figure 3-6:

Figure 3-6: Flaps [9]



A characteristic distinguishing flight control elements from a generic wingbox assembly is that a flight control element is a non-static component, which means that it requires interphase components for actuating and pivoting such as hinges, bearings and fittings.

A wingbox assembly consists of the following basic elements as shown in Figure 3-7: top skin, bottom skin, leading edge, trailing edge, ribs and spars. The architecture is the same for aluminum frames and composite frames. The manufacturing process varies according to the general dimensions of the part; however, the basic sub-tasks of assembling a "ladder" with spar and ribs such as drilling, deburring, fastening, shimming, sealing and painting are very similar across product lines [10] . The total labor involved in producing a wingbox aerostructure is proportional to the size of the component. Figure 3-8 shows the difference in planned labor-hours for assembling the same flight control element for two different models. Examples of narrow body models are the A319, 737 and wide-body models are A350 and 777.

Figure 3-7: Wingbox elements [10]

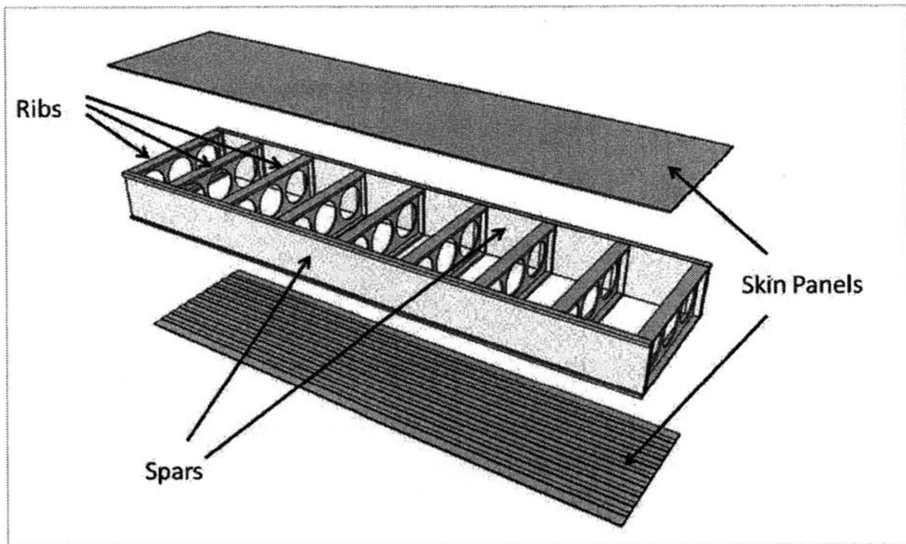
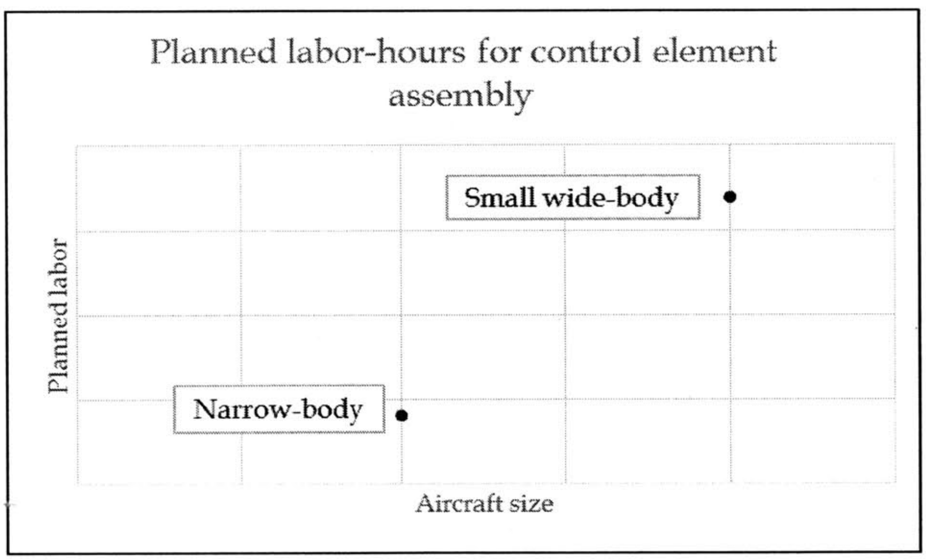


Figure 3-8: Planned labor-hours for flight control elements assembly



NASA's Aircraft Energy Efficiency (ACEE) Composite Structures Program had the objective of advancing the use of composite materials in aircraft structures. For this purpose, engineering and manufacturing activities were developed for an advanced composite inboard aileron for Lockheed L-1011 TriStar (medium-to-long-range, wide-body triple engine airliner shown in Figure 3-9).

Figure 3-9: Lockheed L-1011 [11]

NASA's objective was to develop an interchangeable aileron wingbox but made of advanced composite materials instead of aluminum. The product requirements established for such project where:

1) Direct replacement (interchangeability) of the current metallic aileron in fit and functionality
2) 20% weight savings
3) Feasibility and cost competitiveness
4) Resistance to environments of 219 to 335 K

After the design tradeoff study was performed, the final architecture emerged as shown in Figure 3-10. This basic architecture consists of a multigrid structure with single-piece upper and lower skin panels that are mechanically attached to the elemental structure which is in turn attached to the hinge/fitting elements.

Figure 3-10: Aileron assembly [12]

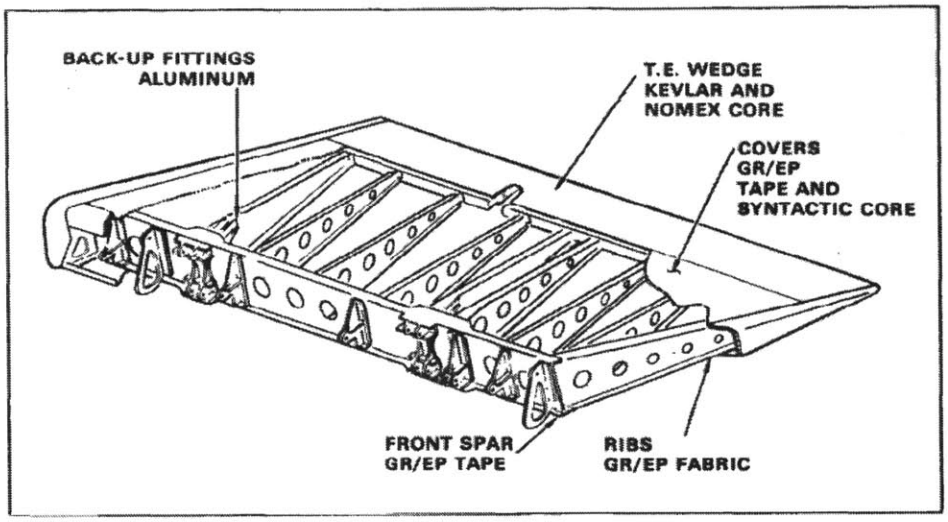
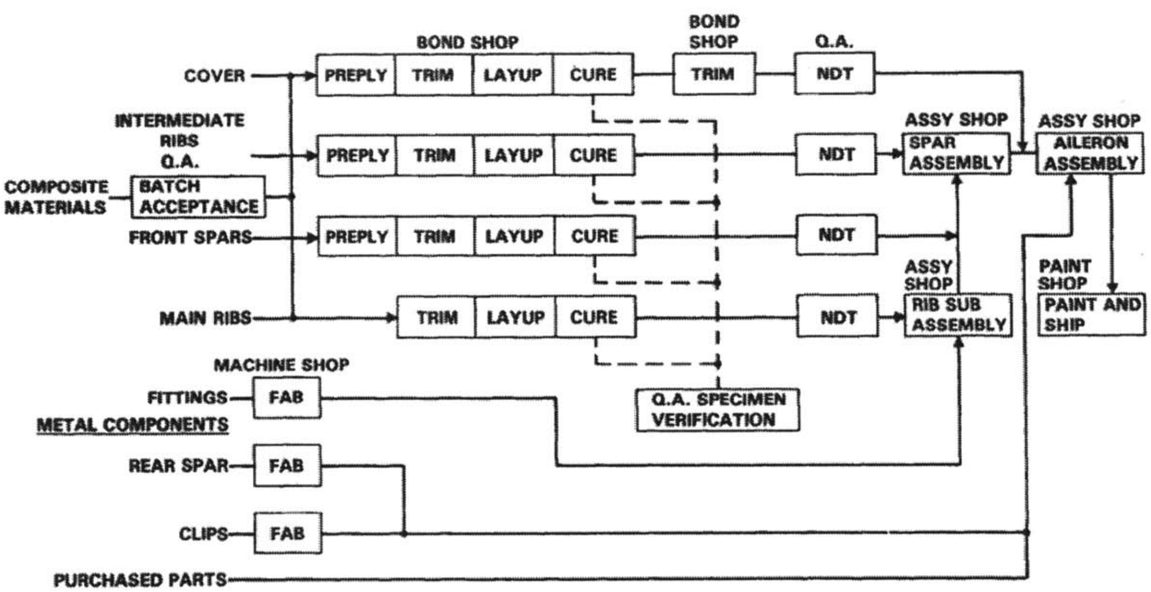


Figure 3. - Advanced composite aileron assembly.

NASA's Aircraft Energy Efficiency (ACEE) Composite Structures Program completed a total of 5 shipsets (ailerons) were completed with the process in a production-like environment. A process flow diagram is provided in Fig 3-11.

Figure 3-11: Process flow diagram



The assembly sequence went as follows firstly, the composite elements (skins, ribs and spars) were fabricated in a specialized composite fabrication shop. Next, the composite elements were trimmed and inspected. Spars and ribs followed parallel sub-assemblies activities before being attached to the skin panels to be finally painted and shipped.

The tolerances employed for the mechanical fasteners were representative of tolerances used nowadays in similar processes. The drilling system employed in this NASA program included a hand-held drill motor assisted with the following elements:

1) Hydraulic cylinder to control feed rate,
2) Bushing foot to stabilize drill bit and drill angle,
3) Coolant system for cooling and flushing the graphite
4) Vacuum system to remove shavings and excess coolant,

For assembling the main ribs sub-assemblies, each consisting of one main rib and 4 aluminum fittings a bench-type fixture was loaded with these components and all attachment holes were drilled. After drilling was completed, the following step was to deburr, and apply faying sealants for wet installation.

The ribs subassembly was located and clamped into the spar assembly fixture, the spar was mounted, hinge and actuator fittings were set to their final positions and all holes were drilled to full size. Holes were deburred, sealant was applied for wet fastener installation, which was the final step.

The final assembly joins together the spar-rib substructure, the rear spar, the skin panels, the trailing edge, fairings and front covers. NASA reported the following assembly sequence:

1) Load front spar assembly, rear spar and closeout ribs
2) Drill attach holes through rear spar and ribs
3) Load upper cover and drill attach holes
4) Remove upper cover, load lower cover and drill attach holes
5) Remove lower cover and permanently fasten upper cover

Finally, the inspection tasks were also documented in this development project: quality assurance inspectors verified part numbers, inspected each single hole for size, tolerance and quality to comply with the typical inspection requirements. Furthermore, each aileron received FAA conformity inspection with the corresponding supporting materials: material acceptance logs, test results and documentation on non-conformance parts.

One of ACEE's main objectives was to accelerate the application of composites to primary structures of civil air transportation by developing and disseminating the fundamental manufacturing techniques for empennage, wings and fuselage sub-structures [7].

A key difference from the process conceived by NASA and the current wing-box production lines is the portion of drilling activities in final assembly that are now automated. Nonetheless, a great part of the job is still performed by hand.

An interesting takeaway from comparing the labor-hours reported by NASA, as shown in Figure 3-12 is that the biggest difference when comparing the manufacturing process of the original aluminum aileron to the composite aileron comes from the fastener installation in final assembly.

Figure 3-12: Cost summary [12]

	Metal Configuration	Composite Configuration
Sheet Metal Fabrication	32%	4%
Composite Fabrication	-	23%
Sub Assembly	21%	-
Final Assembly	35%	54%
Quality Control	12%	19%
	100%	100%

Assembly sequences, processes and tools in modern manufacturing environments are very similar to those described by NASA. That said, and referring back to the labor comparison in Figure 3-8, it is suspected that ergonomic stressors present in a given task, should be of a similar magnitude for different products given the commonality of processes and architectures.

Based on the previous chapter, the first step for a successful execution of an ergonomic improvement program is the prioritization of tasks with the use of a quantitative basis. Considering that most of the ergonomic risk assessment forms show exertion time or time of exposure as a principal factor to measure risk, it is suspected that the labor tracking reports, in combination with the cohort-study approach should result in an acceptable approximation of risk of the current state across flight control element assembly lines for different products.

3.3 Benchmarking the Rough Order of Magnitude Budget Estimate for model acceptability

Every project, from the most simple continuous improvement to the most novel production system design, starts with creating a business case [13]. The decision makers are usually scrutinized to invest in projects that will yield better Return on Investments and positive NPV projections. "The main purpose of the Rough Order of Magnitude (ROM) estimate is to provide decision-makers with the information necessary to make a decision on whether it makes sense to move forward with the project based on the estimated level of effort, in terms of completion time and cost"[8]. When the improvement projects are proposed and discussed, the budget planning is often presented at a Rough Order of Magnitude (ROM). This implies that the information garnered on equipment cost, savings, non-recurring labor hours and other resources are approximated. According to the Project Management Institute (PMI), the acceptable accuracy of a ROM budget plan is -25 percent to +75 percent.

Oftentimes, aerospace factories deal with a wide range of projects run in parallel, either triggered by the need of improving ergonomics, quality, productivity or implementing product design changes, on the ergonomic indicators. Typically, the occupational health representatives strive to plan and execute risk assessments in the workplace as required by program management deliverables; but because of the lack of a baseline quantification of risk for the current state of the operation, observational risk assessments have to be performed ad-hoc.

The guideline provided by the PMI can therefore be benchmarked to create of a Rough Order of Magnitude Risk Profile, that could be used to complement a business case and help to prioritize ergonomic improvement projects and advance them more promptly from the initial proposal stages.

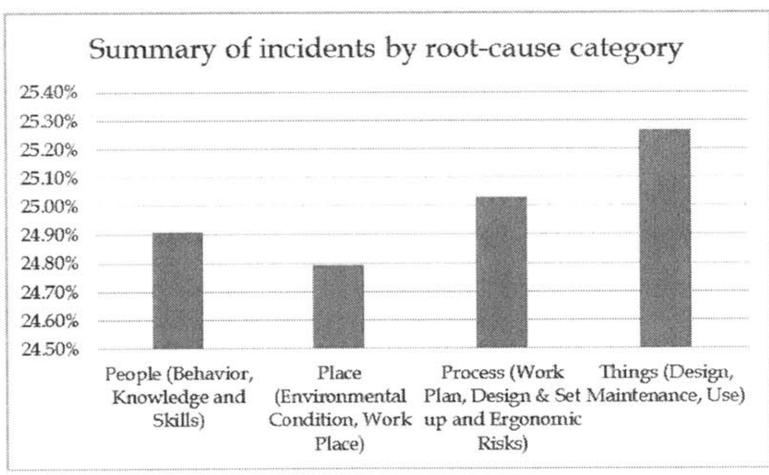
3.4 Rough Order of Magnitude Risk Profile

A fundamental objective of this thesis is to propose a method to quickly approximate "total cost of safety" in order to prioritize resources for workplace improvements. To do so, historical data is seized to test the effect that different tasks have in quality performance and the likelihood of injury. The following section describes the relationship of safety and quality as well as the methodology followed to approximate the ergonomic risk inherent to manual tasks in wingbox assembly processes by trailing a cohort-study approach. A rough order of magnitude (ROM) risk profile is presented for the current state, by using the correlation between the incident rates and accumulated labor-hours per category of activity.

Following the cohort-study approach, incident reports were gathered for 4 production lines the period of time of 15 June of 2014 to 15 June 2015. The first step taken to analyze the dataset was to sort the incident reports by root-cause. The root-cause category is a discrete variable required in the incident report generation and it is helpful to identify if the incident was associated with the production lines or not. The summary for the first data set is shown in Figure 3-13. The discrete values that can be entered in the reporting system for the root-cause field are:

1) People: when the incident is attributable to behaviors and knowledge skills
2) Place: when the incident is attributable to the environment, such as chemicals and temperature
3) Processes: when the incident is attributable to the work plan, workstation design objects and motions related to the manufacturing process
4) Things: when the incident is attributable to objects and motions alien to the manufacturing process but still present in the manufacturing environment

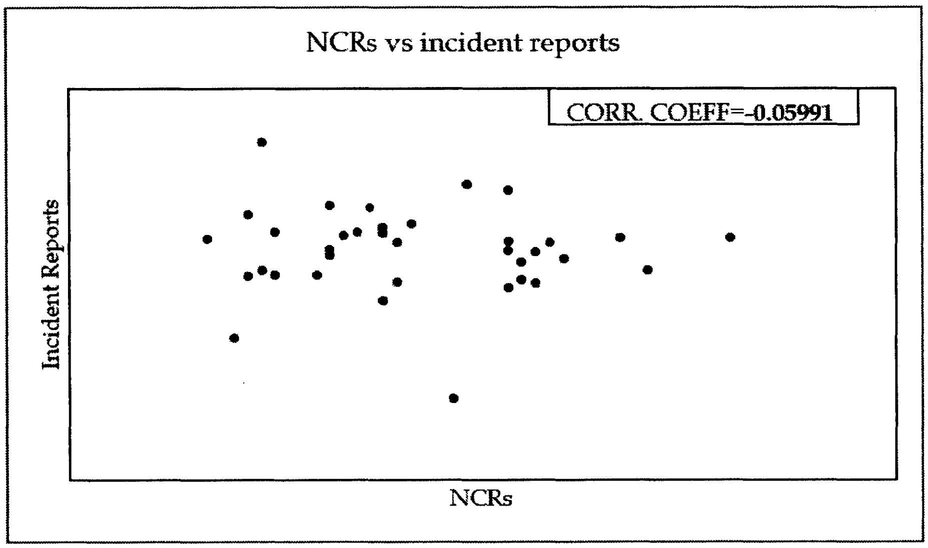
Figure 3-13: Incidents by root-cause



It is noted that the total amount of incident reports are evenly distributed according to root-cause categories. While the "People" category holds 25% of the total incident reports, process and manufacturing environment related incidents (Place, Process and Things) make up approximately 75% of the total of safety incident reports recorded in the year. While behaviors and skills could still be involved in incidents attributable to other root-cause categories, they can only be improved by administrative controls. As discussed in Chapter 2, administrative controls are not as effective as first level improvements done to the workplace, i.e. Place, Process and Things, henceforth emphasis is put on these three categories.

As described in Chapter 2, the "total cost of safety" is composed of direct cost and indirect cost. Direct cost is commonly easier to calculate than indirect costs because of the association of the former with cost of quality. Therefore, the next step was to observe the relationship of incidents and quality defects. The total Non-Conformance Reports (NCRs) associated with the employees that were included in a safety incident report is plotted in Figure 3-14.

Figure 3-14: NCR vs incident reports



An important takeaway is that there is no significant correlation of safety and quality, i.e. employees who were associated with the fewest incident reports did not necessarily report the fewest NCRs. For this reason, a prioritization of ergonomic improvements based merely in quality performance is unfeasible, at least in this specific aerospace manufacturing environment.

The lack of correlation might find its cause in different sources. Firstly, not all of the tasks that could be considered safe, are robust enough when analyzed as a system that involves tools, fixtures and human error. Secondly, some of the tasks that might indeed be risky, are not related to product key characteristics. Tool cleaning, workspace set ups and steps of the process where environmental conditions could be harmful (like painting), are not common originators of NCRs.

Since NCRs cannot be picked as a variable to gauge the urgency of ergonomic improvement for tasks in the manufacturing process, a different variable has to be proposed. In other words, if a positive correlation had been found between NCRs and incident reports in Figure 3-10, it would be easy to take a step further to identify the tasks that the employees with the highest incident rates dedicated most of their time on.

In searching for a different variable, it was found that the commonality of the IAPA and MATRA risk assessment techniques can be leveraged to measure ergonomic risk. This commonality is found in the way how "time of exposure" is factored in the final risk quantification. Therefore a variable that would be expected to have some degree of explanatory capability for incident rates is labor.

For this reason, the next step was to explore the relationship between "time of exposure" and incident reports with the use of labor reports. A labor tracking system is used by every employee to report the start and finish time for every particular task assigned from the work schedule. The aerostructures assembly process is broken up into individual tasks such as drilling, deburring, sealing, fastening (as described in section 3-2) and assigned to a particular shop floor employee.

This tool serves then as the workflow monitoring system where the fabrication and assembly progress of a work order can be tracked and quality representatives are advised when an inspection is required.

For all the employees associated with an incident report, the detailed labor report was extracted for the period of time in question (15 June of 2014 to 15 June 2015) and coupled with the total amount of incidents by employee. This data set is represented by the following table (Figure 3-15):

Figure 3-15: Labor data extract

Employee ID	Activity number	Date	Labor time	Incident reports
Employee 1	Activity (i)	k	X	Total incident reports for Employee 1 (Y)
Employee 1	Activity (i)	k	X	
Employee 1	Activity (i)	k	X	
Employee 1	Activity (i)	k	X	
Employee 1	Activity (i)	k	X	
.	.	.	.	
.	.	.	.	
.	.	.	.	
Employee 2	Activity (i)	k	X	Total incident reports for Employee 2 (Y)
Employee 2	Activity (i)	k	X	
Employee 2	Activity (i)	k	X	
Employee 2	Activity (i)	k	X	
Employee 2	Activity (i)	k	X	
.	.	.	.	
.	.	.	.	
.	.	.	.	
Employee 3	Activity (i)	k	X	Total incident reports for Employee 3 (Y)
Employee 3	Activity (i)	k	X	
Employee 3	Activity (i)	k	X	
Employee 3	Activity (i)	k	X	
Employee 3	Activity (i)	k	X	
Employee 3	Activity (i)	k	X	
Employee 3	Activity (i)	k	X	
Employee 3	Activity (i)	k	X	

Given that incident reports are not systematically associated to specific tasks in the work schedule, the first correlation was approximated by defining an Employee-Activity Risk Rate (EAR). The EAR results from dividing the total of incidents reported for each employee by the total number of tasks reported in the labor tracking system in such way that each task would share an equal fraction of this employee incident rate. The EAR calculation can expressed by the equation 3.1:

(3.1)

$$EAR_{ij}=\frac{\sum Y_j}{\sum_{i=1,\ k=1}^{i=n\ k=n} A_{ijk}}$$

(EAR)= Employee-activity risk rate
i=Activity description (drilling, deburring, sealing…etc.)
j=Employee
k=day
Y= Incident reports
A=Activity

Equation 3.1 is applied to every individual task as shown in figure 3-16:

Figure 3-16: Equation 3.1 applied across employee IDs.

Employee ID	Activity number	Date	Labor time	Incident reports	EAR
Employee 1	Activity (i)	k	X	Total incident reports for Employee 1 (Y)	TOTAL INCIDENTS FOR EMPLOYEE 1/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 1
Employee 1	Activity (i)	k	X		TOTAL INCIDENTS FOR EMPLOYEE 1/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 1
Employee 1	Activity (i)	k	X		TOTAL INCIDENTS FOR EMPLOYEE 1/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 1
Employee 1	Activity (i)	k	X		TOTAL INCIDENTS FOR EMPLOYEE 1/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 1
Employee 1	Activity (i)	k	X		TOTAL INCIDENTS FOR EMPLOYEE 1/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 1
.	.	.	.		.
.	.	.	.		.
.	.	.	.		.
Employee 2	Activity (i)	k	X	Total incident reports for Employee 2 (Y)	TOTAL INCIDENTS FOR EMPLOYEE 2/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 2
Employee 2	Activity (i)	k	X		TOTAL INCIDENTS FOR EMPLOYEE 2/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 2
Employee 2	Activity (i)	k	X		TOTAL INCIDENTS FOR EMPLOYEE 2/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 2
Employee 2	Activity (i)	k	X		TOTAL INCIDENTS FOR EMPLOYEE 2/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 2
Employee 2	Activity (i)	k	X		TOTAL INCIDENTS FOR EMPLOYEE 2/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 2
.	.	.	.		.
.	.	.	.		.
.	.	.	.		.
Employee 3	Activity (i)	k	X	Total incident reports for Employee 3 (Y)	TOTAL INCIDENTS FOR EMPLOYEE 3/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 3
Employee 3	Activity (i)	k	X		TOTAL INCIDENTS FOR EMPLOYEE 3/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 3
Employee 3	Activity (i)	k	X		TOTAL INCIDENTS FOR EMPLOYEE 3/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 3
Employee 3	Activity (i)	k	X		TOTAL INCIDENTS FOR EMPLOYEE 3/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 3
Employee 3	Activity (i)	k	X		TOTAL INCIDENTS FOR EMPLOYEE 3/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 3
Employee 3	Activity (i)	k	X		TOTAL INCIDENTS FOR EMPLOYEE 3/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 3
Employee 3	Activity (i)	k	X		TOTAL INCIDENTS FOR EMPLOYEE 3/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 3
Employee 3	Activity (i)	k	X		TOTAL INCIDENTS FOR EMPLOYEE 3/ TOTAL AMMOUNT OF ACTIVITES BY EMPLOYEE 3

The table shown in figure 3-12 can be pivoted on Activity number (i). By doing so, the total labor-hours was then aggregated and assigned to each task. This preliminary dataset resulted in a list of tasks performed by all employees which were associated with an incident. Thus, a Total Activity Risk Rate (TAR) can be defined for each activity as:

(3.2)

$$TAR_i = \sum_{j=1,\ k=1}^{j=n,\ k=n} EAR_{ijk}$$

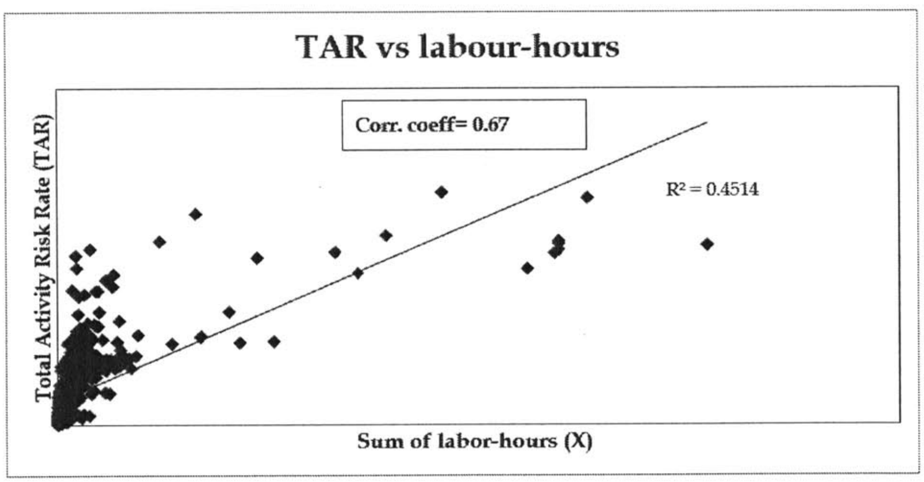
The resulting pivot table is portrayed in Figure 3-17:

Figure 3-17: TAR calculated across activities

Activity number	TAR
Activity 1	Sum of EAR for Activity 1
Activity 2	Sum of EAR for Activity 2
Activity 3	Sum of EAR for Activity 3
Activity 4	Sum of EAR for Activity 4
Activity 5	Sum of EAR for Activity 5
.	.
.	.
.	.

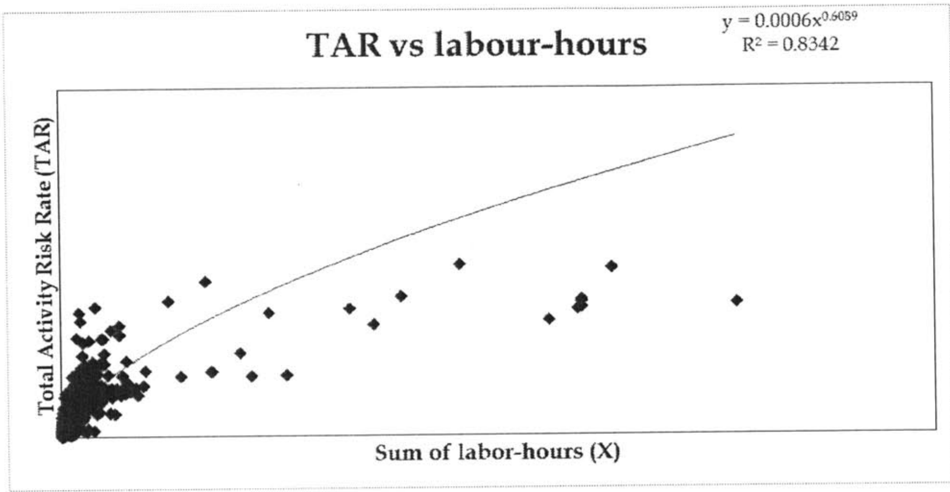
Once a TAR value is available for every activity, this risk value can be plotted against the total labor hours reported in the period of study. Figure 3-18 shows the resulting correlation observed with labor reported for each individual task and the TAR associated to it.

Figure 3-18: Linear regression



The positive correlation encountered should be interpreted as follows: that activities with higher accumulations of labor-hours in the year were performed by employees who reported higher incident rates. While here might be non-linear models that could better fit the TAR, such as the exponential model shown in Figure 3-19, the purpose of this exercise is only demonstrating the positive relation between the TAR and labor hours.

Figure 3-19 Non-linear model regression



The linear correlation coefficient calculated for all activities' TAR and the total labor-hours logged for each one of them encourages to keep evaluating the predictive capabilities of the labor tracking reports and incident report summaries. By leveraging the physical similarities in tools, process and workstation across all the production lines, labor-hours can be understood as the explanatory variable to estimate incident rates based on historical data (cohort-study).

It should be noted that within a year, an employee could have performed risky tasks and non-risky tasks. Because the TAR assigns an equal share of risk to all activities performed by an employee, this data set alone cannot be used to construct a reliable risk quantifier to the activity level. To mitigate this issue, employees who have not been involved in incident reports have to be included to construct a reliable risk profile.

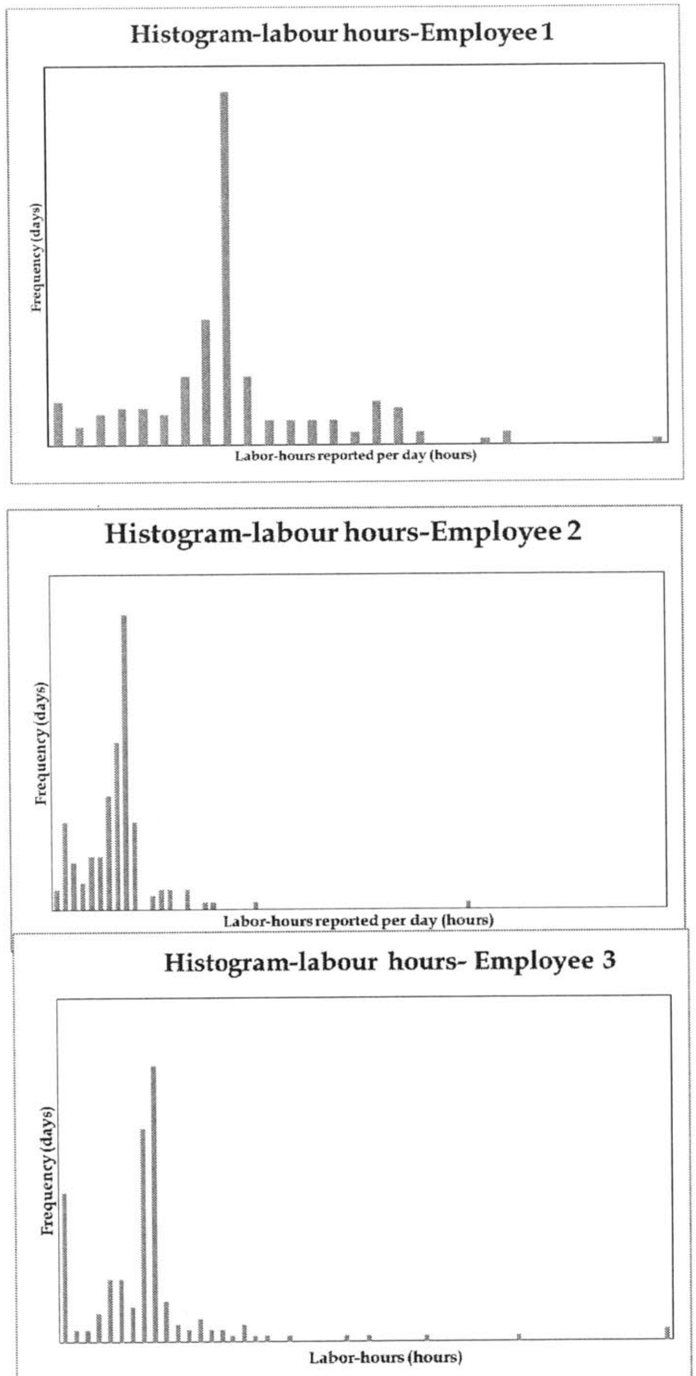
Given that the sum of activities across the production lines is in the order of hundreds and the total of labor-logs is of hundreds of thousands, an activity classification is proposed to reduce the number of variables and enable a linear regression calculation. By aggregating each category's incident rate, a Rough Order of Magnitude statistical risk profile can be obtained.

3.5 Creation and evolution of the model

The first step taken to test the correlation of labor-hours per activity and incident reports was to study the reliability of the labor-tracking system. The labor-hour value is systematically calculated by the labor tracking system as the difference between a task start and finish times reported by the employees. This means that the measure relies on the consistency and accuracy of the employees to report their start and finish times.

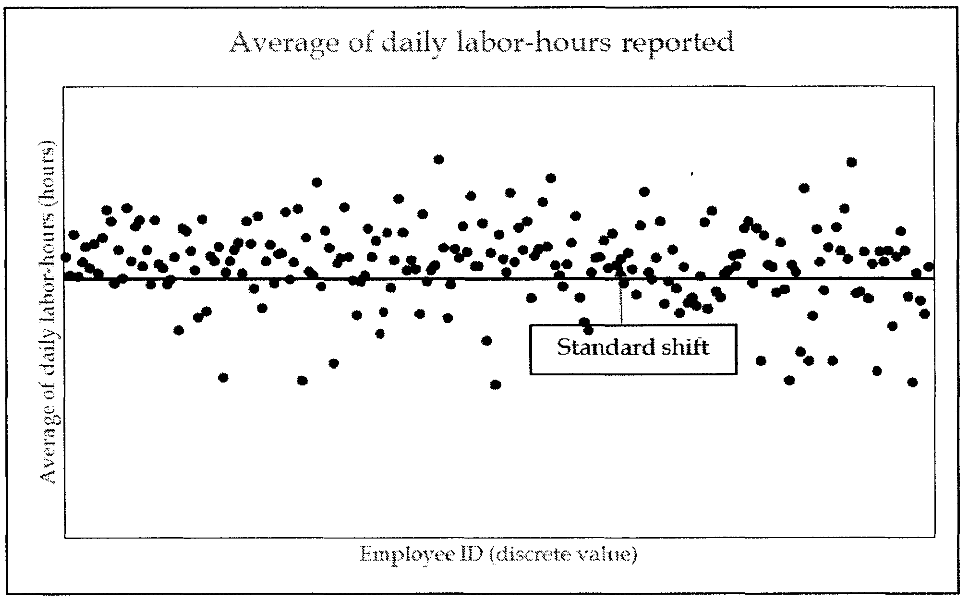
To approach employees labor tracking accuracy, 3 employees were randomly selected from the population of those associated with incident reports to study the distribution of the data. Given that some employees would have reported thousands of different activities throughout the year, a "standard shift day" was assumed to be the target mean of daily labor hours. Ideally each employee's daily labor report should total a "standard-shift". Figure 3-20 shows the histogram for three employees during the time span of this study (June-15-2014 to June-15-2015).

Figure 3-20: Employee labor tracking variability



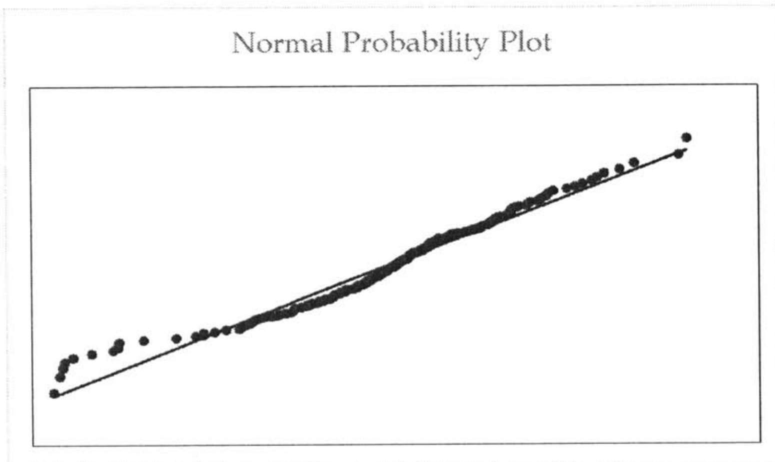
Although there are several days in which the sum of hours reported deviated significantly from the standard shift, it can be noticed that the values are slightly evenly distributed around that value. From the histograms created with the daily data of labor-hours logs, it can also be noticed that accuracy varies significantly from employee to employee and not every employee reports daily labor-hours in a normally distributed manner. But if every employee report is treated as a sample of one year worth of daily labor-hour logs and the average of these samples are analyzed, as per the Central Limit Theorem, it can be noticed that the employees' daily averages look normally distributed. Figure 3 -21 shows the scatter plot of the daily average for the entire cohort considered in this study:

Figure 3-21: Daily average of labor-hours reported per employee



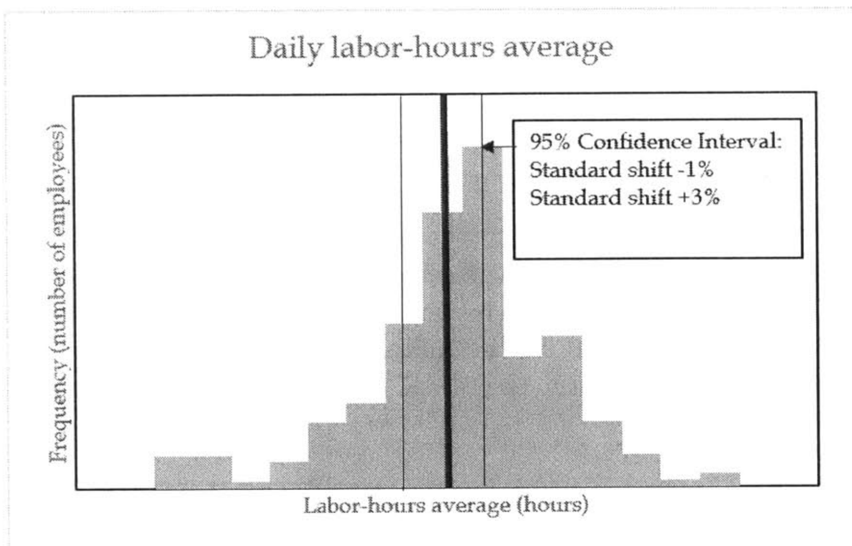
In order to construct a regression model that relates labor-hours and incident reports, the normality of the labor-hour reports has to be tested. Figure 3-22 shows the distribution of the averages for all employees of total labor-hours. After excluding the bottom outliers, the distribution of daily averages appears to be normal, as it can be appreciated in Figure 3-22.

Figure 3-22: Normal probability plot for daily averages



The sum of labor-hours allocated to each activity was estimated to fall within -1% and +3% from the standard shift value with a confidence interval of 95%:

Figure 3-23: Confidence interval for daily average



A variation of 4% from the standard shift value seems an acceptable indicator of the accuracy of the total labor that an activity would accumulate in a year. As will be discussed further, the ROM risk profile is constructed using the aggregated labor for the entire year, not the individual daily logs.

3.6 Data analysis

Once the injury reports were gathered, the next step was to extract the history of labor-hours for production lines A, B and C. The timeframe of interest remains to be June-15-2014 to June 15-2015. Since employees report start and finish time for every unitary operation, this dataset includes hundreds of thousands of entries. The data extracted is exemplified in Figure 3-24:

Figure 3-24: Labor-hours extract

Employee ID	Activity	Labor-hours	Product
Employee 1	Activity 1	X	Product A
Employee 1	Activity 305	X	Product A
Employee 1	Activity 23	X	Product A
Employee 1	Activity 1	X	Product A
.	.	.	.
.	.	.	.
Employee 2	Activity 14	X	Product B
Employee 2	Activity 37	X	Product B
Employee 2	Activity 221	X	Product B
.	.	.	.
.	.	.	.
.	.	.	.
Employee 3	Activity 16	X	Product C
Employee 3	Activity 2	X	Product C
Employee 3	Activity 29	X	Product C

$$[\,j\,] \qquad [A_{ijk}] \qquad [\,X_{ijkl}\,] \qquad [\,l\,] \tag{3.3}$$

i = Activity description (drilling, deburring, sealing…etc.)

j = Employee ID

k = day

l = Production line

A_{ijk} = Activity i performed by employee j on day k

X_{ijkl} = Time logged to activity i by employee j on day k in production line l

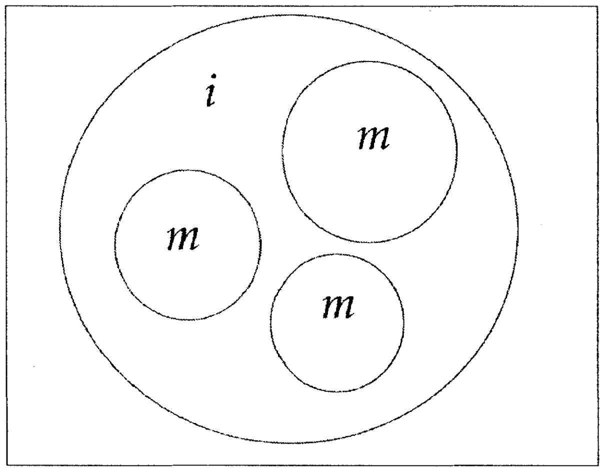
X_{ijkl} denotes each individual labor hour entry in the labor-tracking system. The hypothesis is that the TAR for a given activity is directly proportional to the accumulated labor-hours for similar activities.

(3.4) Hypothesis

$$TAR_{il} \infty \sum_{m \subset i} X_m$$

(every activity category is a subgroup of the population of activities i)

Figure 3-25: Venn diagram for $m \subset i$



i=Activity description (drilling, deburring, sealing...etc.)

m = Activity Category

X_{ijkl} is in the order of hundreds of thousands whereas A_i, the generic tasks repeated cycle after cycle, is in the order of magnitude of hundreds. It should be noted that A_i comes directly from the product assembly instructions.

The hypothesis implies that every A_i should represent a variable in a regression model, notwithstanding the unit of measure is the same: labor-hours. Thus, in order to construct a practical correlation model, the number of variables must be reduced by leveraging the similarities of activities across products and across workstations. A category vector m will be used to denote subsets of activities A_i that are similar by description. A list of Activity Categories was selected to sort the individual entrees and construct the model

The number of categories increases with the sample size since new activities start to arise, i.e. as employees from different workstations are integrated to the dataset, more activities need to be categorized. However, the exercise of assigning each individual entry to a given category is identical for every entry and for every model run described hereafter. The entry allocation exercise is illustrated in Figure 3-26. As it will be described next, the number and criteria for defining the set of categories plays a paramount role in the goodness of fit.

Figure 3-26 Activity category allocation

Employee ID	Activity
Employee 1	Activity 1
Employee 1	Activity 305
Employee 1	Activity 23
Employee 1	Activity 1
.	.
.	.
.	.
Employee 2	Activity 14
Employee 2	Activity 37
Employee 2	Activity 221
.	.
.	.
.	.
Employee 3	Activity 16
Employee 3	Activity 2
Employee 3	Activity 29

Activity classification	Accumulated labor-hours
Category 1	X
Category 2	X
Category 3	X
Category 4	X
Category 5	X
Category 6	X
Category 7	X
Category 8	X
Category 9	X
Category 10	X
Category 11	X
Category 12	X
Category 13	X
Category 14	X
Category 15	X
Category 16	X
Category 17	X
Category 18	X
.	X
.	X
.	X

(3.5)

$$X_m = \sum_{i=1,\ j=1,\ k=1,\ l=1}^{i=n,\ j=n,\ k=n,\ l=n} X_{ijkl}$$

For every fixed sample of employees, the regression data input is generated simply by pivoting the summary of accumulated hours per category and associating the combination of labor-hours per category to the total of injury reports by employee. The regression data input includes different levels of labor-hours allocated to different combinations of activity categories throughout the year. The regression data input for every model run is illustrated in Figure 3-27:

Figure 3-27: Model regression input array

	Activity category										
	1	2	3	4	5	6	7	8	9	10	Incident reports
Employee 1	x	x	x	x	x	x	x	x	x	x	Y
Employee 2	x	x	x	x	x	x	x	x	x	x	Y
Employee 3	x	x	x	x	x	x	x	x	x	x	Y
Employee 4	x	x	x	x	x	x	x	x	x	x	Y
Employee 5	x	x	x	x	x	x	x	x	x	x	Y
Employee 6	x	x	x	x	x	x	x	x	x	x	Y
Employee 7	x	x	x	x	x	x	x	x	x	x	Y
Employee 8	x	x	x	x	x	x	x	x	x	x	Y

(3.6) Regression model

$$[Y_i] = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ . \\ . \\ X_n \end{bmatrix} \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ . \\ . \\ \beta_n \end{bmatrix} + [\varepsilon]$$

$$\beta \infty TAR$$

$$\beta = Category\ Risk\ Rate$$

$$Y = Total\ Risk\ Rate$$

The main objective of the linear regression model is to determine the Category Risk Rates (β) with the minimum error, in such way that they can be utilized to construct a ROM risk profile based on nominal values of planned labor-hours. The Category Risk Rate will serve as the best estimate of the likelihood of an incident for an activity, workstation and/or production line based on the amount of labor that is put into any of these.

The first linear regression model was created using a total of 11 categories for all activities performed by 133 employees across product lines A, B and C. The regression results are shown in Figure 3-28:

Figure 3-28: First model (*m=11, i=133, l=2)*

Regression Statistics	
R Square	0.133368618
Adjusted R Square	0.054583947
Observations	133

Regression parameter	Coefficients	P-value
Intercept	0.569853966	3.556E-05
Category 1	-0.001006013	0.6326875
Category 2	0.000225691	0.9178733
Category 3	-0.956261211	0.2196166
Category 4	-0.00010552	0.8909456
Category 5	0.005439514	0.0078242
Category 6	0.000287748	0.6260782
Category 7	-0.000969745	0.5011194
Category 8	-0.007442857	0.2087321
Category 9	-0.000500905	0.2923877
Category 10	-0.00074387	0.8140959
Category 11	-0.000736426	0.5747122

It is suspected that the poor explanatory results derives from the small set of categories used, i.e. activities that are not very similar across product lines may have fallen within the same category. The advantage of having used a small set of categories is the time saved in the manual category allocation, as shown in Figure 3-26. The measure taken to address this is to increase the number of categories by dividing those with the highest P-values. Although Category 5 appears significant in this model, the objective is to construct a risk profile for at least one complete production line. With only one category being significant, a product line cannot be risk mapped. The measures taken towards constructing a model with better fit, was to increase the number of categories. This implies a time consuming allocation exercise, therefore the second iteration if the model focuses only in Production Line A.

The second regression model was created using 30 employees from Product A and a set of 18 categories. The linear regression model display an R square value of 0.65 and an adjusted R square of 0.082. A parameter screening exercise was performed to achieve a better adjusted R square value as shown in Figure 3-29:

Figure 3-29: Parameter screening (*m=18, i=30, l=1*)

Total categories	Rsquare	Rsquare adj
18	0.65	0.082
17	0.65	0.15
16	0.64	0.21
15	0.64	0.26
14	0.63	0.29
13	0.63	0.33
12	0.61	0.34
11	**0.6**	**0.35**
10	0.57	0.35
9	0.57	0.3588
8	0.55	0.33
7	0.5	0.34

As a result from the parameter screening exercise, the optimal number of categories was set to 11. With these many categories, the final regression results are shown in Figure 3-30:

Figure 3-30: Regression model (*m=11, i=30, l=1*)

Regression Statistics	
R square	0.601
Adjusted R	0.35
Observations	30

Regression Parameter	Value	P-Value
Intercept	0.68	<.0001
Category 1	0.005832	0.0167
Category 2	0.0024	0.2576
Category 3	0.0122	0.2801
Category 4	0.00639	0.1749
Category 5	0.031974	0.1876
Category 6	-0.029	0.1498
Category 7	-0.083	0.0101
Category 8	-0.093	0.0426
Category 9	-0.38	0.0027
Category 10	-0.0288	0.0074
Category 11	-0.008	0.0819

The higher significance of this model resulted from the broader set of categories (explanatory variables) than the first model. However, due to the smaller sample size, the applicability of the model to other production lines apart from Product A needs to be assessed. By removing the insignificant terms from the model shown in Figure 3-30, the results obtained are shown in Figure 3-31:

Figure 3-31: Regression model after screening non-significant parameters

Regression Parameter	Parameter Estimate	P-Values
Intercept	1.701028	0.0377*
Category 1	0.0042388	0.0116*
Category 7	-0.086987	0.0107*
Category 8	0.0719106	0.1074
Category 10	0.024889	0.0200*
Category 9	-0.33119	0.0091*

Lastly, by removing category 8, the resulting model is shown in Figure 3-32:

Figure 3-32: Regression model with screened parameters

Regression statistics	
RSquare	0.286432
RSquare Adj	0.172261
Observations (or Sum Wgts)	30

Term	Estimate	P-Value
Intercept	1.8524526	0.0282*
Category 1	0.0046272	0.0074*
Category 7	-0.0832	0.0167*
Category 10	0.0240488	0.0283*
Category 9	-0.191026	0.0322*

Although several categories were found to be significant, the model does not have enough fit nor it has enough variables to risk map an entire production line. The objective is finding a model that has as many categories significant as possible to create a risk profile for entire production lines. This search is done by increasing the sample size, redefining categories and including all employees in these product lines, instead of grabbing a random sample as in the first iteration of the model.

Therefore, the next regression model was constructed with 85 samples and an initial set of 19 activity categories. The linear regression results are shown below after performing the variable screening exercise is shown next in Figure 3-33:

Figure 3-33: Multilinear regression with 85 samples (*j=85, l=4, m=17*)

Regression Statistics	
R square	0.89
Adjusted R	0.87
Observations	85

Regression parameters	**Coefficients**	**P value**
Category 1	0.0126332	0.9475
Category 2	-0.00026	0.827
Category 3	0.000328	0.1362
Category 4	0.0021782	0.7354
Category 5	0.3272565	<.0001
Category 6	-0.154245	<.0001
Category 7	0.0825138	<.0001
Category 8	-0.228185	<.0001
Category 9	0.0473087	0.2057
Category 10	0.0245407	<.0001
Category 11	-0.001971	0.2146
Category 12	0.0680649	<.0001
Category 13	0.00002033	0.9704
Category 14	-0.054055	0.0082
Category 15	0.2687585	0.0003
Category 16	-0.039678	0.2537
Category 17	0.0008962	0.4755
Category 18	-0.002892	0.8012

Although some categories are non-significant it is important to keep them in the study to apply the model across production-lines. If all the categories with P-values below the significance level of .05 were discarded, it would not be possible to construct a ROM risk map for the rest of the production lines, i.e. most of the activities would not fall into significant categories and re-categorizing them into only significant categories would invalidate the regression model. To address the non-significant variables, confidence intervals will be established in upcoming sections to warn about the use of the ROM risk map, but in such way that it could still be used as a guide. However, the model suggests to analyze the categories that were found significant and look for similarities within the sub-set of activities across production lines. For instance, one could take Category 5 and analyze the activities within this category. According to the model, the more labor is put into these activities, the more likely the workstation will generate incident reports. The fact that the parameter effect is positive, with a very low P-value, suggest that most of the activities pose ergonomic risk to some extent. The model can therefore guide the health-and safety groups in the factory to focus first on the categories with the highest effects and highest significance to perform observational risk assessments. Category 5 and Category 15 would be good candidates for further investigation.

To test the model, planned labor-hours for each activity within each production line were entered to the regression model. Since all the activities in the production plan had already been categorized, an ROM risk rate for each activity was calculated as follows:

Figure 3-34: Model test

Activity Description (i)	Planned labor-hours (Xi)	Activity Category βi	ROM Activity Rate
Activity 1	Xi	βi	Xiβi
Activity 2	X	β	Xiβi
Activity 3	X	β	Xiβi
Activity 4	X	β	Xiβi
.	.	.	.
.	.	.	.
.	.	.	.
		ROM Production Line Risk Rate	ΣXiβi

(3.7)

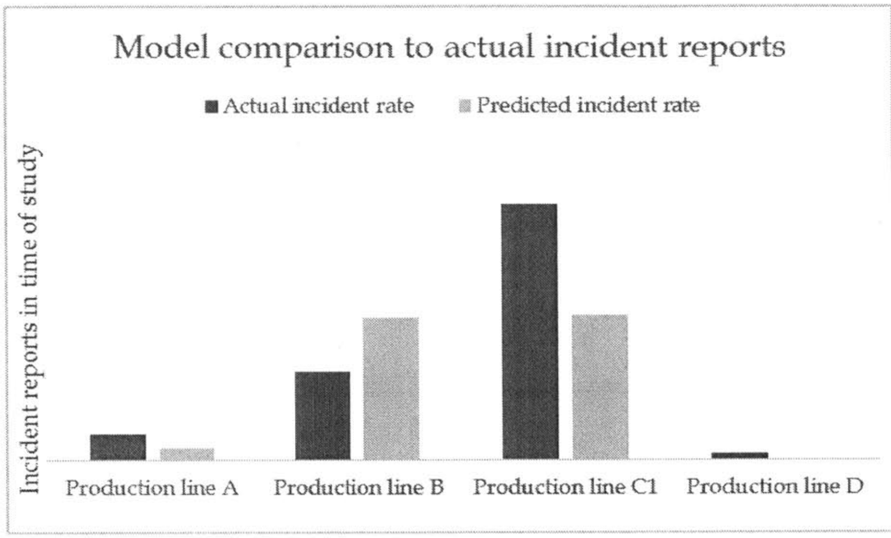
$$ROM\ Activity\ Risk\ Rate = \beta_i X_i$$

(3.8)

$$ROM\ Production\ line\ rate = \sum \beta_i X_i$$

In order to test the model, the ROM Production line rate was compared to the actual number of incident reports. The results for this comparison are shown in Figure 3-35:

Figure 3-35: 85-sample model comparison



The 85-sample model showed 52.3%, 62%, 43% and 100% of error for product lines A,B,C1 and D respectively.

A final model was created with a total of 96 samples, resulting in a less accurate model than the previous one.

Figure 3-36: Multi-linear regression using 96 samples.

Regression Statistics	
Multiple R	0.74
R Square	0.54
Adjusted R Square	0.45
Standard Error	1.58
Observations	96

As mentioned before, the definition of categories is crucial for model accuracy. The loss of correlation in the last run is suspected to be derived from the capability of the categories to describe similitudes between tasks. As the sample size increases, activities for which a classification was not encountered were grouped in a generic "error" category whose β parameter results to be significant. As the sample size increase, expertise in the manufacturing process needs to be involved to assign granularity and reliability to the set of categories to maintain the levels of correlation achieved with previous sample sizes.

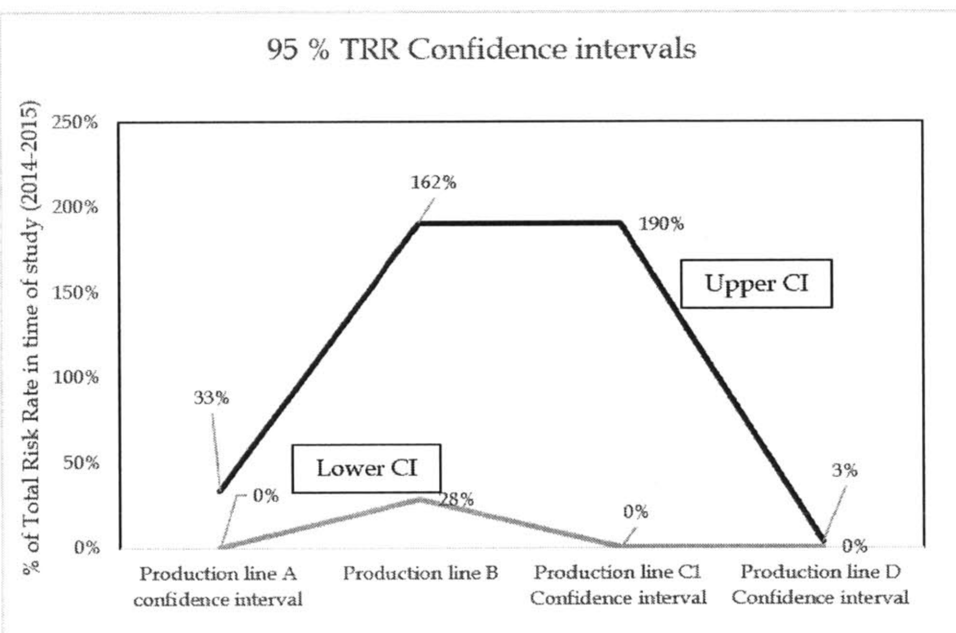
The model with the highest prediction capability (85-samples) was then selected to pilot the ROM statistical risk profile across product lines. Such risk per activity was achieved by simply reporting the product of the standard labor-hours planned per activity and its corresponding Category Risk Rate. It is worthy to remember that CRR (β) is the best estimate of the likelihood of incident as a function of labor, as described in equation 3.4 previously. When constructing the

ROM. The Category Risk Rate was assumed to be 0 for those activities that resulted in a negative Risk Rate, i.e. a negative effect in the regression model multiplied by the planned labor-hours. Negative CRRs (βs) come from the fact that some employees that spent more time in certain activities were consistently associated with less incident reports. Categories 6 and Category 8 (β_6 and β_8) are particular be interpreted as "safe" to perform, but not necessarily risk-reducing. A typical example of a task that would fall into this category are the reporting tasks; tasks that involve reporting information in a computer or also "idle-unassigned", i.e. the time an operator stands-by while an inspection task is completed. It makes intuitive sense that these type of activities are low risk, and could possibly contribute with a reduction of the TRR for particular task, workstation and production line. For example, if a workstation combines a task that is ergonomically inadequate, but "idle" times are assigned in the right proportion, these idle times could lower the overall risk rate of the workstation. However, "idle" time implies underutilization of resources. Therefore, a conservative measure can be taken by simply considering the negative CRRs as risk neutral (0). By taking all of the previous assumptions into consideration, the resulting statistical risk profiles are shown in Appendix 3.

3.7 Confidence intervals by production line and by activity

The ROM Risk Rate value are computed for individual task or a full production line as in equations 3.7 and 3.8. Results and confidence intervals for different production lines are shown in Figure 3-37:

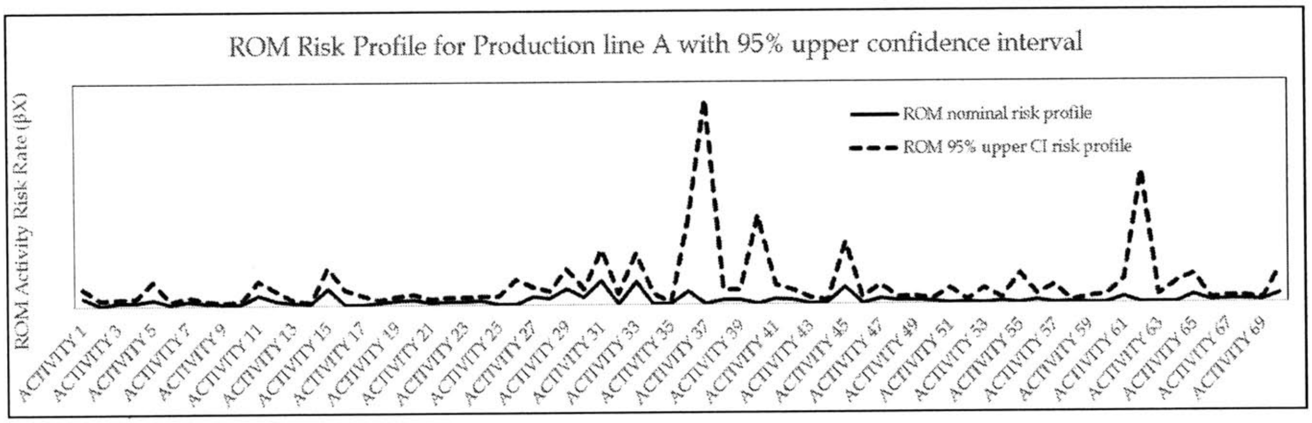
Figure 3-37: Confidence interval for TRR



The confidence interval is useful to discern for which production lines the model has better fit. While the regression model has some degree of prediction capability for Production Line B and C1, it is not as accurate as for Production Line A and D. This is due to the inevitable use of less significant categories, to keep the model consistent across production lines. The lack of fit for production lines B and C1 come from the fact that many activities fell into risk categories with poor regression parameter estimates. It is important, however, to take a closer look to Production lines A and D at the activity level and make a similar exercise, i.e. identify those activities where a positive risk rate was calculated with enough statistical significance.

In order to identify risky activities with an acceptable level of statistical significance, it is worthwhile to look at confidence intervals at the activity level. By doing so, investment decisions can not only be made by the nominal TRR predicted by the model, but especial focus can be put in those with tighter Confidence Intervals. The confidence interval for production line A is shown in figure 3-38:

Figure 3-38: ROM risk profile for production line A

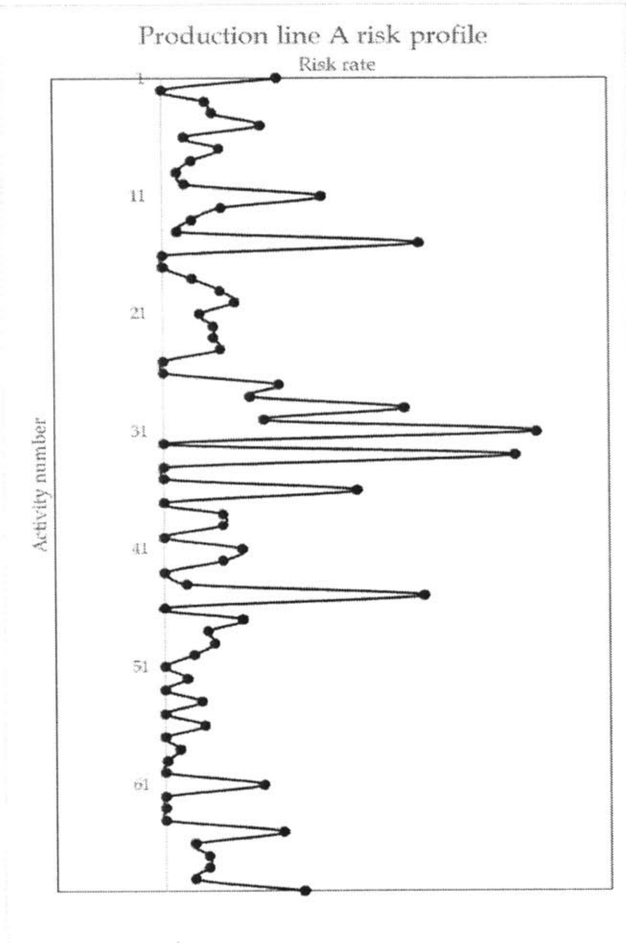


The upper confidence interval should be interpreted as a measure of statistical significance. Higher confidence interval values do not mean high ergonomic risk, they mean risks calculated with poor statistical significance (recall Figure 3-33).

To make a sound prioritization of observational risk assessments, a balance between high Activity Risk Rate and statistical significance should be considered.

The Nominal ROM risk profiles for each production lines are shown in Figures 3-38, 3-40 and 3-41:

Figure 3-39: Nominal ROM for production line A



As shown in figure 3-36, this production line has one of the best statistical significances. When ranking the activities from high to low by Risk Rate, and also considering the offset from the 95% Upper Confidence Interval, the following table is obtained:

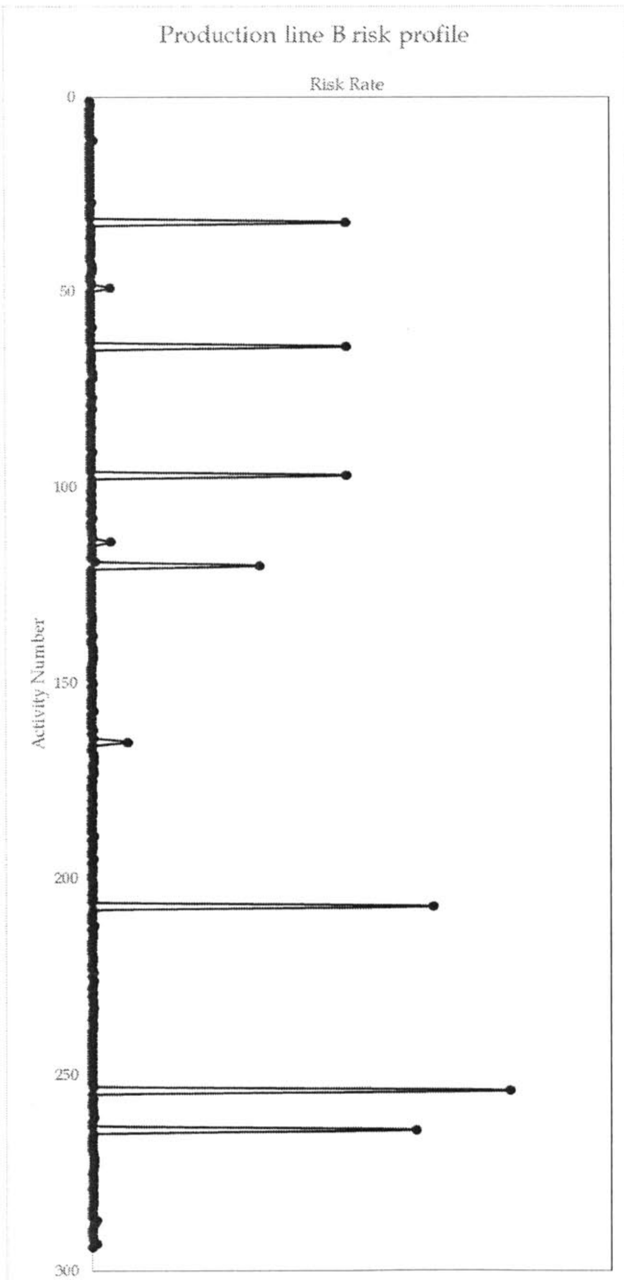
Figure 3-40: Activities ranked by risk rate

Operation Description	Risk Rate	UPPER CI	Difference
ACTIVITY 31	0.0016728	0.0007621	0.0009107
ACTIVITY 33	0.0015744	0.0007621	0.0008123
ACTIVITY 45	0.00116506	0.0033891	0.00222404
ACTIVITY 15	0.001148	0.0007621	0.0003859
ACTIVITY 29	0.0010824	0.0007621	0.0003203
ACTIVITY 36	0.00087128	0.0149883	0.01411702
.	.	.	.
.	.	.	.
.	.	.	.

Activities 31 and 33 (skin panels installation) look like the best candidates to perform a risk assessment on. It must be reiterated that the risk rates refer to likelihood of injury based on a regression model. A full observational risk assessment with any of the tools discussed in Chapter 2 should be employed to confirm if any poor ergonomic condition is present, and how sever it is.

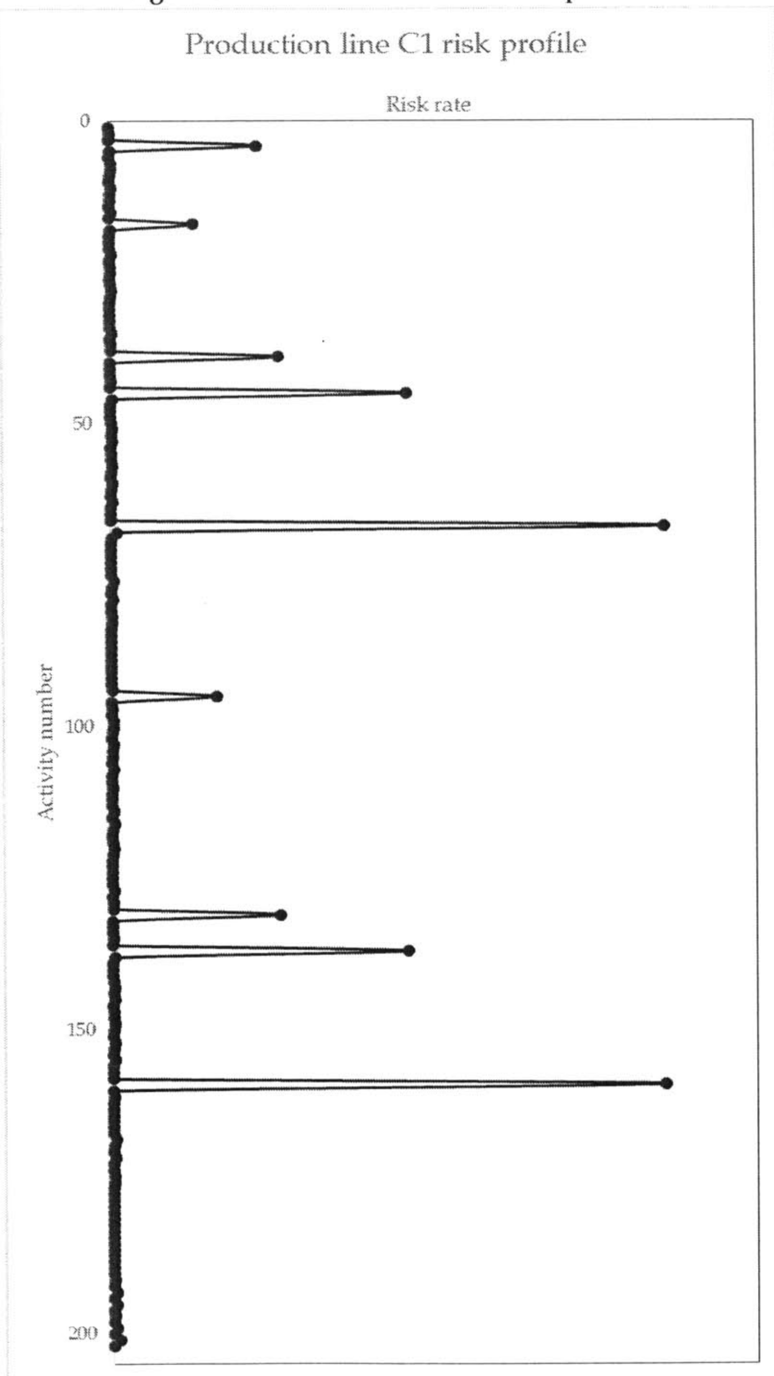
A similar exercise could be performed for the remainder of the product lines:

Figure 3-41: Nominal ROM for production line B



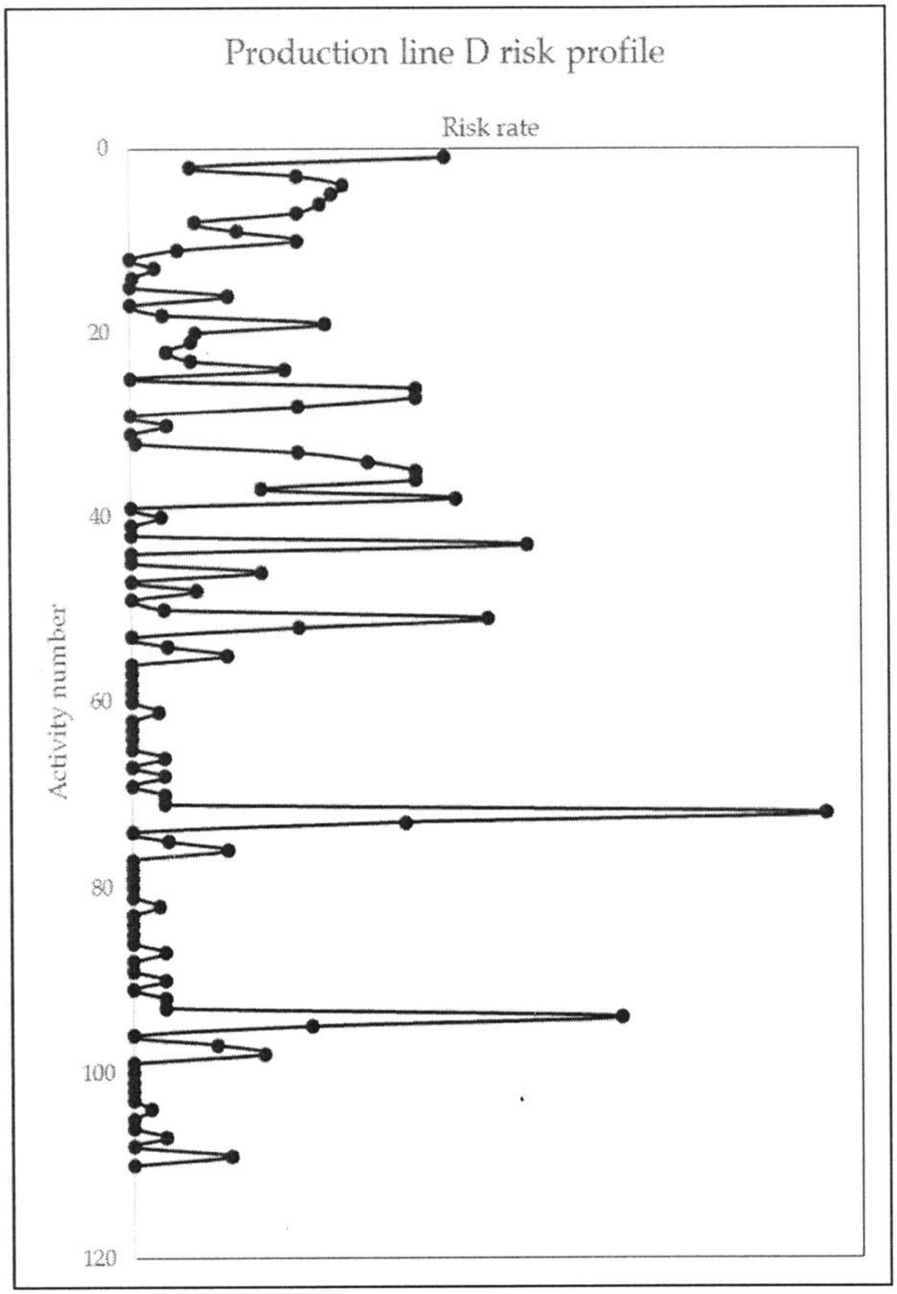
As mentioned before, the model performs poorly on Product Line B (recall figure 3-36). The few activities that look risky. This product in particular is significantly bigger in size, as compared to the ones assembled in Production Line A and C1. The recommendation is to build a separate model for this product line, using only employees exclusive to it. Similar conditions were encountered for Production Line C1, as shown in Figure 3-42:

Figure 3-42: Production Line D risk profile



The results for production line D are similar to those found for production line A, as can be noticed from Figure 3-43:

Figure 3-43: Nominal ROM risk profile for production line D



A similar exercise to the one performed for production line A can be done for production line D:

Figure 3-44: Activities ranked by risk rate

Activity	Risk Rate	Upper CI	Difference
Activity 72	0.0019024	0.224103126	0.222200726
Activity 94	0.0013448	0.158417727	0.157072927
Activity 43	0.0010891	0.006744735	0.005655635
Activity 51	0.000984	0.11591541	0.11493141
Activity 38	0.0008962	0.01592877	0.01503257
Activity 1	0.00087128	0.005395788	0.004524508
Activity 26	0.0007872	0.092732328	0.091945128
Activity 27	0.0007872	0.092732328	0.091945128
Activity 35	0.0007872	0.092732328	0.091945128
Activity 36	0.0007872	0.092732328	0.091945128
Activity 73	0.0007544	0.088868481	0.088114081
Activity 34	0.000656	0.07727694	0.07662094

In this case, the highest risk rates also have a big gap to the confidence interval. Activity 43 and Activity 1 seems risky with a low gap to the confidence interval and would be worthy to consider for performing a full observational risk assessment. Both activities are related to painting and fixture cleaning operations.

3.8 Conclusions

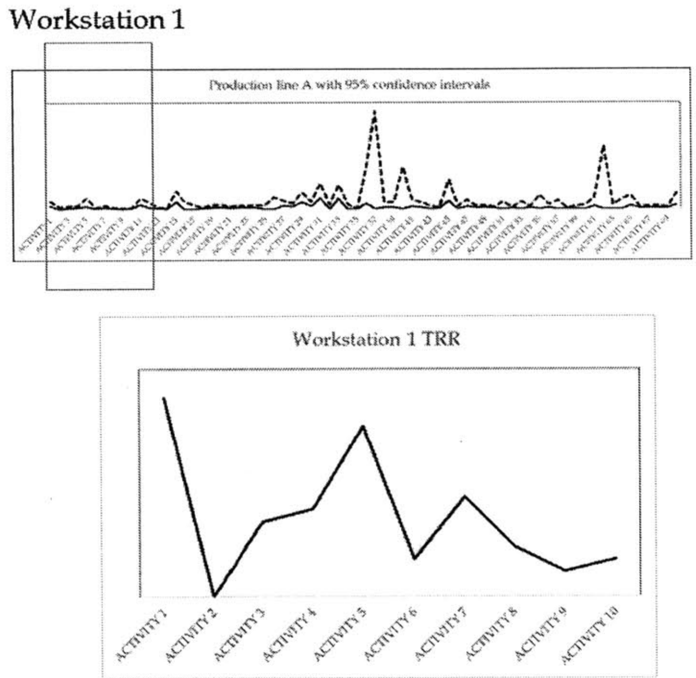
The Category Risk Rates (β) result practical to:

1) Quick assessment of the impact in *Total Risk Rate* (TRR) of automation projects
2) Pinpoint the activities in the current state with the highest Total Risk Rate (TRR)
3) Quick risk assessment of the impact of changes in statement of work for shop floor employees.

By using the CRR approach, automation projects can now be complemented with the ergonomic benefits as reflected with a decrease in TRR for a given workstation. Without having to perform an entire observational risk assessment, the manufacturing engineering groups can complement their business cases with the ROM risk quantification to strengthen project proposals. As projects move further in the implementation roadmaps, observational risk assessments can now be performed to quantify in more detail the ergonomic benefits of an engineering control being implemented.

When designing moving lines, now a TRR can be easily calculated for activities or combination of activities that will be performed for more extended periods of time in the future state, i.e. assuming an employee is currently responsible for performing activities 1 through 10 in production line A in workstation one. The current TRR calculated for workstation one is shown in Figure 3-45:

Figure 3-45: Example of ROM risk assessment for current state applied to the workstation level



The total workstation risk rate in the current state can be calculated as:

(3.9)
$$TRR = \sum \beta_m X_{il}$$

$$TRR\ (current\ state) = \beta_1 X_{1,1} + \beta_2 X_{2,1} + \beta_3 X_{3,1} + \cdots \beta_3 X_{10,1}$$

The result will be roughly the area under the TRR profile for workstation 1. Assume now that a moving line is being evaluated for implementation. As a result of the change in process flow, the employee who currently performs activities 1-10 is now going to perform activities 4, 5 and 6 for the entire shift.

The resulting TRR for the new workstation (or statement of work) for this employee would be:

(3.10)
$$TRR\ (future\ state) = \beta_4 X_{4,1} + \beta_5 X_{5,1} + \beta_6 X_{6,1}$$

But because the total labor-hours planned for 10 activities in the current state must equal the total labor-hours for only 3 activities in the moving line, the labor-hours for the future state must have higher values. In other words, the moving line aims the employee to perform less tasks but multiple times during the day to achieve higher production rates.

(3.11)
$$X_{4,1\ (future\ state)} + X_{5,1\ (future\ state)} + X_{6,1\ (future\ state)} = X_{1,1\ (current\ state)} + X_{2,1\ (current\ state)} + \cdots X_{10,1\ (current\ state)} = standard\ shift$$

In this example, having employee 1 allocating his/her entire shift to activities 4, 5 and 6 will result in an increase of 101% (2.013 times) of TRR. This is the result of adjusting the labor-hours for these 3 activities to match the standard shift, based on the increased production rate achieved by the moving line.

(3.12)

$$TRR_{future\ state} = 2.013 TRR_{current\ state}$$

Action can be taken by either risk assessing these 3 activities before implementing the moving line, or redesigning the workflow to avoid that this particular sequence of activities is performed by a single employee with the given workstation conditions.

An additional exercise can be performed by the process engineering organizations to evaluate the possibility of reducing the TRR of the workstation by fully automating a particular task. Taking again the example of workstation 1, the resulting benefits are obtained in terms of reduced TRR by automating any of the 10 activities performed manually in it:

Figure 3-46: ROM reduction of TRR

Project	Reduction in workstation TRR
Full automation activity 1	26%
Full automation activity 2	0%
Full automation activity 3	10%
Full automation activity 4	11%
Full automation activity 5	22%
Full automation activity 6	5%
Full automation activity 7	13%
Full automation activity 8	6%
Full automation activity 9	3%
Full automation activity 10	5%

With an R square value of 0.89, the 85-sample risk profile provides an acceptable reference guide if compared to the guideline provided by the PMI (-25% +75%) and to start evaluating automation projects.

Although the model shows overall statistical significance for some of the βs, it should be perceived only as a guide to prioritize resources and a quick assessment tool to complement project proposals. Several categories of activities fall within this range of acceptance from the final model as seen in Figure 3-47.

Figure 3-47: Confidence intervals for each category

Category	Confidence interval one sided width
Category 1	-908%
Category 2	132%
Category 3	588%
Category 4	32%
Category 5	-23%
Category 6	14%
Category 7	-32%
Category 8	156%
Category 9	36%
Category 10	-159%
Category 11	31%
Category 12	5368%
Category 13	-73%
Category 14	52%
Category 15	-173%
Category 16	278%
Category 17	-790%

3.9 Recommendations

The time tracking system can be easily improved to obtain live-data on pain and discomfort, with the same accuracy that labor is monitored. If a shop floor employee was requested to briefly rank the level of discomfort in a particular zone of their body right after reporting the task as finished, a wider response "Y" would then enable better models. Further-more these models could be also automated to broadcast provide live-indicators the same way production and quality is visually displayed in companies motivated by lean.

Companies already use visual elements for shop floor employees to communicate pain and discomfort [10]. Visual elements that can be easily managed and updated can have strong impact in the safety culture and they are an easy source of data.

3.10 Chapter 3 references

[1] N. Pearce, "Classification of epidemiological study designs," *Int. J. Epidemiol.*, vol. 41, no. 2, pp. 393–397, Apr. 2012.

[2] "www.teachepi.org - A website resource for learning and teaching epidemiology." [Online]. Available: http://www.teachepi.org/. [Accessed: 15-Feb-2016].

[3] "9.6 - Example of a Cohort Study | STAT 507." [Online]. Available: https://onlinecourses.science.psu.edu/stat507/node/63. [Accessed: 15-Feb-2016].

[4] R. B. Warnecke, A. Oh, N. Breen, S. Gehlert, E. Paskett, K. L. Tucker, N. Lurie, T. Rebbeck, J. Goodwin, J. Flack, S. Srinivasan, J. Kerner, S. Heurtin-Roberts, R. Abeles, F. L. Tyson, G. Patmios, and R. A. Hiatt, "Approaching Health Disparities From a Population Perspective: The National Institutes of Health Centers for Population Health and Health Disparities," *Am. J. Public Health*, vol. 98, no. 9, pp. 1608–1615, Sep. 2008.

[5] "Federal Aviation Administration." [Online]. Available: http://www.faa.gov/. [Accessed: 16-Feb-2016].
[6] "Ailerons." [Online]. Available: https://www.grc.nasa.gov/www/k-12/airplane/alr.html. [Accessed: 01-Apr-2016].
[7] "Rudder - Yaw." [Online]. Available: https://www.grc.nasa.gov/www/k-12/airplane/rud.html. [Accessed: 01-Apr-2016].
[8] "Horizontal Stabilizer - Elevator." [Online]. Available: https://www.grc.nasa.gov/www/k-12/airplane/elv.html. [Accessed: 01-Apr-2016].
[9] "Flaps and Slats." [Online]. Available: https://www.grc.nasa.gov/www/k-12/airplane/flap.html. [Accessed: 01-Apr-2016].
[10] J. Herrera, *Evaluation of control systems for automated aircraft wing manufacturing*. c2013., 2013.
[11] "Lockheed L-1011 TriStar 1/50/100/150/200/250, pictures, technical data, history - Barrie Aircraft Museum." [Online]. Available: http://barrieaircraft.com/lockheed-l-1011-tristar-150100150200250.html. [Accessed: 01-Apr-2016].
[12] C. F. Griffin and E. G. Dunning, "Development of an advanced composite aileron for the L-1011 transport aircraft," *ResearchGate*, Mar. 1982.
[13] pmdocuments, "How to Develop a Rough Order of Magnitude Estimate (ROM Estimate)," *Project Management Documents and Templates*. .

Chapter 4: Continuous improvement and collaborative robots

The following chapter provides an overview of collaborative robotics, their capabilities, limitations, current applications in different industries in order to understand their compatibility with operational excellence methodologies such as continuous improvement, lean manufacturing and six-sigma within the aerospace industry.

4.1 The history of automation and collaborative robots

Companies that show the highest level of productivity, measured in revenue per employee, are those who strive to attract the best talent to ignite and sustain innovation. McDonalds with 400,000 employees reaches $60,000 of revenue per employee whereas Facebook and Google have 30,000 and 32,000 employees respectively and report revenues per employee on the order of millions. These companies evidence the levels of productivity that can be attained when technology and innovation are encouraged, not resisted [1]. This comparison does not prove that a company such as McDonalds rejects new technologies to improve its processes, however, it brings up the opportunity that exists for it to automate process and steer its human capital from monotonous tasks to technology development.

It is important to notice that the speed with which automation will be displacing people in the upcoming years, has no precedent, as noted by Federico Pistono [1]. While some economists refer to the Industrial Revolution and unemployment data to show that catastrophic unemployment has never happened, even by looking at the biggest leaps of innovation, some of them fail to consider the fact that the evolution of human intelligence is much slower than the growth pace of machine intelligence [1]. This thesis projects a future state of manufacturing systems where humans can be physically enhanced and amplified by technology, not displaced.

Throughout history, automation of manual tasks has brought value to society. In the aircraft industry context, by effectively reducing manufacturing costs, automation indirectly should result in more affordable air travel. A common and outdated assumption when framing automation is perceiving it as means to reduce labor cost; therefore, technology is commonly defamed the manufacturing environment as a threat to human employment. As Thomas Mortimer condemned in the 18th century: "...those [machines] which are intended almost totally to exclude the labor of the human race" [1]. Such statements fall short when the overall impacts of innovation are taken into account. In the short term, machines might indeed take away jobs, but in the long run, innovation and automation has led to more jobs [3]. However, cases where machinery design was merely motivated to replace human activity are encountered throughout history. A good example is the "spinning jenny" invented in England with the motivation of avoiding high wages [3].

Advancing into the 19th century, the Luddite fallacy emerged as the observation that mechanization and automation pose economic risks, especially for those companies producing goods consumed by the workers. While machinery might be feared to replace workers at a faster rate than they can find other occupations, the fallacy rests in the fact that destroying assets that are meant to increase the overarching welfare of society, displacing workers from the industry to more service oriented jobs [2]. But similar to the remarks by Pistono [1] noted modern economists such as David The author [2] sustain the opinion that automation contributes to "growing inequality"[3]. The author also arguments that the effects of technology are diverse, but tend to improve the productivity of educated workers while having unsubstantial effect on the productivity or compensation of the less-skilled workforce. Pistono supports that a real concern is that the greatest aspiration of some workers is to have a monotonous mechanical job which is just enough to pay bills; he considers this to be an "insult to the dignity of every individual" [1]. The current distribution of employment in the US reflects that nearly half of the workforce belongs to professions that were created a long time ago, supporting the argument that new technologies does not always result in new jobs. For the most part, in an era dominated by consumer-electronics, computer science engineers and software developers barely make to be 0.72% of the workforce. [4]

An important breakthrough made by Ford to bear in mind is "standard work". With the dilution of complexity, it was possible to transform difficult tasks in small and simple-to execute-mechanical operations [1]. By allowing repetition and monotonous tasks to become more evident, the Henry Ford assembly lines resulted in the first forms of automation in collaboration with the human elements [1].

According to Pistono, whenever machines displaced human workers in the Henry Ford Era, there was always time to learn a new job, or some operations were complex enough to discourage automation. Task complexity is indeed one of the challenges found by automation within modern aerospace manufacturing processes. Referring back to Chapter 2, a framework then is necessary to gauge which is the adequate level of technology to deploy in the workstation for productivity improvement, without compromising safety.

Chapter 1 emphasized the need of aircraft manufacturers for increased productivity while optimizing the manufacturing process to achieve an injury-free operation. One of the benefits of collaborative automation pertaining to this project, is that scenarios will be researched to prove robots can work side by side with humans, making the workspace a human-inclusive and futuristic ecosystem.

With automotive applications making up for 65% of the robots market in the US, the term "collaborative robots" refers today mostly to those that are capable of working unenclosed, unlike the most predominant robotic technologies in place nowadays in entirely fenced spaces due to the lack of safety features. By offering a bridge between fully automated solutions and manual work, collaborative robots unlock a whole new set of opportunities [5]. With a broad range of capabilities, these type of robots can range from simple lightweight arms to double-armed humanoids relying on different types of technologies and mechanisms or combinations of both to achieve collaborative capabilities [6].

In this regard, "The Second Machine Age" describes how the development of digital technology will amplify human capability to gather and process data in a very similar way to how the steam engine amplified our physical capabilities. [7] The book characterizes computer technologies as "exponential, digital and combinatorial". In the realm of robotics, it is particularly important to consider the *exponential* characteristic of computational capability. The exponential attribute is associated with the Moore's Law, that refers to the fact that computing power that can be obtained with a dollar duplicates every year [7]. With computer power becoming more affordable, new problems can now be addressed with affordable integrated electro-mechanical devise, such as robotics.

Collaborative robotics, also known as lightweight robotics or soft robotics, is the segment within the wide realm of automation that offers two distinctive characteristics: mobility and the capacity to work close to humans. These type of robots also display high payload capacity to weight ratio and operational speeds profiles that resemble those of humans. Some of the typical applications that these technologies were integrated around are:

1) Industrial servicing, assisting operators to access restricted spaces
2) Households (very attractive and growing market)
3) Space applications (due to the lightweight attributes)
4) Medical robotics offering improved accuracy in surgical procedures. [7]

One of the first lightweight robots developed by LWR (Deutsches Zentrum für Luft- und Raumfahrt) is the DLR. The design challenge for this robot was mainly reducing weight to approach the 1:1 payload-to-mass ratio. In 2004 the LWR III was licensed to KUKA, the company kept developing it to release the LBR IV and ultimately the IIWA in 2013, giving birth to the third generation of light-weight robotics. [7]

Since 2009 the KUKA LBR 4 has been used to fully automate the assembly of rear axle gear boxes for Mercedes-Benz. In December 2012 Daimler Benz agreed to research the cooperation of human workers and KUKA LBRs in assembly tasks. To date more than 500,000 rear axle gearboxes have been successfully assembled using the assistance of these robotic solutions. [7]

Most of the robots currently in place within aerospace manufacturing environments serve to perform repetitive tasks that also require high levels of accuracy. The way these industrial robots achieve such accuracy and repeatability is through the use of stiff and heavy manipulators. At the other end of the spectrum, a lightweight robot requires more sophisticated feedback control systems, which have to be more sensitive to external physical stimuli to ultimately offer the adequate balance of safety features and accuracy to make interaction with humans feasible. [7]

There are two main design approaches taken by companies when designing lightweight robots: modular mechatronics and tendon actuation approaches. The common features of both approaches are:

1) Low weight achieved with the use of light metals and composite materials
2) Low power consumption mainly due to reduced inertias
3) Safety features embedded in the mechanical transmission system.

The modular mechatronic approach offers self-contained systems in which the electronics are packed within the joint structure. Additionally, these type of robots rely on high torque and moderate-speed motors for faster dynamic responses designed for high load/weight ratios and full state measurements in the joints, combining torque sensing with position sensing to offer a safety-compliant behavior. Tendon actuated light-robotics have their actuators packed in the base so that the total mobile mass is minimized.

Additional examples of early light-weight robotics are:

1) The Barrett arm, cable-driven by actuators located in the base of the structure
2) The Mitsubishi PA10, a redundant arm with a total weight of 38 kg and the ability to handle 10 kg payload
3) The Kuka lightweight arm that offers 7 degrees of freedom and a weight/load ratio close to 1:1 which is also revolutionary because of its torque control interphase
4) The MIRO is a product inspired in surgical applications with 3kg of payload, 7 joints that can be torque-controlled and an architecture that is compatible with standard endoscopic instruments. (7)

4.2 Capabilities and limitations of collaborative robots

The main focus of control design for collaborative robots is finding the balance between productivity and safe interaction with humans. In comparison to the standard industrial robot, the following characteristics are the main differentiators of collaborative robots according to [8] and [9]:

1) Extensive use of feedback through vision, force, and proximity sensing elements at the TCP and joints
2) Control logic that constraints force for safe interactions
3) A position control that compensates for vibrations and steady state error
4) Control logic for unexpected collisions
5) Overcurrent detection and passivity based-control
6) Easy programming through "teaching" for some models.

Due to all these control elements, safety functions such as autonomous security stops and collision help robot integrators to avoid the need for fences and safety guards when they are deployed in the workplace.

There are two terms that refer to this type of robots: force-limited robots and collaborative robots. The terms are interchangeably used throughout the literature but the main characteristics for each of these, according to [9], are:

Force limited robots: typically characterized by power and force-limiting through torque sensors, rounded shapes and covered motors to reduce the severity of impacts.

Collaborative robots: those that can work side by side with humans but are not necessarily force limited. An industrial robot with a monitoring system for a defined operating area would fall into this category. Oftentimes these are also referred to as Cobots.

Regardless of the term, any robot that fits either or both categories should allow one or several of the 4 types of collaboration according to [9]:

1) Safety Monitored Stop: the robot interrupts its task when a human is within the safety defined area, generally through proximity sensing
2) Hand guiding: when the robot can be hand-guided or hand-taught. With this functionality, paths can be easily programmed for pick and place applications, for example.

3) Speed and separation monitoring: similar to the safety monitored stop, this functionality allows the robot to operate in a safe mode, by reducing speeds for example, when a human is detected in a pre-designated area; this might also be achieved by either vision detection or proximity sensing.
4) Power and force limiting: abnormal forces ban be dissipated when detected.

That said, a comprehensive list of most available models that fit either or both of these categories can be found below:

ABB YuMi: Originally called FRIDA (Friendly Robot for Industrial Dual-Arm) is dual-arm robotic solution offered by ABB and targeted for the consumer electronics manufacturers. It is light-weight (38 kg), compact and suitable for assembling small parts (payload of 500g) with high accuracy (0.02 mm). With this set of characteristics, this robot could find vast potential applications in the toy and watch industries [10] [9]. YuMi price is approximately $40,000 [11]

ABB Roberta (Gomtec): A six-axis collaborative robot, designed to be easily transported around factory environments while providing a high payload-to-weight (19 kg of weight, payload of 8 kg)ratio [12]. By acquiring Gomtec, ABB intends to complement its product portfolio, leaving YuMi to handle smaller parts, while dedicating Roberta to higher payload applications [13]. A Roberta can be programmed by hand-guiding, has safety nodes on each axis, is equipped with a camera and a fingertip force sensing system. It is offered in 3 different sizes for different payload requirements (4, 8 and 12 kg). Roberta base price will be approximately €30,000 [14].

Bionic Robotics- BIOROB: Characterized by its lightweight and passive safety systems, this robot specializes in pick-and-place, inspection and collaboration tasks by using a patented technology inspired by the elastic muscle-tendon biomechanical joints of the human arm. This tendon driven system mimics human movement and opens up new areas of research for robot-embodied intelligence. Bio Robotic models offer up to 0.2 mm of accuracy and a nominal payload of 800 g. [15].

BOSCH-APAS: This is the first robot to be certified for human collaboration by the German Employers' Liability Insurance Association [9]. It is equipped with a tactile detection wrap and has speed limiting functionalities. It includes 2D and 3D vision capabilities and a 3-finger gripper. With combining these features, the APAS robot has unique competitive advantages in safety, mobility and reliability.

FANUC CR-35IA: This model can handle up to 35 kg of payload. While unexplored applications might have been enabled by FANUC by offering the highest payload for a collaborative robot, it is designed to be ground-fixed and it has limited mobility due to its size and dimensions. Nevertheless, it offers the accuracy and repeatability of an industrial robot while offering some of the benefits that can be obtained from other collaborative robots in the marketplace.

F&P PERSONAL ROBOTICS - PRob 1R: These robots are force limited and are also equipped with cushion wrap that minimizes the chance of harm in the case of collision. It has 4 to 6 axis and it provides an easy web-based programming tool. It is moreover fully integrated, with all electronic components packaged within the mobile elements for easy relocation and deployment. It includes a P-GRIP modular end effector and allows for multi-channel controls. Its main advantages are the intuitive user-interphase, compactness and versatility made possible by axis modularity; the PRob 1R has payback periods of around 6 to 12 months. [16]

KAWADA INDUSTRIES - NEXTAGE: With dual 6-axis arms, dual camera and a mobile base, KAWADA offers unparalleled mobility capabilities coupled with a GUI to facilitate robot operation. Additionally, the source code for programming is General Public License. A distinctive safety feature in the NEXTAGE system, is the ability of the robot to keep its elbows within the workspace to avoid collisions; the NEXTAGE is also equipped with 80-watt power motors that do not exert hazardous forces. Additional safety features such as protective stops can be used by adding proximity detectors.

KUKA - IIWA: the "Intelligent Industrial Work Assistant" weights from 22 to 29 kg and handles payloads from 7 to 14kg, depending on the chosen variant. It is targeted to high precision (repeatability of 0.1 mm) assembly operations such as surgery assistance and hose assembly [17]. Like the human arm it has 7 axes, each one equipped with integrated sensors for tight position control or sensitivity. It can be programmed through JAVA.

Universal Robots: Universal Robots is a collaborative robots manufacturer providing a portfolio of products (UR3, UR5, UR10) to handle payloads ranging from 3 to 10 kg with a repeatability of up to 0.1 mm. They are well known for being easy to set up and operate without the need for programming skills. Universal robots can be programmed by manually moving the TCP from one point to point (hand-teaching) or using a pendant. The price range for universal robots is $23,000 to $45,000.

4.3 The importance of continuous improvement for commercial aerospace manufacturers

As of 2015, the aerospace industry is a multibillion dollar industry dominated by Boeing and Airbus. Airbus emerged from the coalition of three European economic powers to enter the market and to compete against Boeing and McDonnell Douglass. The main difficulties Airbus faced before firmly establishing its position in the market were lack of subsidies from the government, limited private investment, due to the high risks inherent in the industry, and lengthy product development processes[15].

The passenger airline industry, being the principal customer of commercial aircraft manufacturers, was analyzed by Sanka Illangakoon using Porter's Five Forces framework [17]. It is worthy to analyze the conditions under which Boeing and Airbus are competing to gauge the importance that continuous improvement plays in their strategies to moving forward to increase production rates [18].

The bargaining power of buyers: from 2000-2010 the emergence of low cost carriers increased the demand for narrow body models by 75%. The panorama for the upcoming decade reflects more options for airliners (buyers) than just the Boeing 737 and the Airbus A320 series. The Mitsubishi Regional Jet, the Bombardier C-Series, the Comac ARJ21 and the Embraer ERJ 145 are emerging as options to the 737 and the A320 that shift the bargaining balance to buyers, in this case constituted by airline operators.

The bargaining power of suppliers: Both aircraft manufacturers engage suppliers and subcontractors around the world to furnish parts to the final-assembly plants. Most of these suppliers are highly specialized, such as those dedicated to composite material fabrication, engine production and avionics. The high costs associated with shifting subcontractors balance the bargaining power towards the suppliers according to analysis performed by [18] Illangakoon.

Threat of substitutes: Despite the obvious alternatives to air transportation including cars, car pooling, boats buses and trains, flying is still the most effective and convenient means to transport long distances, especially long-haul travel over oceans and between countries[19]. Where commercial aviation is the predominant alternative, the outlook for the aerospace market is strong in accordance with the SWOT analysis performed by Marketline [20]. However, the likelihood of someone driving or taking trains poses a slightly higher threat for regional carriers. Time, money and personal preference are the factors to consider to better weigh the threat [21]. The hub and spoke represents one of the main advantages of air traveling, since many destinations can be reached from a single point of origin. Although ground travel might become an alternative for the so called "spoke travelers", a study revealed that convenience and valuing time over money make them choose flying for the most part. Nevertheless, autonomous driving might become an important substitute for short haul flights in the next few years [22].

Threat of new entrants: The Boeing Company SWOT analysis also mentions that the company will be encountering aggressive competition from other companies competing for market share such as Airbus, Embraer and Bombardier, and potential additional competitors from Russia, China and Japan. Boeing's predictions are that in the next 20 years China will become the biggest plane market surpassing the US, demanding 6330 airplanes [23].

Although China has demonstrated the market and airplane development capabilities, it confronts the heritage of the major airframe dominants and has not demonstrated mass production capabilities [24]. Nevertheless, Commercial Aircraft Corporation of China, Ltd (COMAC), the Chinese state-owned aerospace manufacturer, has recently formed partnerships with Bombardier aiming to place "cross-market single-aisle narrow body jets" in emerging markets. This relationship is preceded by successful partnerships in other ventures like the high-speed train. [25]

The new entrants might see an incentive to jump into the competition, but will not pose a significant threat to the current market shares from the major manufacturers unless operation efficiency and effective integration of technologies are completed in record time. Also, the missed delivery dates by both Airbus and Boeing could become a motivator for switching, especially with Russia and China receiving financial supports from their governments.

Effects on competitive rivalry: Airbus and Boeing still account for the biggest fraction of the market, confronting very little competition from Ilyushin, Tupolev, Bombardier and Embraer. Although the two major competitors remain addressing the opportunities of previous models on their new airplane programs, the market is which they operate is highly competitive [26]. Airplane prices, being a main driver in the decision for selecting an aircraft supplier, has started shifting airlines from one company to another. Ryanair and Easyjet are examples of low-cost operators terminating negotiations with Boeing and shifting to Airbus mainly because of the difference in price [24].

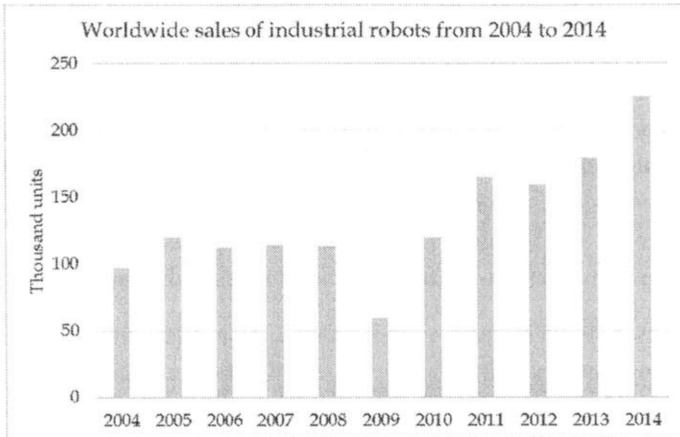
Considering the current forces in the commercial aviation market and the increasing demand for new airplanes discussed in Chapter 1 it can be noticed that strategies to reduce costs and increase productivity must be accelerated by Boeing [27]. As discussed throughout this thesis, a proven strategy is to draw lessons learned from outside the aerospace industry and strive for operational excellence [28]. Such was the case of the Nine Steps program lead by the 737 assembly line, which showed that adapting best practices such as value stream mapping, point-of-use staging and moving lines which resulted in reducing cycle times by half [28]. Upcoming programs with ambitious productivity targets, such as building 125 units/year of the 777x, will pose unprecedented technology challenges [29] that will require the fast integration of new technologies (including robots) for in-house fabrication, assembly and inspection.

The hay bale seat loader is well known case of fast innovation referenced often as a hallmark process improvement project resulting from the application of continuous improvement [30]. This is one of many examples in which off-the-shelf technology combined with lean production methodologies can unlock opportunities for significant efficiency improvements and cost reductions; investments decisions that are founded on the basic principles of operational excellence help to allocate the right technologies to the right steps in the process. With standardized manufacturing techniques advancing airplane manufacturing to be "more repeatable and predictable" robotic interventions will be easier to integrate to new assembly lines such as the 777x and current production models [28]. Successful integration of advanced manufacturing (including robotics) with lean methodologies can quickly remove wasteful repetitions, achieve direct delivery of parts to the assembly stations, improving sequencing of parts to reduce inventory, reducing overhead costs and thereby easing cash flow overall [31].

4.4 Penetration of robotics in aircraft manufacturing

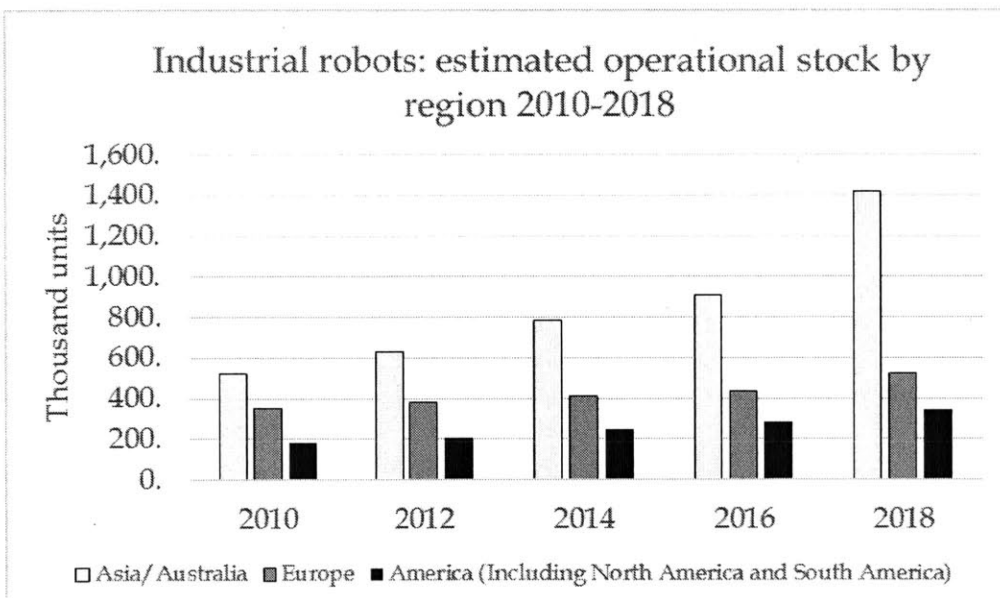
According to the International Federation of Robotics, 2014 recorded the biggest volumes of robots sales in history. The automation trend gained momentum since 2010 mainly because of the accelerated advancements in robotic technologies and the need for automation competitive markets. With a CAGR of approximately 17% from 2010 to 2014, approximately 225,000 industrial robots were demanded in 2014 (Figure 4-1) [30].

Figure 4-1: Worldwide sales of industrial robots[33]



The average global robot density is approximately 66 industrial robots installed per 100,000 employees [32]. The main markets within this time frame (2010-2014) were in Asia, Australia and New Zeland, with the highest demand registered for 3 consecutive years, even though Australia and New Zeland are not the biggest robot manufacturing countries. The main driver of the growth is the automotive industry, the main consumer of robots, totaling 43% of the share [32]. The projected operational stock of multipurpose industrial robots will reach about 1.5 million stock units in Asia/Australia [34].

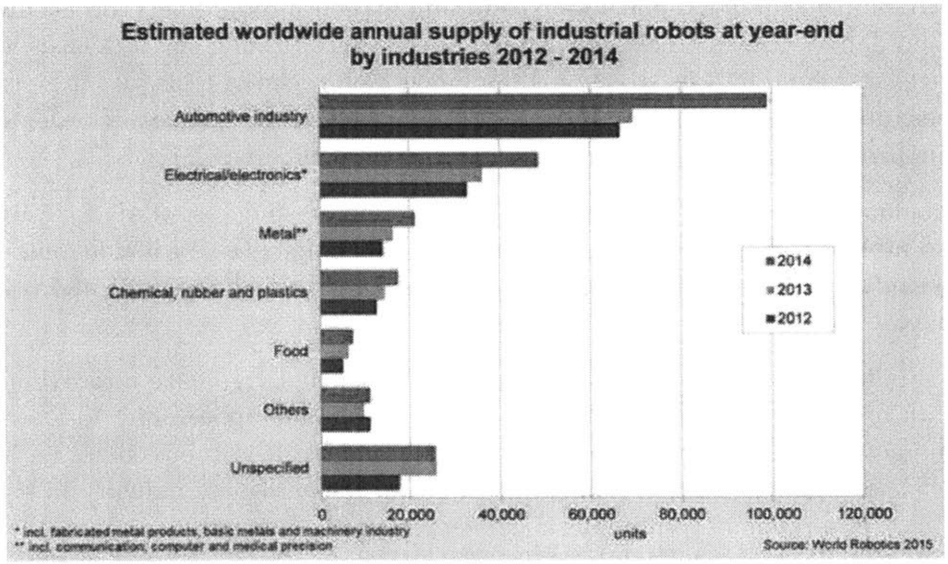
Figure 4-2: Industrial robots: estimated operational stock by continent.



The second place in robot usage is electronics, including computers, radios, TV, communication devices, medical equipment, precision and optical instruments reaching 21% of total sales in 2014.

By looking at the estimated annual supply of industrial robots, it is noted that there is an opportunity to push technology into aircraft manufacturing (Figure 4-3).

Figure 4-3 : estimated annual supply of industrial robots[32]



The opportunity in aerospace for industrial robotics can be amplified by the objective of making airplane assembly more "repeatable" as mentioned earlier. The aerospace niches for robotics do not stop in final assembly, they can become visible for the suppliers as a result of "flexible manufacturing process" which are trending up in factories of main suppliers such as GE Aviation, Honeywell, Rockwell Collins, Spirit AeroSystems and UTC Aerospace Systems [11]. As rising and maintaining output rate, quality and safety performance becomes a necessity for all these companies, automation and autonomation become a vital resource.

The main applications of robotics in aerospace according to [35] are:

1. Drilling and fastening
2. Inspection
3. Welding
4. Sealing and dispensing
5. Rigid manufacturing

Boeing presumably will invest about $1 billion in automation [11] within the next few years to drive up efficiency in drilling, fastener insertion, riveting, sealing, coating, material handling, carbon-fiber layup and machining operations, deburring and shot peening. According to Gerald Young, giving a keynote in AeroDef Manufacturing Summit [36], Boeing is strategically aiming to create agile systems through "an integrated family of robots, low-cost intelligent systems and lightweight flexible equipment." While many studies have been written about robotics in the aerospace industry, this thesis complements the field with a different approach, focusing mainly on employees' safety and finding opportunities for collaborative automation. Although the collaborative robots market is estimated to reach over $1 billion from approximately $95M in

2015 [37]; this project comes at a time when there is a vast and unexplored potential for this technology to address all the challenges listed previously in the aerospace manufacturing environment.

Similarly, Airbus has aggressive plans to expand automation through the "The Factory of the Future"; this initiative focuses on lessons learned after years of testing smart devices internally [12]. A key aspect behind Airbus strategy is the integration of smart tools into the production systems. These tools use live data (gathered and analyzed at the source) in order to create inherently intelligent production systems as a modernization initiative. [38]

Aerospace manufacturing is undoubtedly an exciting and interesting case study for automation, with final assembly volumes not being appealing enough at a first glance when making business decisions, the industrial engineering innovations will help approach the quantification of benefits in a different way.

Employees should be empowered and encouraged to problem solve, make improvements and own the credit for doing so. Collaborative robots offer a unique opportunity to learn how to optimally interact with new technologies in the worksite and create virtuous circles for increased performance. The project is therefore meant to empower the aerospace industry in its journey towards the next generation of continuous improvement methodologies.

4.5 Continuous improvement

The term "lean manufacturing" was developed in The Machine that Changed the World to create a guide for organizations to specify and quantify value, create better alignment in the sequence of actions that create value and avoid interruptions. The key elements for a lean production systems are:

1) Minimize intermediate inventories
2) Optimize the geographical location of internal supplies
3) Kanban system
4) Reduce setup
5) Standardize work
6) Allow workers to be multifunctional
7) Continuous improvement of processes
8) Poka-yokes.

Continuous improvement, also known as *Kaizen* or *Continual Improvement* is "the ongoing improvement of products, services or processes through incremental and breakthrough improvements", "method for identifying opportunities for streamlining work and reducing waste"[39], "Kaizen, also known as continuous improvement, is a long-term approach to work that systematically seeks to achieve small, incremental changes in processes in order to improve efficiency and quality"[40].

For some authors Six-Sigma, Kaizen and Lean are simply variations of continuous improvement, but all are consistent in acknowledging its roots in the Japanese manufacturers in the decade of the 1950s. The most renowned continuous improvement technique was proposed by J. Edward Deming to execute continuous improvement projects is well known in the industrial environment as the PDCA (Plan-Do-Check-Act) cycle which will be described in more detail in the next chapter.

Continuous improvement might be perceived as an inhibitor for innovation in the research and development organizations. 3M and GE are examples of companies that have been loosening their continuous improvement methodologies to drive up innovation. [41]. The article suggests that the continuous improvement methodologies or techniques should not be applied generically to all parts of the organization. "The kind of rigor required in a manufacturing environment may be unnecessary, or even destructive, in a research or design shop" [38].

However, the opposite might also slow down the flow of innovation from the labs to the shop floor; by treating integration of off-the-shelf technologies as big R&D programs, the timelines for implementation is often times compromised. It is convenient, however, that the teams responsible for developing and integrating new technologies understand the process improvement methodologies and toolboxes that the manufacturing groups work with. Continuous improvement and six-sigma tools should not be perceived as brake mechanism for innovation but as accelerators. This project demonstrate how collaborative robotics can flow from the lab to the shop-floor with the use of continuous improvement roadmaps.

The application of lean manufacturing in the aerospace industry has facilitated its immersion into the continuous improvement culture. The moving line for example, offer powerful mechanisms to identify and eliminate waste, since it creates sense of urgency.

4.6 Summary

The 5 force analysis of the commercial aircraft industry reveals the need to intensify action in continuous improvement and automation. Through the overview of technologies currently available and their capabilities, the next chapter will demonstrate how one of these robots can easily be deployed to take over a repetitive task through a fast-track implementation plan based on continuous improvement roadmaps.

There is a significant difference in the timelines for research and development to technology integration and implementation. The main hurdles for automation comes from procedure and process constrains in complex organizations. Finding projects and gauging the size and the level of technology required in the worksite requires a pragmatic and holistic approach, especially when considering problem solving with the use of new robotic technologies.

4.7 Chapter 4 references

[1] R. J. Rosen, "In Praise of Short-Term Thinking," *The Atlantic*, 03-Sep-2015.

[2] "Chapter 2: The Luddite Fallacy," *Robots Will Steal Your Job, But That's OK.* [Online]. Available: http://robotswillstealyourjob.com/es/read/part1/ch2-luddite-fallacy. [Accessed: 27-Nov-2015].

[3] T. Lehman, "Countering the Modern Luddite Impulse," *Indep. Rev.*, vol. 20, no. 2, pp. 265–283, Fall 2015.

[4] "Chapter 9: Unemployment Tomorrow," *Robots Will Steal Your Job, But That's OK.* [Online]. Available: http://robotswillstealyourjob.com/es/read/part1/ch9-unemployment-tomorrow. [Accessed: 27-Nov-2015].

[5] E. H. Oestergaard, "Collaborative Robots for DIY AUTOMATION," *Prod. Mach.*, vol. 15, no. 3, pp. 32–36, Mar. 2015.
[6] "The Realm of Collaborative Robots – Empowering Us in Many Forms," *Robotics Online*. [Online]. Available: http://www.robotics.org/content-detail.cfm/Industrial-Robotics-Industry-Insights/The-Realm-of-Collaborative-Robots-Empowering-Us-in-Many-Forms/content_id/4854. [Accessed: 10-Nov-2015].
[7] J. B. Rebitzer, "Book Review: The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies," *Ind. Labor Relat. Rev.*, vol. 68, no. 2, pp. 460–461, Mar. 2015.
[8] G. Hirzinger and A. Albu-Schaeffer, "Light-weight robots," *Scholarpedia*, vol. 3, no. 4, p. 3889, 2008.
[9] "Robotiq: Industrial Robotic Gripper Manufacturer," *Robotiq*. [Online]. Available: http://robotiq.com/. [Accessed: 12-Feb-2016].
[10] "YuMi | ABB." [Online]. Available: http://new.abb.com/products/robotics/yumi. [Accessed: 13-Feb-2016].
[11] "ABB confirms pricing of YuMi at Hannover : Robotics Update." .
[12] M. Bélanger-Barrette, "New Collaborative Robot called Roberta - Your New Best Friend." [Online]. Available: http://blog.robotiq.com/bid/71048/New-Collaborative-Robot-called-Roberta-Your-New-Best-Friend. [Accessed: 13-Feb-2016].
[13] "ABB positions Roberta alongside YuMi with Gomtec acquisition : Robotics Update." .
[14] I. Bonev, "Who Is Gomtec, the Collaborative Robotics Company Acquired by ABB?," 14-Apr-2015. [Online]. Available: http://spectrum.ieee.org/automaton/robotics/industrial-robots/who-is-gomtec-the-collaborative-robotics-company-acquired-by-abb. [Accessed: 13-Feb-2016].
[15] "Technical Data - EN BionicRobotics." [Online]. Available: http://www.bionic-robotics.de/en/products/technical-data. [Accessed: 13-Feb-2016].
[16] M. Bélanger-Barrette, "F&P Robotics Releases a New Collaborative Robot." [Online]. Available: http://blog.robotiq.com/fp-robotics-releases-a-new-collaborative-robot. [Accessed: 06-Apr-2016].
[17] "ROS-Industrial Kuka LBR-iiwa community meeting," 11:48:23 UTC.
[18] S. Illangakoon, "The rise of Airbus from market challenger to global leader: Marketing perspective," *Competitive factors in the Aircraft Manufacturing Industry (Airbus*, 27-Mar-2011..
[19] "Alternatives to Flying: Other Ways to Get From Here to There," *Wise Bread*. [Online]. Available: http://www.wisebread.com/alternatives-to-flying-other-ways-to-get-from-here-to-there. [Accessed: 26-Nov-2015].
[20] "The Boeing Company SWOT Analysis," *Boeing Co. SWOT Anal.*, pp. 1–10, Sep. 2015.
[21] "The Industry Handbook: The Airline Industry," *Investopedia*. [Online]. Available: http://www.investopedia.com/features/industryhandbook/airline.asp. [Accessed: 25-Nov-2015].
[22] J. Cidell, "Spoke airports, intentional and unintentional ground travel, and the air travel decision-making process," *Transp. Res. Part Policy Pract.*, vol. 69, pp. 113–123, Nov. 2014.
[23] "Boeing Sees Demand in China for 6,330 Airplanes Valued at Nearly $1 Trillion - Aug 25, 2015." [Online]. Available: http://boeing.mediaroom.com/2015-08-25-Boeing-Sees-Demand-in-China-for-6-330-Airplanes-Valued-at-Nearly-1-Trillion. [Accessed: 13-Feb-2016].

[24] J. L. Fuentes, "Commercial Aircraft Corporation of China (Comac) attempts to break the Airbus-Boeing duopoly, will it succeed? : an industry analysis framework applied," Thesis, Massachusetts Institute of Technology, 2011.
[25] "Bombardier ramps up Chinese partnership, faces new challenge." [Online]. Available: http://www.cbc.ca/news/canada/montreal/bombardier-ramps-up-chinese-partnership-faces-new-challenge-1.1351009. [Accessed: 06-Apr-2016].
[26] "Airbus Group SE (formerly Airbus Group NV) SWOT Analysis," *Airbus Group NV Previously Known Eur. Aeronaut. Def. Space Co. EADS NV SWOT Anal.*, pp. 1–10, Sep. 2015.
[27] "Boeing: Long Term Market." [Online]. Available: http://www.boeing.com/commercial/market/long-term-market/. [Accessed: 27-Nov-2015].
[28] J. R. Black, *Lean Production: Implementing a World-class System*. Industrial Press Inc., 2008.
[29] S. Trimble, "Documents reveal Boeing's route to high 777X output," *Flight Int.*, vol. 187, no. 5495, pp. 14–15, Jun. 2015.
[30] "News Releases/Statements," *MediaRoom*. [Online]. Available: http://boeing.mediaroom.com/2003-07-01-Converted-Farm-Machine-Improves-Boeing-Production-Process. [Accessed: 11-May-2016].
[31] T. Hepher, A. S. A. 29 2015, and 2:24 Am, "Boeing wants to go deeper into Toyota-style 'lean' production for planes," *Business Insider Australia*. [Online]. Available: http://www.businessinsider.com.au/r-boeing-looks-to-car-industry-expert-for-jet-production-savings-2015-4. [Accessed: 26-Nov-2015].
[32] "Statistics - IFR International Federation of Robotics." [Online]. Available: http://www.ifr.org/industrial-robots/statistics/. [Accessed: 13-Feb-2016].
[33] "North American industrial robot unit sales growth 2015 | Statistic," *Statista*. [Online]. Available: http://www.statista.com/statistics/217544/growth-of-north-american-industrial-robot-industry-by-customer-segment/. [Accessed: 30-Nov-2015].
[34] "Industrial robots: estimated operational stock by region 2018 | Forecast," *Statista*. [Online]. Available: http://www.statista.com/statistics/281379/estimated-operational-stock-of-industrial-robots-by-region/. [Accessed: 30-Nov-2015].
[35] M. Bélanger-Barrette, "Top 5 Robotic Applications in the Aerospace Industry." [Online]. Available: http://blog.robotiq.com/bid/70043/Top-5-Robotic-Applications-in-the-Aerospace-Industry. [Accessed: 13-Feb-2016].
[36] "Assembly Automation Takes Off in Aerospace Industry." [Online]. Available: http://www.assemblymag.com/articles/92790-assembly-automation-takes-off-in-aerospace-industry. [Accessed: 30-Nov-2015].
[37] "Collaborative Robotics Market Exceeds US$1 Billion by 2020." [Online]. Available: https://abiresearch.com/press/collaborative-robotics-market-exceeds-us1-billion-/. [Accessed: 13-Feb-2016].
[38] "How Airbus Uses Smart Tools for 'Factory of the Future,'" *RTInsights Team*.
[39] L. I. 236 2nd A. S. Franklin and T. 37064 1-844-L. Support:219-7424, "What is Continuous Improvement?," *LeanKit*. .
[40] "What is kaizen (or continuous improvement)? - Definition from WhatIs.com," *SearchManufacturingERP*. [Online]. Available: http://searchmanufacturingerp.techtarget.com/definition/kaizen. [Accessed: 14-Feb-2016].

[41] R. Ashkenas, "It's Time to Rethink Continuous Improvement," *Harvard Business Review*, 08-May-2012. [Online]. Available: https://hbr.org/2012/05/its-time-to-rethink-continuous. [Accessed: 14-Feb-2016].

Chapter 5: PDCA using a collaborative robot

With the context provided on ergonomics and collaborative robotics, the last part of this thesis bringing together the ROM risk profile and collaborative robotics by documenting the execution of a continuous improvement project, targeted to improve ergonomics. This chapter begins with a brief review on the definition of continuous improvement, and how it is executed in an aerospace manufacturing environment. To do so, the D1-9000 is used as the roadmap for carrying on a continuous improvement project. The D1-9000 is a detailed tutorial through which The Boeing Company outlines the tools available to planning and executing a continuous improvement projects for its suppliers. Following the D1-9000 roadmap on-hand, the project planning and execution is given step by step from sections 5.3 through the end of the chapter. The first step, "problem identification", is performed with the aid of the ROM risk profile developed in Chapter 3 to estimate the benefit of applying a collaborative robot to a manual machining operation within a flight control element assembly station. Root-cause analysis and action plan are described in sections 5.4 and 5.5. In section 5.6 the manual machining task is detailed and a deterministic calculation is presented to understand the control variables and their effect in the process output. These variables are brought to an Input-Process-Output (IPO) Model of the flight control element assembly station with a collaborative Robot. A designed experiment is done to estimate the effect of the input variables on the flushness of the flight control element (output of the process) as well as its effect on flushness variability. The results of the experiment were processed to construct a linear regression model, which is in turn used at sections 5.7 and 5.8 to perform process optimization and a process capability simulation.

5.1 Continuous improvement in aerospace

The Continuous Improvement concept, as proposed by William E. Deming, is one of the most influential contributions of the Japanese production systems of the 1950s to the western industry [1]. Masaaki Imai, another well renowned proposer of Continuous Improvement, derives the concept from *kaizen*, which means change to improve. Deming and Imai [2] are acknowledged as the two pioneers and promoters of continuous improvement as an organizational philosophy. The following are the common elements found in their descriptions of continuous improvement:

1. Continuous Improvement is an on-going cycle, a way of operating, not a one-time project
2. A Continuous Improvement culture has to engage everyone in the organization
3. The objective is improving performance through the identification of areas of improvement and elimination of waste.

In the Total Quality Management movement, Deming articulates 14 points for companies to improve performance and adopt a continuous improvement philosophy [1]. Two of the key points outlined by Deming that encourage the implementation of collaborative robotics in aerospace production systems are:

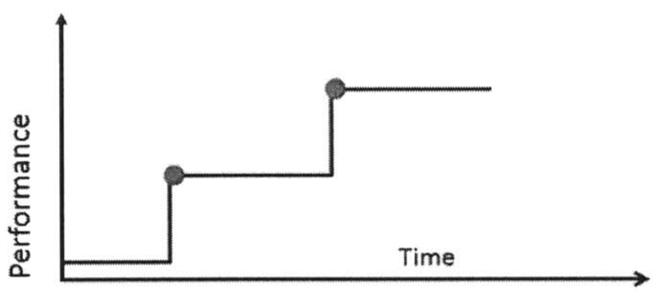
1. To cease dependency of inspection by embedding quality into the manufacturing processes
2. Break down barriers between departments, to facilitate people in design, research and production to work to solve and prevent problems.

The Academy of Aerospace Quality (AAQ) acknowledges that Continuous Improvement is a strategy with two main components: Breakthrough Improvement and Kaizen.

The "breakthrough" improvement strategies relate to improvements achieved by technological development. Kaizen improvements, on the other hand, are meant to be embedded in the day to day activities [1]. When categorizing continuous improvement efforts, a commonplace distinction between breakthrough and kaizen improvements is budget. Making improvements with the use of technology development requires strategic budget planning and a prioritization of engineering resources to develop tailored solutions to tackle specific problems. Reiterating the argument made in Chapter 2, the prioritization of continuous improvement efforts is better done when a performance measurement method is in place to identify and gauge the need for projects.

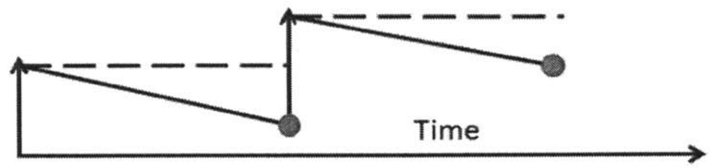
According to Deeming, 94% of defects are attributable to systems, while only 6% are attributable to people [1]. Continuous Improvement projects are therefore targeted to detect and prevent failures at a system level. Additionally, Imai suggests that the ideal result of a successful breakthrough improvement project is not only failures are prevented, but performance is increased and sustained over time in the production system as illustrated in Fig. 5-1:

Figure 5-1: Theoretical breakthrough improvement [1]



However, Imai also remarks that that there is a probability that the improvements achieved by a breakthrough project through a one-time effort will decline over time, as depicted in Figure 5-2:

Figure 5-2: Real trend after a breakthrough improvement [1]



Therefore, the AAQ suggests that a combination of breakthrough and kaizen improvements is indeed achievable to ensure that the improvements made with technology interventions in the shop-floor are sustained. This project demonstrates how collaborative robotic technologies can be developed and accelerated towards implementation by embracing a kaizen philosophy.

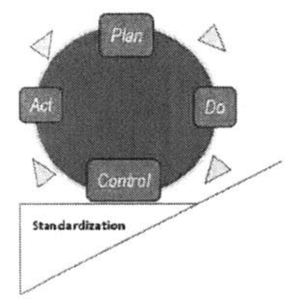
The following section describes in more detail how continuous improvement is exercised in the aerospace industry.

5.2 Continuous improvement roadmaps in the aerospace industry

Standard models and quality management systems have been created in the last 30 years, such as the ISO 9000, with the objective of guiding and measuring companies in their pursuit of operational excellence. Within the aerospace industry the AS9000- AS9100 is the Aerospace Basic Quality System Standard that includes the twenty elements ISO 9001 with complementary qualifications and notes. The standard was created by the Aerospace and Defense Division of the American Society for Quality Control with representatives from AlliedSignal, Allison Engine, Boeing, General Electric Aircraft Engines, Lockheed-Martin, McDonnell Douglas, Northrop Grumman, Pratt & Whitney, Rockwell-Collins, Sikorsky Aircraft, and Sundstrand [3].

Referring back to Deming's Plan-Do-Check-Act (PDCA) Cycle, the first step on the road towards a successful implementation of a continuous improvement project is "planning". This step should be based on detailed analysis of the current-state and setting objectives for increasing performance towards a future-state. Figure 5-3 illustrates the elements of the PDCA cycle:

Figure 5-3: The PDCA Cycle [1]



To convey the tools available for executing a PDCA cycle, the D1-9000 document was developed by Boeing for its suppliers [4] as fundamental part of its Quality Management System. The document describes continuous improvement as the subsequent step of the problem solving workflow:

Step 4: Continuous improvement

After completion of the analysis and improvement steps for a chosen objective, the improvement process returns to the top of figure 1.0.1 and a new problem, process, or product is chosen for analysis.

Figure 5-4 [4]: Figure 1.0.1 from D1-9000

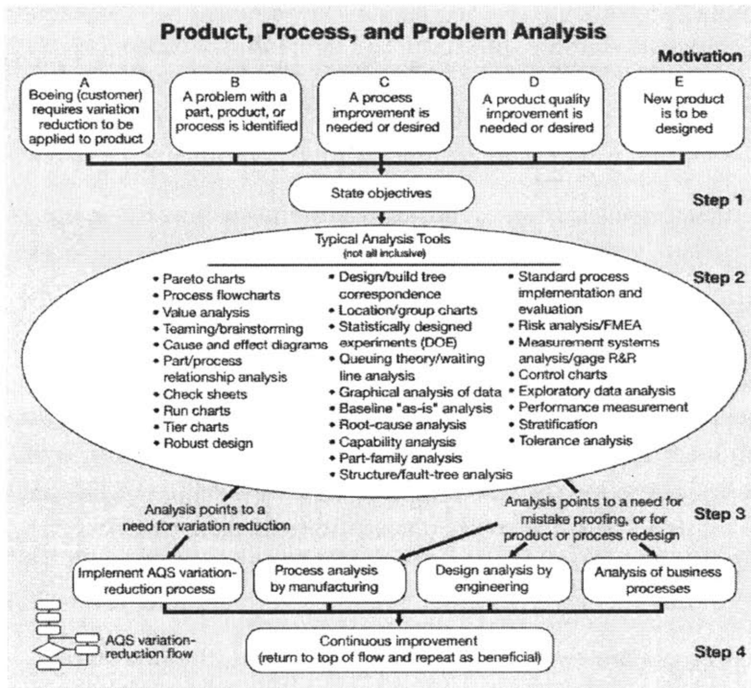


Figure 1.0.1

Steps 1-3 relate to root cause analysis and objective identification. The D1-9000 is evidence of PDCA being well known and practiced within the aerospace industry. Boeing promotes continuous improvement with its' suppliers as a mean to comply with the Basic Quality System and the Advanced Quality System.

The PDCA is disaggregated by the D1-9000 as follows:

Figure 5-5: Figure 1.0.1.2 from D1-9000 Basic Problem-Solving Flow

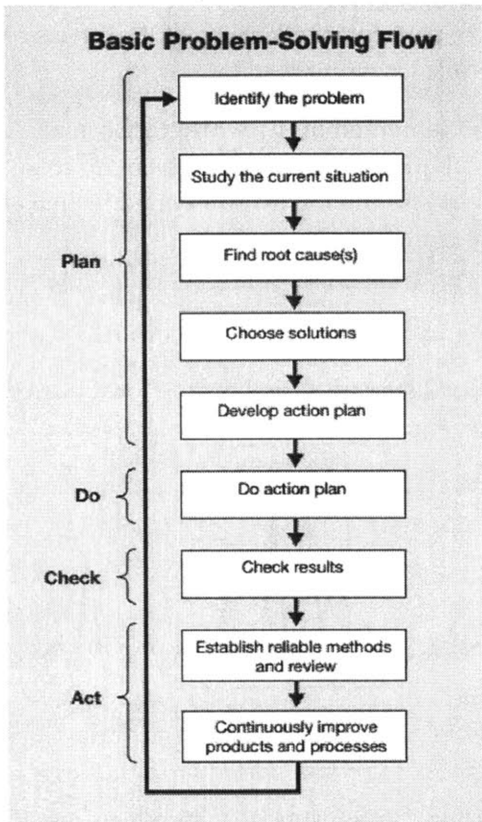


Figure 1.0.2.2 Basic Problem-Solving Flow with PDCA Cycle

Historically, Continuous Improvement initiatives have been usually triggered by quality performance metrics. The D1-9000 document suggested that the first step in the Advanced Quality Flow "*...consists of the analysis of the products, processes, and problems relating to continuous quality improvement*". Because of the direct costs associated with defects, quality performance can be easily monitored and quantified, hence making the problem-identification stage of the continuous improvement cycle relatively easy to establish. However, as discussed in Chapter 2 and 3, the pivotal objective of this project is continuous improvement for safety, which is difficult to quantify. The next section refers to the proposed methodology to close this gap.

The following sections describe how this problem solving roadmap, grounded on the Continuous Improvement methodology, can be followed to improve safety performance with collaborative robotics.

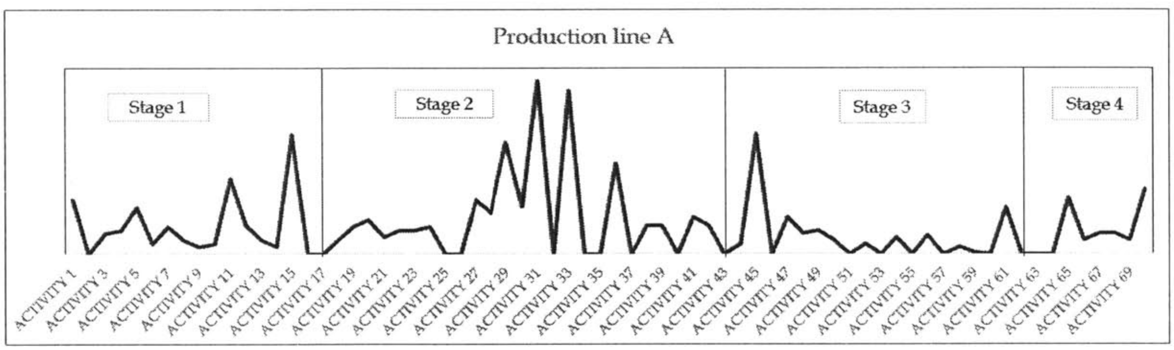
5.3 Identifying the problem and studying the current situation

One of the differentiators of collaborative robotics in comparison to other categories of industrial robots is the amount of integration that they require for final implementation on the shop floor. That said, one of the present challenges faced in implementation is the workforce acceptance of collaborative robots in production [5] . The human response to motion of collaborative robots is by itself a wide area of research, particularly because of the effects of human-robot interaction in workstation and team fluency [6].

The first collaborative robot implemented in the workplace can a have a huge cultural impact on how the workforce perceives robotic assistance. For that matter, an application with the highest level of technology development and the lowest safety and technical risk was selected to launch a continuous improvement project.

The ROM risk profile developed in Chapter 3 was used to measure the benefits that a collaborative robot would bring in regards to safety to Production line A:

Figure 5-6: ROM statistical risk profile for Production Line A



The selected robot is targeted for activities 44 and 45 which are blind fastener machining and inspection. As noted in Figure 5-6, these activities are currently performed at the beginning of each assembly order in Stage 3. The Total Risk Rate (TRR) would be reduced by 40% in the future state of Stage 3, as calculated by the ROM statistical profile:

Figure 5-7: Stage 3 ROM

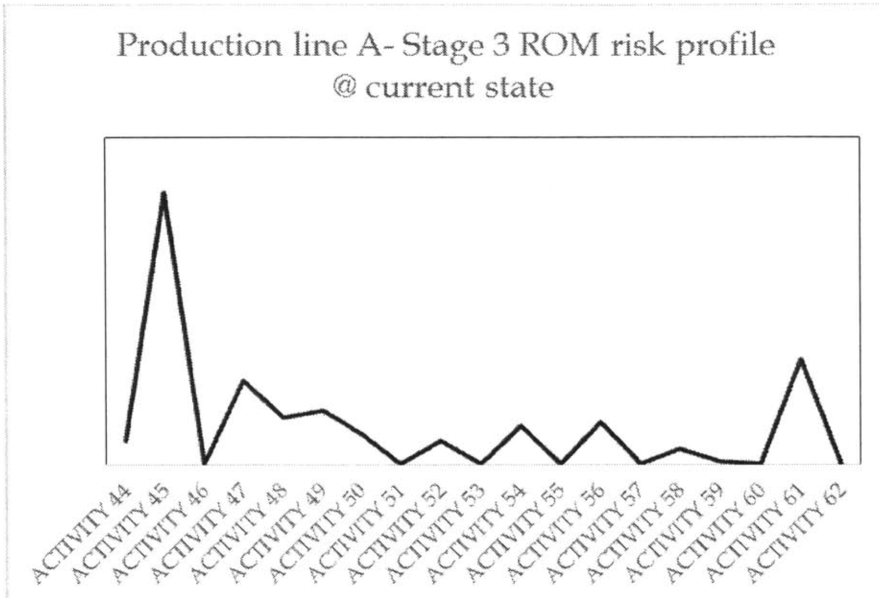
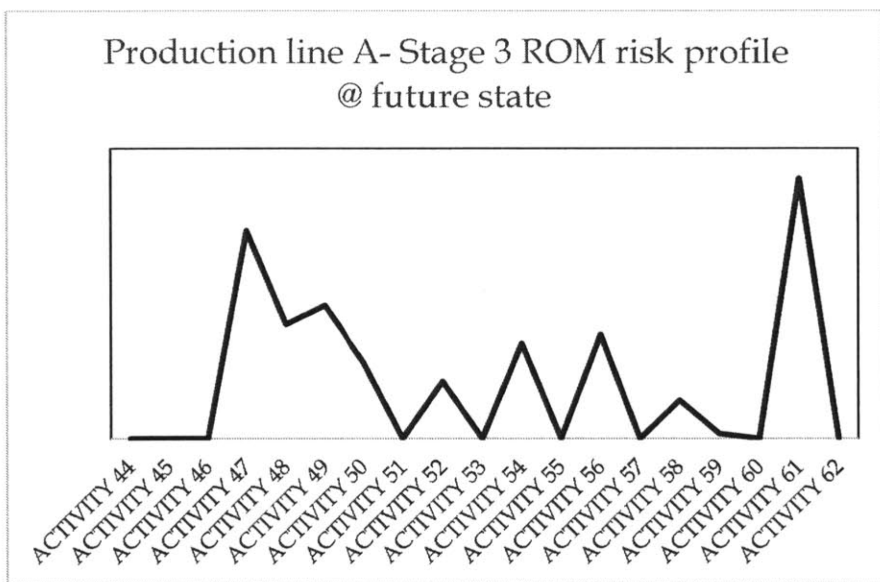


Figure 5-8:: Future state



5.4 Finding the root causes and choosing the solution

From performing an observational ergonomic risk assessment at Stage 3, it was evident that activities 44 and 45 are a source of musculoskeletal stressors. The main drivers of discomfort for the operators are application of force in an awkward posture, vibration and short repetition cycles. Moreover, these activities are performed under very similar conditions and with similar tools in other production lines, as discussed in section 3.2. Several potential solutions were evaluated through a weighted criteria matrix. The solutions ranged from full-size industrial robots, to uncontrolled mechanical devices to assist the operator while performing the task, including a collaborative robot. As a result of this exercise, it was found that the collaborative robot showed an advantage in the following criteria:

- Stage of technology readiness: There is no hardware to be developed or certified to automate the machining task. All the components are off-the-shelf.
- Estimated time to implementation. The levels of technology readiness in combination with the inherent safety features included in the robot control system are likely to reduce the integration activities as compared to a non-collaborative industrial robot
- Technical risk of implementation. The robot had already gone through feasibility test runs
- Predicted industrial safety risk after implementation. Previous risk assessments had been done for the future state.
- Cultural value. Having a collaborative cell on the shop-floor would reveal more opportunities for human-robot interactive tasks across production lines.
- Overall cost/benefit ratio. The upfront investment on a collaborative robot is lower than a common industrial robot.

5.5 Developing the action plan

As specified in D1-9000, the "Doing" stage of the PDCA cycle should focus on providing evidence of variation as shown in Figure 5-9. This step was divided into the sub-tasks of identifying, measuring and determining causes of variability for activities 44 and 45.

Figure 5-9: Figure 1.0.2.3 from D1-9000 [4]

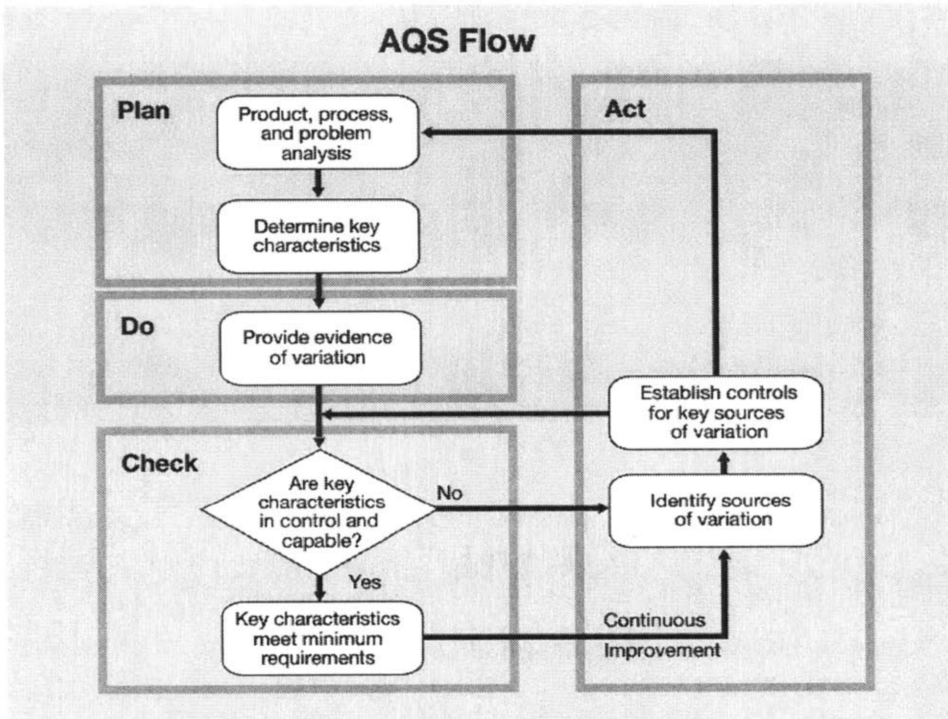


Figure 1.0.2.3 AQS Flow With PDCA Cycle

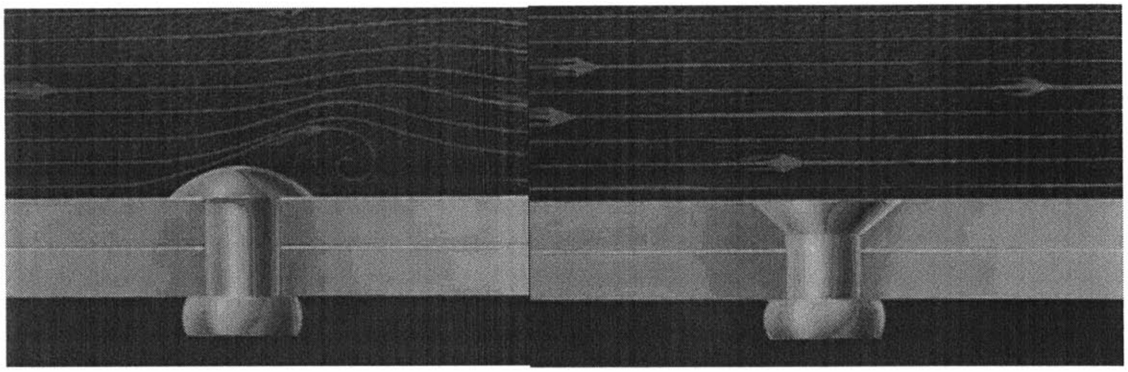
The action plan for improving the blind fastener machining and inspection process are:

1) Study the fundamental physics of the machining process to understand the deterministic sources of variation
2) Measure the input variability, i.e. state of the parts flowing into the process
3) Hypothesize effects of the process control variables in the collaborative robot
4) Design and conduct experiment to test the effect of the control variables
5) Model the process based on the significant effects of the control variables
6) Determine optimal process settings
7) Simulate process with optimal settings
8) Calculate theoretical process capability

5.6 Fundamentals of stem machining analysis and requirements development (Step 1)

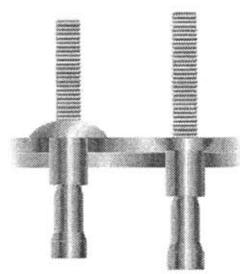
Flush fasteners are commonly used in aerospace surfaces (Figure 5-10) to avoid induced turbulences from projections that non-flush fasteners would create [7].

Figure 5-10: Flush fasteners [7]



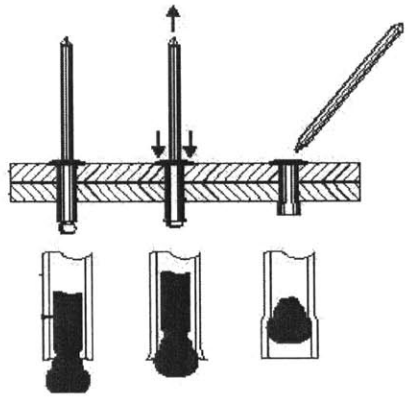
Additionally, *"blind fastener systems are used where the structure design or the assembly sequence does not allow access from both sides of the assembly"* [8]: A blind fastener is typically installed by inserting the fastener through the matched hole of two components.

Figure 5-11: Blind fasteners [9]:



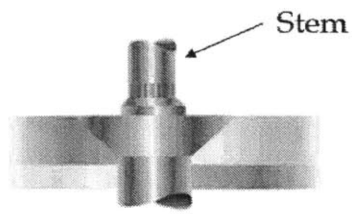
Then, the mandrel is pulled into the fastener body against the plates that are being assembled together. The sequence takes place as shown in Figure 5-12:

Figure 5-12[10]: Installation of blind fasteners



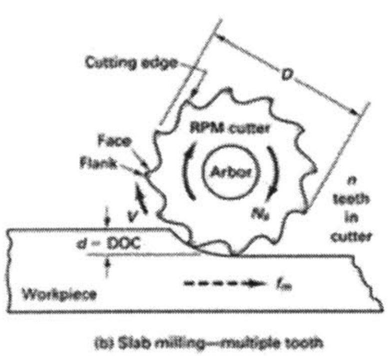
After the rivet is installed, the stems are usually machined to achieve perfect aerodynamic flushness [11]. The stem is illustrated in Figure 5-13:

Figure 5-13: Steam break [9]



Blind fastener stem machining requires an industry standard tool [12]. And the process can be characterized as a horizontal milling operation as in Figure 5-14:

Figure 5-14: Horizontal slab milling [13]



From a deterministic standpoint, force and cutting speed are the main control variables in this manufacturing process. In order to understand the effect of these control variables on flushness, a baseline calculation for force and cutting speed can be obtained from deterministic machining formulas. From [14] it is known that the machining operation relies in the force applied by the cutting tool to the workpiece:

(5.1) Equation 1.4 from [13]

$$P_c = F_c v$$

Pc: Required Cutting Power
F_c= Orthogonal force (in the direction of the tool motion) from Merchant model
v: cutting speed

Based on equation 5.1, the required machining force can therefore be estimated as the product of the chip load, feed rate and specific cutting force as follows [15]:

(5.2)

$$Pc = \frac{h * f * v_c * K_c}{60 * 10^3} = MRR^* P_f$$

Pc: Required Cutting Power
h: chip load
f: feed rate
v_c: cutting speed
K_c: Specific cutting force
P_f: power constant factor

Considering the required material removal rate as:

(5.3)

$$MRR = n\mu\pi\emptyset^2/4t$$

*t= total cycle time – n (v_{TCP}*s)*
MRR: material removal rate
n: number of fasteners in production element
μ: average stem height
s: average space between fasteners
v_{TCP}:: TCP speed in-between fasteners
$\emptyset$: stem diameter
t: machining time

Considering also the magnitude of the spindle speed in this operation and the chip load *h*, the force requirement results in <1 N. However, since the robot controller does not have enough resolution while operating in force control mode [16], process capability will be tested using higher levels of down force.

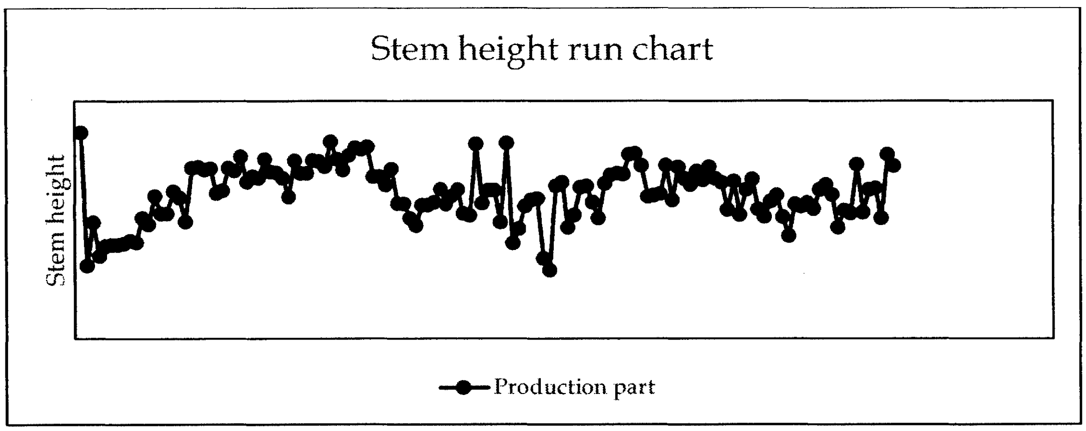
It should be noted that equation 5.2 assumes a rigid machining center. When performing the task with a light robot, vibration and the force control in the machining-feed direction should also be taken into account as sources of variation.

5.7 Blind fastener input height variability

A variable of interest in most machining operations is the Material Removal Rate. For this particular application, the flight control element in question is assembled with more than 100 blind fasteners. The flight control element flows on the assembly line from Stage 2 to Stage 3 with the blind fasteners in place and ready to be machined. The total amount of material to be removed by the machining operation defines operational requirements for the collaborative robot, such as the cycle time. The fastener stem height is not constant, it varies according to thickness of the parts being assembled and the stem trimming tool.

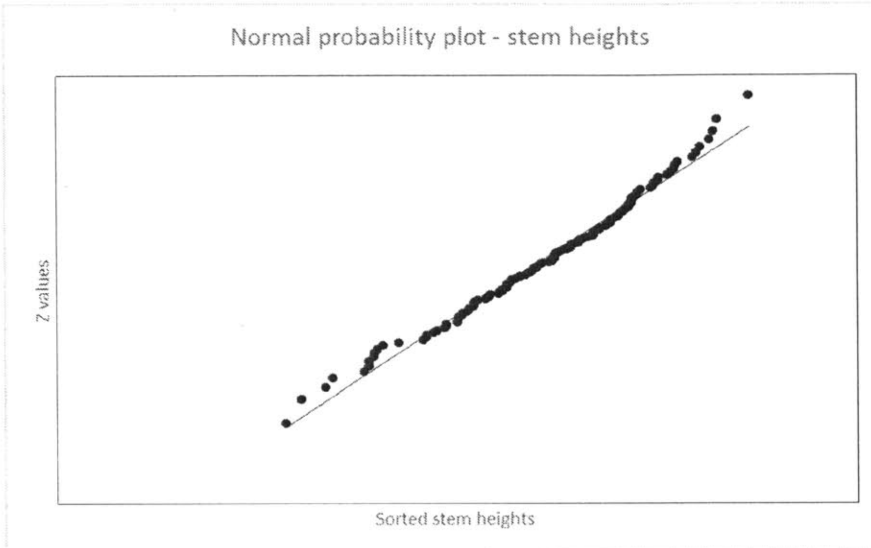
To measure the stem height variability all fastener stems were measured for a flight control element prior to entering Stage 3. The stem height run chart is shown in Figure 5-15:

Figure 5-15: Stem height run chart:



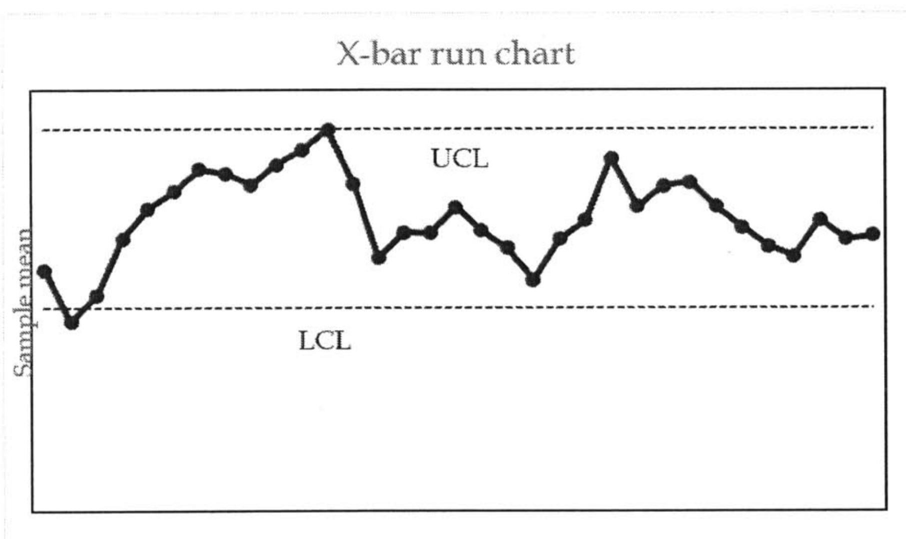
The points were plotted according to the fastener sequence of installation. Trends can be identified within the same element, such as the one encountered in the first quarter of the data points, the distribution of the heights can be perceived as normal. Deterministic factors such as difference in grip lengths, related to the thickness of the different components being assembled, and specific operator trends in particular sections of fasteners can be considered to optimize the machining parameters. However, the initial approach is to determine if a fixed setting of force and speed is robust enough to machine a full flight control element. The normal probability plot for the fastener stems before machining is shown in Figure 5-16:

Figure 5-16: Normal probability plot



The stem height variability will be important to understand to construct a simulation model. Shewhart suggests a minimum of 25 points for setting up a control chart [17]. Given the availability of 140 data points coming from the same flight control element, an X-bar chart was created with a sample size of 4 to obtain 35 points. Confidence intervals for the mean and standard deviation are calculated in section 5.5:

Figure 5-17: X-bar chart for stem heights with sample size 4



The control limits where set using the Shewhart approach [17]

(5.4)

$$UCL = \bar{\bar{x}} + 3\frac{\bar{S}}{C_4\sqrt{n}}$$

$$LCL = \bar{\bar{x}} - 3\frac{\bar{S}}{C_4\sqrt{n}}$$

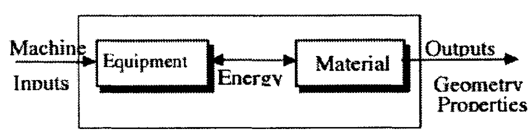
$$C_4 = \sqrt{\frac{2}{n-1}}\,\frac{\left(\frac{n}{2}-1\right)!}{\left(\frac{n-1}{2}-1\right)!}$$

By applying the WECO rules [16], it was determined that the stem heights within a flight control element are not within statistical control, i.e. different fasteners or groups of fasteners on an aerostructure follow different distributions. But because the process capability of the robot is to be assessed with a unique setting of force and speed, it will be discussed in section 5.8 how confidence intervals for the variance can be determined and used it as a conservative value of variability and proceeding to a machining simulation.

The next step towards calculating process capability is performing a design of experiments and testing the robot accordingly to quantify the effect of the control parameters on the process output.

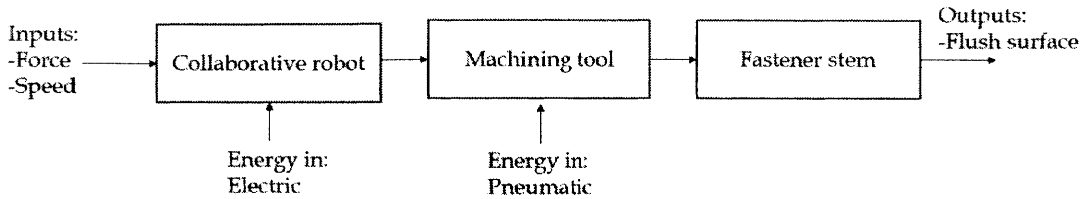
5.8 Input-Process-Output energy diagram for machining with a collaborative robot (Step 3)
According to Hardt, et. al [18] every manufacturing process has only two outputs from the physical standpoint: changes in geometry and/or changes in intrinsic material properties. Such outputs are achieved by an application or removal of energy [18] throughout the surface or the volume of the work material.

Figure 5-18: IPO diagram [17]



Thus, describing the energy interactions in the stem machining process with an Input-Process-Output (IPO) model is useful to understand the role of robot parameters as described in further sections. The energy IPO model is shown in Figure 5-19:

Figure 5-19: IPO diagram for stem machining



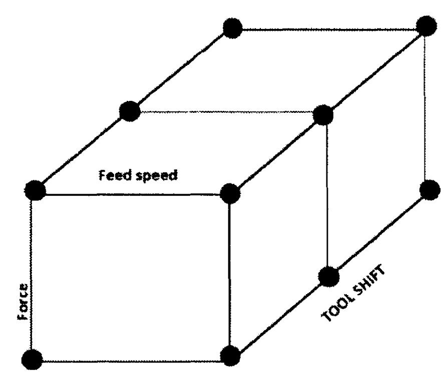
It has already been mentioned in section 5.3 that force is a deterministic parameter in the machining process. Therefore, the robot force and speed control play an important role in the use of a collaborative robot because of the following two requirements:

1. All fastener stems must be machined within the planned cycle time in the current state
2. A maximum speed of Tool Center Point (TCP) motion set by safety standards. This is important especially when setting up the speed for TCP motion in between fasteners.

5.9 Design of experiments (Step 4)

Three parameters that can be determined for a collaborative robot to perform the machining task: force, speed and also cutter position with respect to the fastener centerline (tool shift). Force and speed are continuous variables while tool shift is a discrete variable. An experiment was designed to evaluate the effect of these parameters with two levels for force and speed, and three different cutter positions. The experiment space is illustrated in Figure 5-20:

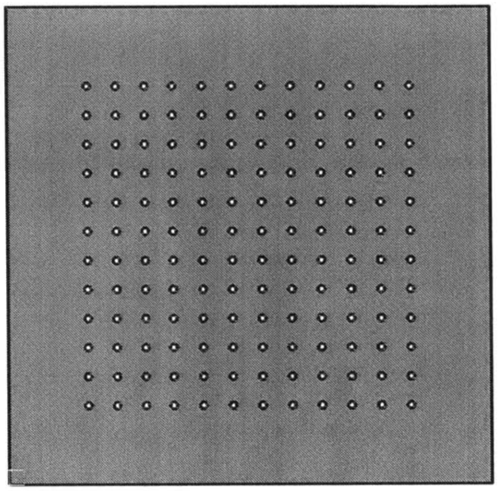
Figure 5-20: Design of Experiments



Instead of consuming a production part to perform the test, a coupon was employed. The coupon is constructed from a 12x12 in carbon fiber composite plate which provides space for a total of 144 fasteners, using spacing between fasteners representative of that found in the actual flight control element.

Figure 5-21: Test coupon

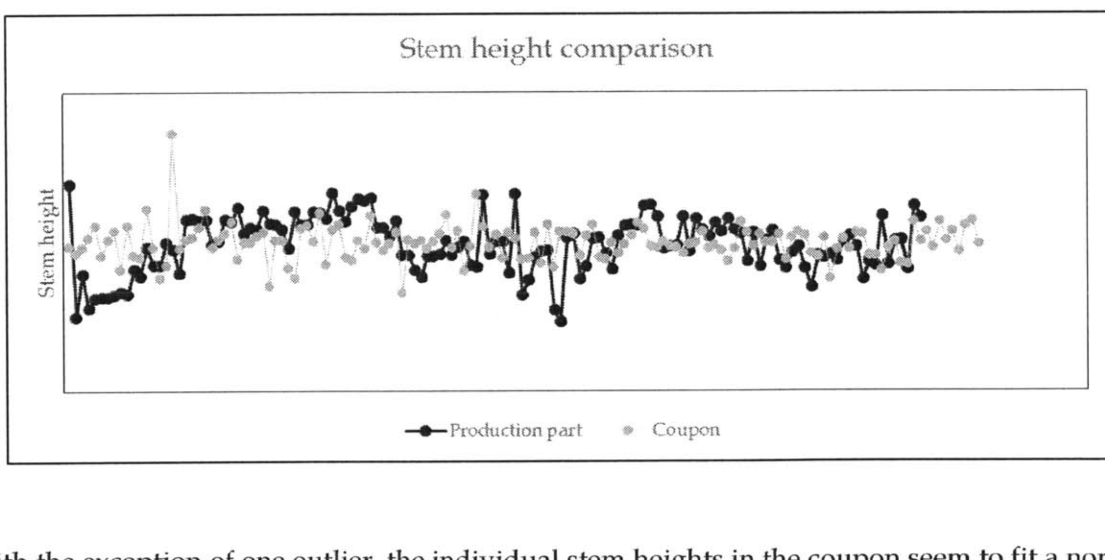
Test coupon. 12" x 12" carbon fiber composite plate. 144 countersunk holes equally spaced



Therefore, it was possible to run 12 replications for every combination of force, speed and tool shift. These 12 replications will be also useful to measure tool wear, which will be discussed in Section 5.8.

Drilling and countersink were performed in the coupon using production tools. Additionally, production fasteners were installed in the coupon using production hardware. The resulting stem heights are plotted to be compared with the actual flight element measured in section 5.4:

Figure 5-22: Stem height comparison between production part and coupon



With the exception of one outlier, the individual stem heights in the coupon seem to fit a normal distribution better than the production element, as shown in Figure 5-23:

Figure 5-23: Distribution of stem heights

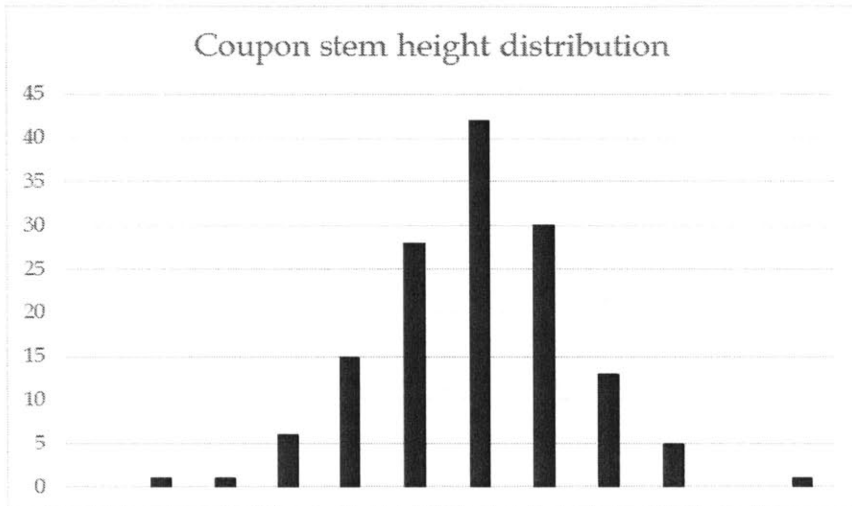
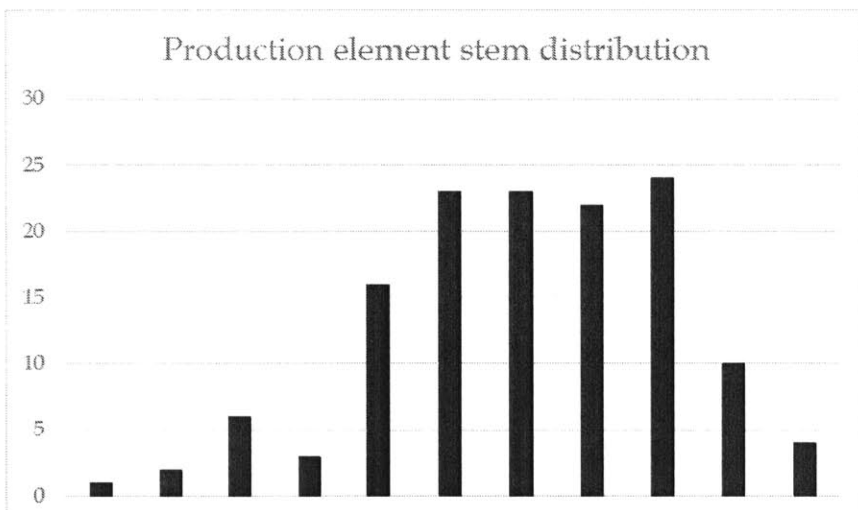


Figure 5-24: Distribution of stem heights



It was discussed in section 5.3 why the initial stem heights are important for the machining process. It is important too to understand the differences in variability between the test coupon and the actual flight control element. To measure the difference in mean and input variability, confidence intervals for the mean and standard deviation were calculated for both (coupon and production element) with significance of 95%. Despite the relatively big sample size and the consistency of the aerospace assembly process, the population standard deviation cannot be assumed to be those obtained from the production element as mentioned in section 5.3; therefore the t-student distribution was employed with n-1 degrees of freedom and α=.05 to estimate confidence intervals for stem height means and standard deviations as follows:

(5.18) Confidence interval for stem height mean, variance unknown [19]

$$\bar{x} - t_{\alpha/2,n-1}s/\sqrt{n} \leq \mu \leq \bar{x} + t_{\alpha/2,n-1}s/\sqrt{n}$$

Production element μ CI: $\bar{x}_{production} \pm 3.1\%$
Coupon μ CI: $\bar{x}_{production} \pm 1.77\%$

(5.19) Confidence interval on the variance [19]

$$\frac{(n-1)s^2}{\chi^2_{\alpha/2,n-1}} \leq \sigma^2 \leq \frac{(n-1)s^2}{\chi^2_{1-\alpha/2,n-1}}$$

$0.16\ \%\bar{x}_{production} \leq$ Production element $\sigma^2 \leq 0.24\%\ \bar{x}_{production}$
$0.052\ \%\bar{x}_{coupon} \leq$ Coupon $\sigma^2 \leq 0.071\%\ \bar{x}_{coupon}$

Thus,

$10.32\%\ \bar{x}_{coupon} \leq$ Coupon $\sigma \leq 12.05\%\ \bar{x}_{coupon}$
$18.08\ \%\bar{x}_{production} \leq$ Production element $\sigma^2 \leq 22.46\%\ \bar{x}_{production}$

It can be noted from the histograms in Figure 5-23 that the production element has an apparent higher standard deviation than the coupon; so although the sample mean of the production element is actually lower than that of the coupon, the confidence intervals on the mean and standard deviation reflect the higher variability that must be considered going forward in the analysis. It is suspected that the fasteners in the production element follow different distributions depending on their location and the parts that they hold on together. A further analysis is suggested for future work by segregating sections of fasteners according to their location.

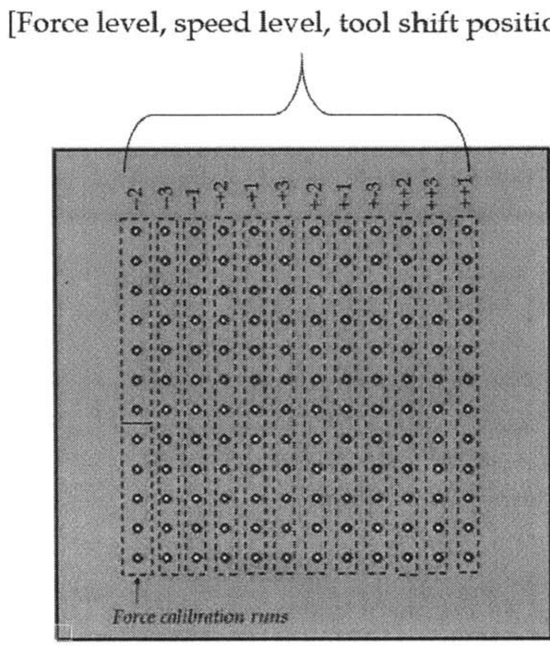
5.10 Experiment

The settings for each experimental run are described in Appendix 5. The initial run was performed with 5 N and resulted in a defect (flushness spec not met). It is suspected that this is due to low resolution in robot force control [14]. The next 4 runs were performed to select the final low and high values for the rest of the test. 10 N and 20 N were selected as the final settings for the rest of the test.

It is important to highlight that four different cutting tools were employed to avoid deterministic effects of tool wear. Therefore, each tool was used to machine three rows (one for each force and speed setting) with each row being machined using a single tool shift. This way a given tool was used only to machine a total of 12 fasteners with each cutting zone (center, left and right).

Each row of 12 fasteners was machined with a fixed setting of force, speed and tool shift as shown in figure 5-25:

Figure 5-25: Test sequence.

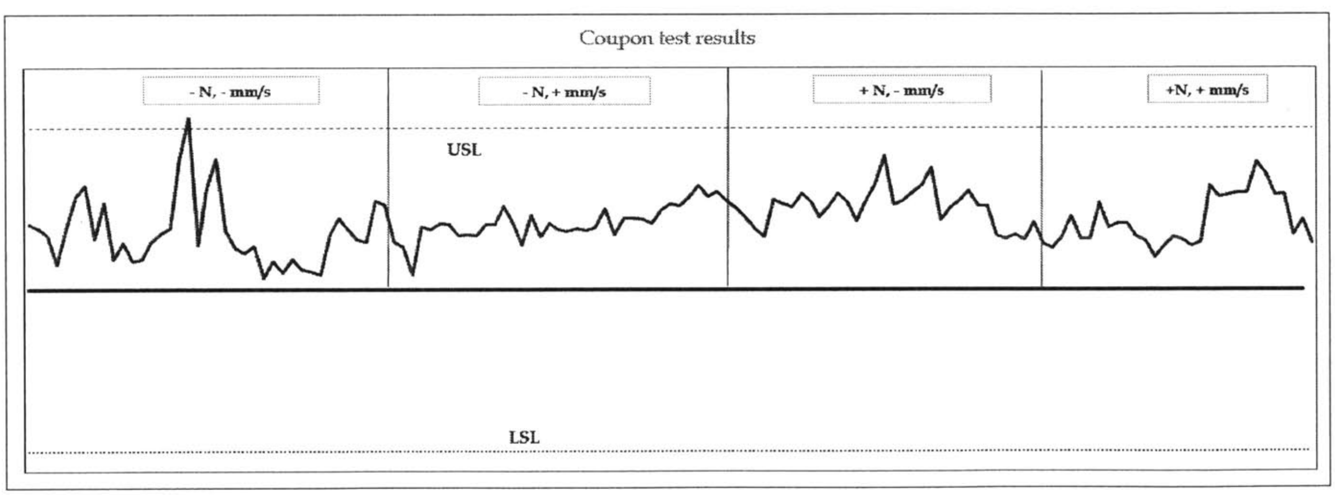


5.11 Experiment results

After the test runs were completed, the resulting flushness was measured using a digital flushness gauge. The flushness measurements were plotted in Figure 5-26:

Figure 5-26: Flushness results.

Each block includes 36 runs with a fixed force (N) and speed (mm/s) setting, 12 at each tool shift position.



From Figure 5-26 several observations can be made:

3. Most of the runs fall within the Upper Specification Limit (USL)

4. Using a low force and low speed seems to promote higher flushness variability

5. There seems to be a deterministic factor from runs 36-72 (second block in Figure 5-26) that causes the flushness to trend up

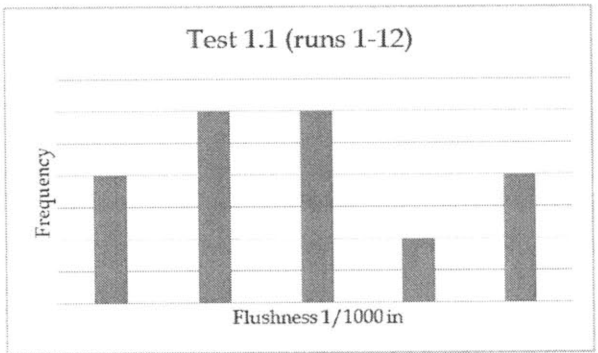
6. Low force and high speeds seem to promote lower flushness variability

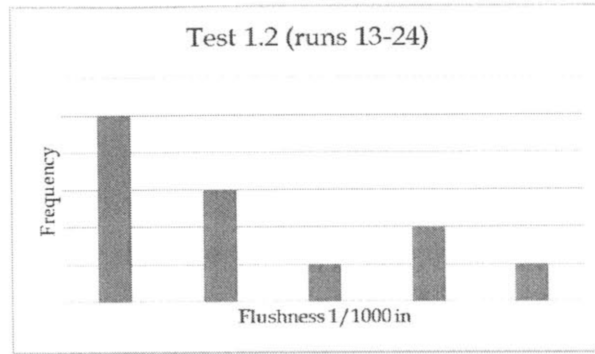
7. None of the runs resulted in flushness below the Lower Specification Limit because of the machining tool design and initial calibration, i.e. if the cutter is properly calibrated, it is physically impossible to remove material below the aerospace surface level. The bilateral tolerance specification was written for different kind of machining tools (end mills for instance).

It is of particular interest to determine if the tool shift has a significant effect on the resulting flushness. If there was a significant effect, different parameters of force and speed would be required for different tool shifts, if tool life were to be maximized.

Having a sample size of 12 for each run makes it difficult to assess normality. The histograms of Test Block 1.1 (runs 1-12 at low force and low speed) and Test Block 1.2 (runs 13-24 at low force and high speed) are provided in Figure 5-27:

Figure 5-27: Histograms for Test Blocks 1.1 and 1.2

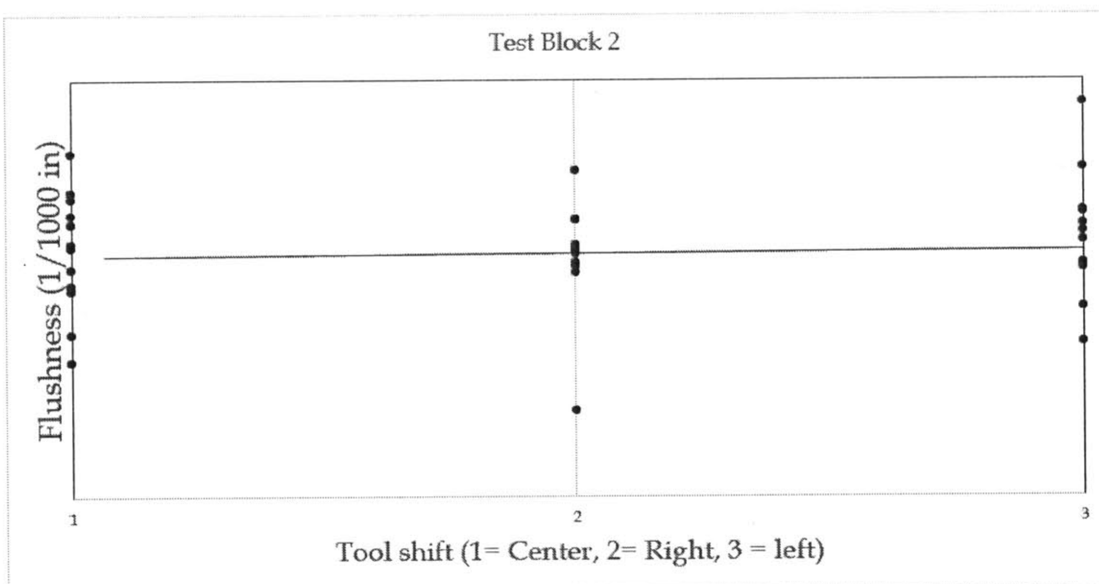


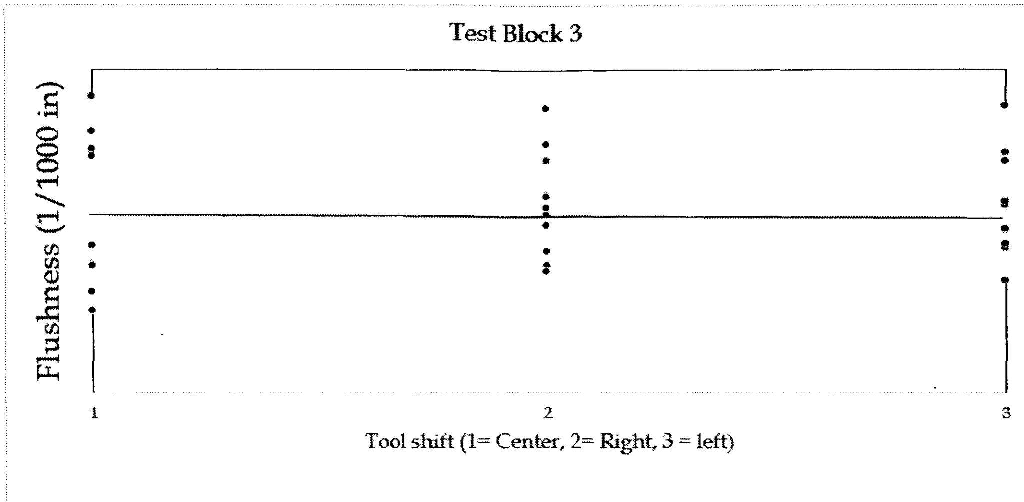


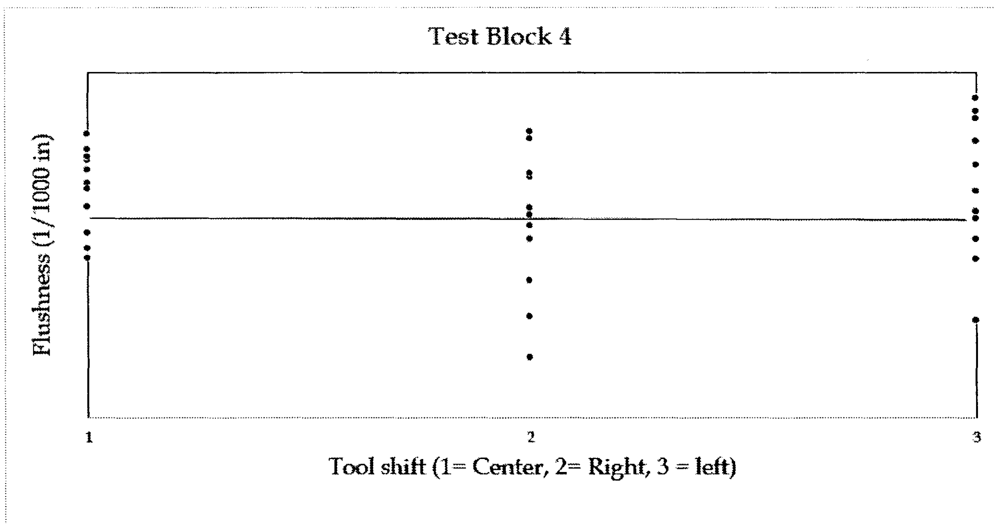
Although the data distribution is difficult to assess, the tool offset effect can be evaluated through a non-parametric tests for each sample of 12 runs with fixed settings of force and speed.

Assuming the flushness is indeed normally distributed, a median test can be performed to determine if there is a difference in mean from using the cutting tool at different offsets. Test Block 1 was excluded from the median test since it includes calibration runs. The median test results for Test Block 2, 3 and 4 are shown in Figure 5-28:

Figure 5-28: Median test for tool shift







The Chi-Square Values for all each median test are:

Figure 5-29: Median test

	Chi-Square	P-Value
Test Block 2	1.94	0.38
Test Block 3	1.091	0.57
Test Block 4	0.64	0.72

According to the P-values, none of the Test Blocks showed different flushness results for different tool-shift values. This makes intuitive sense since the cutter has the same geometry across its surface. This also means that a single setting of force and speed can be used when optimizing parameters for maximum process capability.

5.12 Process model (Step 5)

A linear regression was performed on the different levels of force and speed. The first approach was to estimate the effects of force and speed on flushness with a total of 140 runs (the four calibration runs were discarded):

Figure 5-30: Regression model for flushness

Regression Statistics	
Multiple R	0.932932711
R Square	0.870363443
Adjusted R Square	0.86217767
Standard Error	0.001318237
Observations	140

Regression parameters	**Coefficients**	**P-values**
Intercept	0	
Force (N)	0.000224134	1.22373E-33
Speed (mm/s)	-0.000656285	0.038688958

Two observations should be made from these results:

1) The change in force has a positive effect on the flushness value, which would imply that higher forces result in poorer flushness values (higher stem height measurements), which is counterintuitive. It is suspected that the variability of the initial stem heights has an effect on the flushness value as well. Thus a variable to measure the total material removed will be introduced in the following section
2) The change in speed results in better flushness (lower height values). This is suspected to be a result of operating the collaborative robot in position control in the machining direction, while the force control is only applied to the Z coordinate.

It is important to notice that the flushness value does not provide any information on the total material removed through the machining operation. To better assess the overall machining performance, the total material removal can be approximated by including the initial stem height. This "height removed" is introduced as the output variable to construct a linear regression model.

An additional linear regression model was run using the initial stem heights and therefore modifying the response variable from flushness to linear material removal variable as follows:

(5.21)

$$\Delta h = h_0 - h_f$$

Δh: Linear material removal
h_o: initial stem height
h_f: stem height after machined

Figure 5-31: Regression Model for Linear Material Removal

Regression Statistics	
Multiple R	0.96
R Square	0.92
Adjusted R Square	0.92
Standard Error	0.01
Observations	140

Regression parameters	*Coefficients*	*P-value*
Intercept	0	
Force (N)	0.0022	9.03525E-34
Speed (mm/s)	0.0103	0.001066312

With an R square value of 0.96 and an adjusted R square of 0.92, the model has enough accuracy to calculate the optimal parameters. This model shows a positive effect of force and speed on total material removed. This makes sense according to the fundamental physics of machining:

(5.20)

$$Pc = \frac{h * f * v_c * K_c}{60 * 10^3} = MRR * P_f$$

MRR ∞ Machining power ∞ v_c and K_c

v_c: cutting speed

K_c: specific cutting force

5.13 Parameter optimization (Step 6)

To approach the force and speed setting optimization, a linear material removed prediction model was constructed as follows:

(5.22)

$$\Delta h = \frac{\partial \Delta h}{\partial F} F + \frac{\partial \Delta h}{\partial v} v + \varepsilon$$

Δd: *material removed*

$\frac{\partial \Delta h}{\partial F}$ *linear effect of force*

$\frac{\partial \Delta h}{\partial v}$: *linear effect of cuting speed*

ε: *process variability*

The sensitivities for this process were determined by the regression model in section 5.6

Then ,

(5.23)

$$\Delta h = 0.0022f + 0.103v + \varepsilon$$

To approximate the process variability (ε), estimations for the effects on the standard deviation $\sigma_{\Delta d}$ were calculated also using a linear regression model:

Figure 5-32: Regression model for variance

Regression Statistics	
Multiple R	0.84
R Square	0.71
Adjusted R Square	0.58
Standard Error	0.00
Observations	12

Regression parameters	*Coefficients*
Intercept	0.00000
Force (N)	0.00024
Speed (mm/s)	0.00169

5.14 Parameter optimization and Cpk Calculation (Step 7)

With these linear estimates now available, the obvious optimal setting (high force, high speed) was simulated for process capability by defining:

(5.24)

$$\overline{h_f =} \ \boldsymbol{h_0} - \boldsymbol{\Delta h}$$

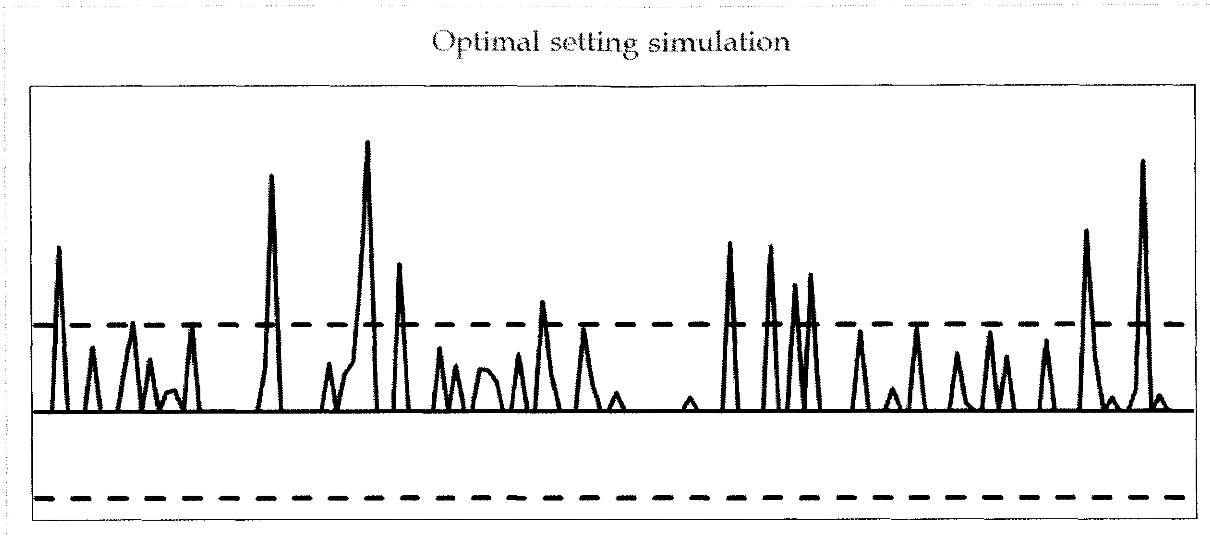
$$\boldsymbol{h_0} = \boldsymbol{N}(\boldsymbol{\mu_{h_0}}, \boldsymbol{\sigma_{h_0}})$$

$$\boldsymbol{\Delta h} = \boldsymbol{N}(\boldsymbol{\mu_{\Delta h}}, \boldsymbol{\sigma_{\Delta h}})$$

$$\boldsymbol{\mu_{\Delta h}} = \mathbf{0.00022}\boldsymbol{F_{max}} + \boldsymbol{0.0016 V_{max}}$$

$$\boldsymbol{\sigma_{\Delta h}} = \mathbf{0.00022}\boldsymbol{F_{max}} + \boldsymbol{0.0016 V_{max}}$$

Figure 5-33: First simulation



The simulated process capability was calculated as:

(5.25)

$$\textbf{Simulated } Cp_k = \textbf{Min}\left(\frac{USL - \overline{h_f}}{3\overline{\sigma_{\Delta h}}}, \frac{\overline{h_f} - LSL}{3\overline{\sigma_{\Delta h}}}\right)$$

USL: Upper specification limit
LSL: Lower specification llimit
$\overline{h_f}$: *Simulated flushness (sample mean)*
$\overline{\sigma_{\Delta h}}$: *simulated standard deviation*

The resulting process capability was 0.39. There were two issues encountered with this simulation:

1) Most of the deviation from a robust process (higher Cpk) comes from the high variability predicted by the model which could potentially be mitigated by shifting the mean through extrapolated force and speeds
2) This model does not take tool wear into account

In order to proceed and construct a reliable and conservative process simulation, tool wear has to be considered. Machining tool wear itself is a vast area of research but the most important types of wear related to this machining process are abrasion and adhesion [20].

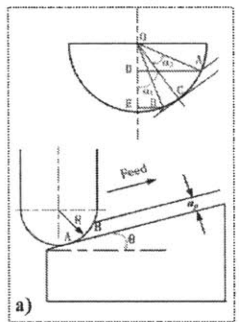
The main driver of the type of wear is the tool-chip interface temperature which depends on cutting speed and feed. Various models have been proposed for predicting and optimizing tool life for given machining conditions.
One example is proposed by [21] for predicting the flank wear in cemented carbide tools as:

(5.21)

$$\Delta VB = 0.9439 v^{1.8696} f^{4.5863} a_p^{0.5698} \Delta L^{0.1256}$$

v: cutting speed
f: feed rate
a_p: geometric parameter to determine effective cutting radius (Figure 5-30)
ΔL: cut length

Figure 5-34: cutting tool analysis



For the model in 5.21,the relationship between the flank wear (VB) and time is missing, therefore the model cannot be applied to estimate the effect of tool wear in flushness.

Another example of flank wear model is proposed by [22]:
(5.22)

$$\frac{d(\mathrm{VB})}{dt} = \frac{(1-\tan\gamma_0 \tan\alpha)}{\tan\alpha} \left\{ 6.7736 \times 10^{-3} \left(\frac{K V_c F_{nw}}{b(\mathrm{VB})}\right) \left(\frac{H_a^{n-1}}{H_t^{n}}\right) + 8.4947 \times 10^{-11} e^{(16.3 \times 10^{-4} T_f)} \left(\frac{V_c F_{nw}}{b(\mathrm{VB})^2}\right) + 407.6155 \sqrt{V_c/(\mathrm{VB})}\, e^{-20018.04(T_f+273)} \right\}$$

With
K, K_1 Constants
Cutting velocity (m/min)
F_{nw} Normal force on the tool flank due to flank wear alone (N)
VB flank wear length
H_a Hardness of the abrasive particle at any temperature T (°C)
H_t Tool hardness at any temperature T (°C)
V_c Cutting velocity (m/min)
b Width of cut (mm)

A complex geometric and thermal analysis would be required to apply either of these models and the results would still not be directly applicable to the specific stem machining operation. The differences in the machining process such as cutter material properties and fastener stem geometry deviate considerably from those used in these two models [17], [18].

Regardless of the details of this machining process, the typical wear curve for a cutting tool is shown in Fig 5-25 [23]

Fig 5-35: Tool wear

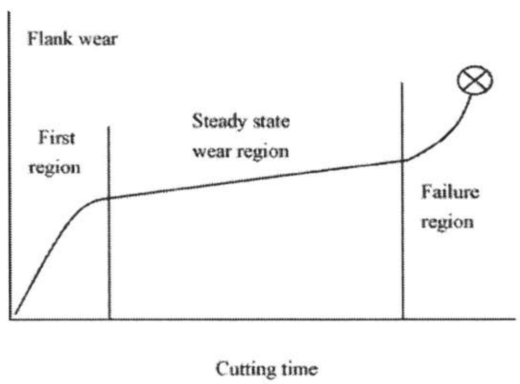
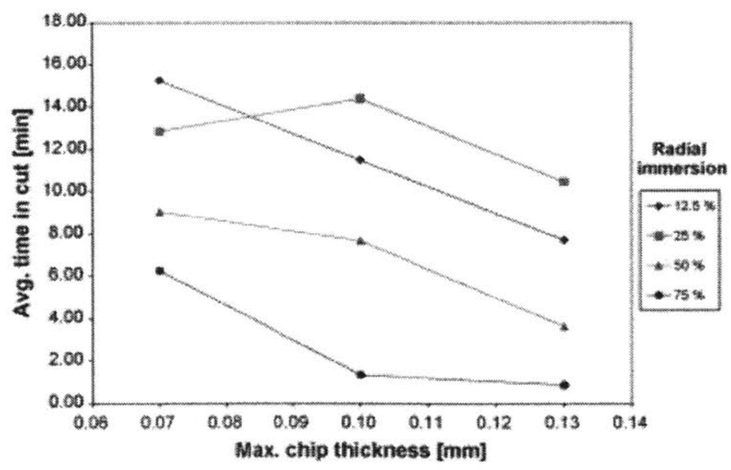


Fig. 10. Typical curve of flank wear vs. cutting time.

Additionally, according to [24] the total cutting life of a tool in a milling operation is predicted to decrease according to the chip thickness as follows:

Fig 5-36: Cut time vs chip thickness



The milling machining operation is characterized by interrupted cutting action, similar to milling. Differently than turning, in a milling-like operation each tooth of the tool produces chips of variable thickness [23]. When the cutting tool starts wearing out and the edges lose sharpness, the resulting effect is an increase in the required cutting force and as well as in higher temperatures [16].

While none of these models are directly applicable to this specific stem machining process, it is important to integrate the effects of tool wear to simulate the machining process. As commented by [16], tool wear influences the force that the robot should sustain to machine the fasteners to the required flushness level.

Considering the number of cutting edges of the tool used in this application, the expected tool life based on [17] is more than 5 times higher than the actual replacement interval. Despite the procedure observed in the workstation being this conservative, simply because the tool has a finite life, tool wear has to be considered when determining process capability.

Theoretically, cutting tool wear plays a deterministic factor in final flushness when the cutting force is set constant (as shown in equation 5.20). Hence, tool wear should be perceived as a downward trends in total material removed. The cumulative sum methodology suggested by Montgomery [25]could be helpful to assess trends in each one of the runs.
The discrete time integrator for the cumulative sum function is defined as:

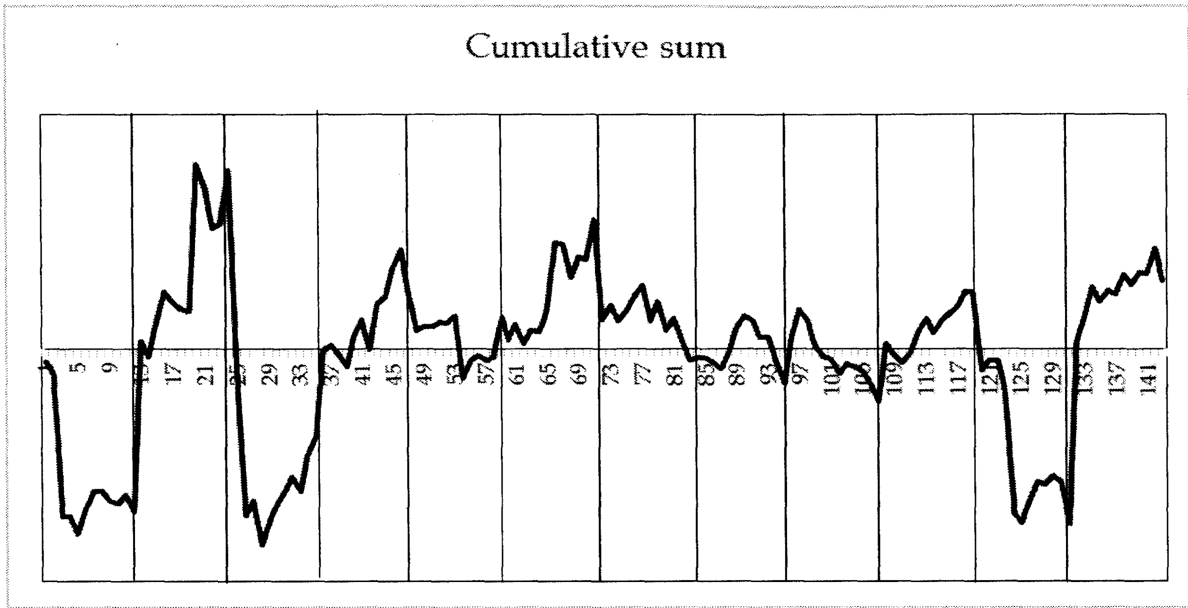
(5.23)

$$I_j = \sum_{i=1}^{j} (d_i - \bar{\bar{d}})$$

I_j: Cumulative Sum Integrator
h: sample height
d_i: total removal rate
$\bar{\bar{d}}$: average removal rate

Since total material removed is a random variable ($E\{d-\mu_d\}=0$) , any bias in d will be reflected in the form of a trend.

Figure 5-37: Cumulative sums for 144 runs



Since each run of 12 fasteners was performed with a different force and speed setting, the next step was to observe the slope of each individual run for the fastener lines that showed trends in the Cumulative Sums. It can be noticed from Figure 5-34 that only 4 of the 12 runs show downward slopes, which means that tool wear cannot be predicted accurately with only 12 replications.

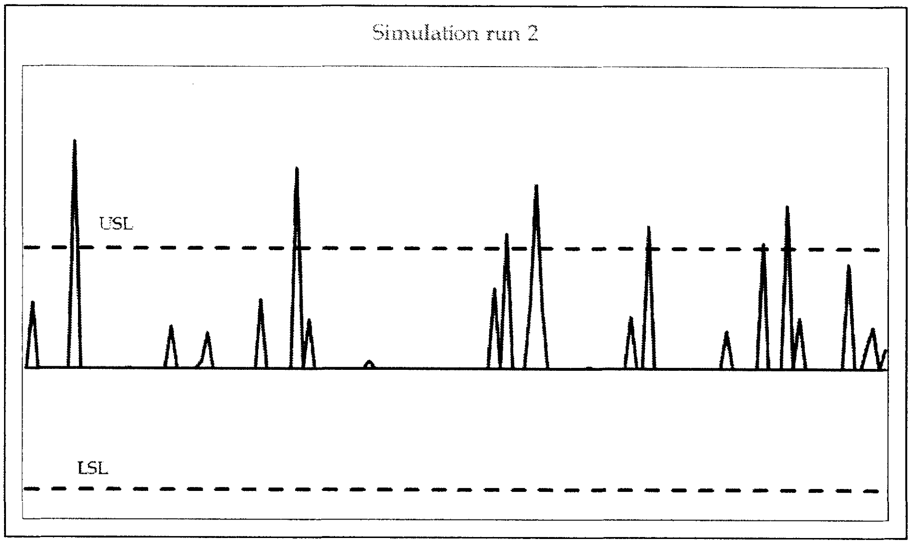
To make a conservative simulation of the machining process, a tool wear factor was extracted from the experimental runs that showed a consistent decrease in linear material removal. By analyzing the linear trend using least square values and identifying the highest effect with highest R square from the cumulative sum exercise.

Figure 5-38: Material Removal Trend (Effect) per test setting

Test setting	Effect	Rsq
1	-0.00060	0.56
2	-0.00010	0.48
3	-0.00010	0.35
4	-0.00010	0.21
5	-0.00010	0.16
6	-0.00010	0.40
7	-0.00010	0.38
8	-0.00007	0.06
9	0.00001	0.00
10	0.00001	0.01
11	0.00005	0.19
12	0.00030	0.29

Thus, the linear tool wear value from test setting 12 was brought into the process simulation as the tool wear estimator. This represents the best estimate of the downward slope of linear material removal obtained from this experiment. Additionally, an extrapolated value from the optimal setting used on the first simulation was found at 1.25x the high-force parameter and 1.5x the high-speed parameter. This value was manually sought where a good balance between simulated sample mean and standard deviation was encountered for reasonable Cpk values. A second simulation run with these parameters provided the following results:

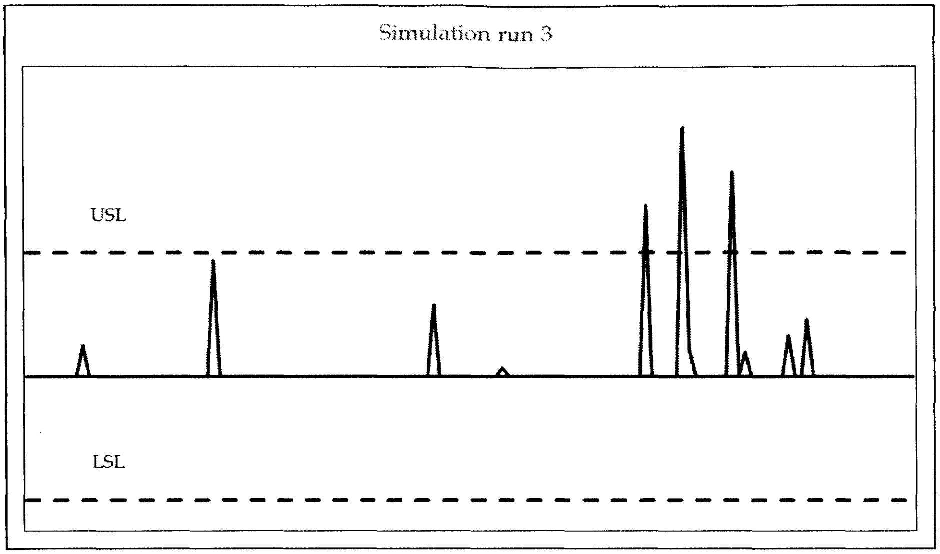
Fig 5-39: Simulation 2



The simulation was done assuming that the cutting tool is shifted three times throughout one full cycle. The resulting simulated Cpk from this run was 0.89. It was found that the linear factor used to simulate tool wear in this simulation implies that the cutting tool have to be replaced before one third of the operation is complete. Considering that in the current state the cutting tool has enough life for at least one cycle, i.e. machining one flight control element, this wear value seems overly conservative.

Henceforth, the second highest value for linear tool wear in Figure 5-34 seems more accurate. Next, a simulation was performed using the tool wear value in row 11. The simulation results are shown in Figure 5-40

Fig 5-40: Simulation run 3

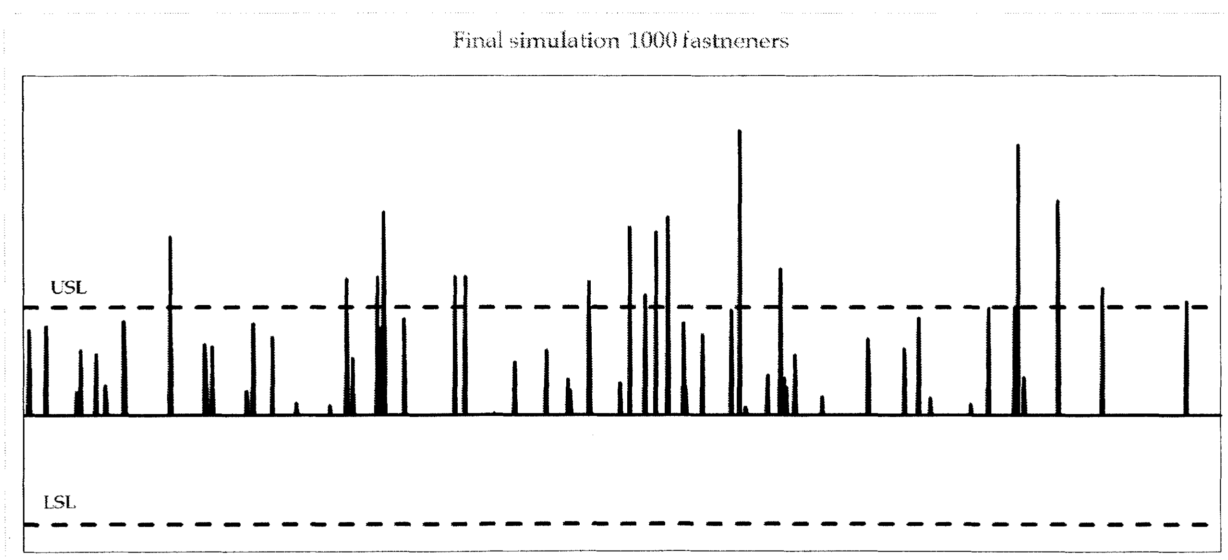


The resulting simulated Cpk for this simulation run was 1.19, which seems more consistent with the test results.

5.15 Checking results

For a long run estimate of Cpk, a final simulation of 1000 fasteners was done using the same settings as shown in Figure 5-41:

Figure 5-41: Final simulation



The resulting simulated Cpk value for 1000 fasteners is 1.42. Although this theoretical process of 1.127 capability provides grounding for establishing a statistical process control as suggested by AS9103, further testing is suggested to acquire more detailed understanding of the process natural variation and the effect of the control parameters in tool wear. The simulation encourages to test the suggested optimal settings for force and speed in a production like environment, such as the one used to determine the parameter effects on the output (flushness). This type of testing being relatively quick and inexpensive to perform, provides significant insight into the process capability of the collaborative robot.

A final test run would be necessary to obtain experimental results on the cutting tool wear. As mentioned previously the geometric complexity of the tool, the uniqueness of this machining operation and materials used pose difficulties on applying empirical models as well as models developed for other machining operations.

The last chapter discusses the final steps in the continuous improvement roadmap (Figure 5-5) towards implementation. Following the last steps in the "problem solving road map" reliable methods should be established for ensuring that the workstation is safe, delivers output within the planned cycle time and quality standards. Finally, the implementation of the robot unlocks a wide range of potential application in other production lines. Implementing the collaborative workstation also enables the generation of more data that could lead this machining process to a statistical process control rather than full inspection.

5.16 Chapter 5 appendix

Table 5-1: DOE runs

Pattern	Force Value	Speed Value	Cutter Shift
−−1	low	low	left
−−2	low	low	center
−−3	low	low	right
−+1	low	high	left
−+2	low	high	center
−+3	low	high	right
+−1	high	low	left
+−2	high	low	center
+−3	high	low	right
++1	high	high	left
++2	high	high	center
++3	high	high	right
−−1	low	low	left
−−2	low	low	center
−−3	low	low	right
−+1	low	high	left
−+2	low	high	center
−+3	low	high	right
+−1	high	low	left
+−2	high	low	center
+−3	high	low	right
++1	high	high	left
++2	high	high	center
++3	high	high	right
−−1	low	low	left
−−2	low	low	center
−−3	low	low	right
−+1	low	high	left
−+2	low	high	center
−+3	low	high	right
+−1	high	low	left
+−2	high	low	center
+−3	high	low	right
++1	high	high	left
++2	high	high	center
++3	high	high	right

Pattern	Force Value	Speed Value	Cutter Shift
−−1	low	low	left
−−2	low	low	center
−−3	low	low	right
−+1	low	high	left
−+2	low	high	center
−+3	low	high	right
+−1	high	low	left
+−2	high	low	center
+−3	high	low	right
++1	high	high	left
++2	high	high	center
++3	high	high	right
−−1	low	low	left
−−2	low	low	center
−−3	low	low	right
−+1	low	high	left
−+2	low	high	center
−+3	low	high	right
+−1	high	low	left
+−2	high	low	center
+−3	high	low	right
++1	high	high	left
++2	high	high	center
++3	high	high	right
−−1	low	low	left
−−2	low	low	center
−−3	low	low	right
−+1	low	high	left
−+2	low	high	center
−+3	low	high	right
+−1	high	low	left
+−2	high	low	center
+−3	high	low	right
++1	high	high	left
++2	high	high	center
++3	high	high	right

Pattern	Force Value	Speed Value	Cutter Shift
−−1	low	low	left
−−2	low	low	center
−−3	low	low	right
−+1	low	high	left
−+2	low	high	center
−+3	low	high	right
+−1	high	low	left
+−2	high	low	center
+−3	high	low	right
++1	high	high	left
++2	high	high	center
++3	high	high	right
−−1	low	low	left
−−2	low	low	center
−−3	low	low	right
−+1	low	high	left
−+2	low	high	center
−+3	low	high	right
+−1	high	low	left
+−2	high	low	center
+−3	high	low	right
++1	high	high	left
++2	high	high	center
++3	high	high	right
−−1	low	low	left
−−2	low	low	center
−−3	low	low	right
−+1	low	high	left
−+2	low	high	center
−+3	low	high	right
+−1	high	low	left
+−2	high	low	center
+−3	high	low	right
++1	high	high	left
++2	high	high	center
++3	high	high	right

Pattern	Force Value	Speed Value	Cutter Shift
−−1	low	low	left
−−2	low	low	center
−−3	low	low	right
−+1	low	high	left
−+2	low	high	center
−+3	low	high	right
+−1	high	low	left
+−2	high	low	center
+−3	high	low	right
++1	high	high	left
++2	high	high	center
++3	high	high	right
−−1	low	low	left
−−2	low	low	center
−−3	low	low	right
−+1	low	high	left
−+2	low	high	center
−+3	low	high	right
+−1	high	low	left
+−2	high	low	center
+−3	high	low	right
++1	high	high	left
++2	high	high	center
++3	high	high	right
−−1	low	low	left
−−2	low	low	center
−−3	low	low	right
−+1	low	high	left
−+2	low	high	center
−+3	low	high	right
+−1	high	low	left
+−2	high	low	center
+−3	high	low	right
++1	high	high	left
++2	high	high	center
++3	high	high	right

5.17 Chapter 5 references

[1] "Deming's 14 Points | Academy of Aerospace Quality." [Online]. Available: http://aaq.auburn.edu/node/997. [Accessed: 24-Feb-2016].

[2] E. Sundqvist and F. Backlund, "Continuous improvement in project-based organizations? A management perspective," in *17th QMOD-ICQSS Conference*, 2014.

[3] "Aerospace Basic Quality System Standards - AS 9000, AS 9100." [Online]. Available: http://www.omnex.com/members/standards/as9000/as9000.aspx. [Accessed: 25-Feb-2016].

[4] "Boeing Suppliers - Doing Business with Boeing." [Online]. Available: http://www.boeingsuppliers.com/. [Accessed: 02-Mar-2016].

[5] H. Ding, M. Schipper, and B. Matthias, "Collaborative behavior design of industrial robots for multiple human-robot collaboration," in *2013 44th International Symposium on Robotics (ISR)*, 2013, pp. 1–6.
[6] P. A. Lasota and J. A. Shah, "Analyzing the effects of human-aware motion planning on close-proximity human-robot collaboration," *Hum. Factors*, vol. 57, no. 1, pp. 21–33, Feb. 2015.
[7] "HOW IT WORKS: WWII Aircraft Flush Riveting (720p)." [Online]. Available: http://104.131.131.142/videos/view/IDbTUt3OG9s/HOW-IT-WORKS-WWII-Aircraft-Flush-Riveting-720p.html. [Accessed: 27-Feb-2016].
[8] "Pages - Blind Fasteners." [Online]. Available: http://www.lisi-aerospace.com/products/fasteners/blind-fasteners/Pages/default.aspx. [Accessed: 26-Feb-2016].
[9] "AvStop » Number One Online General Aviation News and Magazine." [Online]. Available: http://avstop.com/. [Accessed: 27-Feb-2016].
[10] "Blind Rivets." [Online]. Available: https://www.nutty.com/Blind-Rivets_c_265.html. [Accessed: 07-Apr-2016].
[11] "Cherry Aerospace." [Online]. Available: http://www.cherryaerospace.com/. [Accessed: 26-Feb-2016].
[12] Steven Ward, *Rivet Shaving 101*. .
[13] "⚡Presentation 'Chapter 24: Milling DeGarmo's Materials and Processes in Manufacturing.'" [Online]. Available: http://slideplayer.com/slide/3470294/. [Accessed: 05-Mar-2016].
[14] J. P. Davim, *Machining : fundamentals and recent advances*. New York ; London : Springer, 2008., 2008.
[15] "MITSUBISHI MATERIALS CORPORATION Formulae for Cutting Power." [Online]. Available: http://www.mitsubishicarbide.net/contents/mhg/ru/html/product/technical_information/information/formula4.html. [Accessed: 02-Mar-2016].
[16] "Seek using force - 16117 | Universal Robots Support." [Online]. Available: http://www.universal-robots.com/how-tos-and-faqs/how-to/ur-how-tos/seek-using-force-16117/. [Accessed: 02-Mar-2016].
[17] "6.3.2. What are Variables Control Charts?" [Online]. Available: http://www.itl.nist.gov/div898/handbook/pmc/section3/pmc32.htm. [Accessed: 05-Mar-2016].
[18] D. e. Hardt, "Modeling and control of manufacturing processes: getting more involved," *Trans. ASME J. Dyn. Syst. Meas. Control*, vol. 115, no. 2B, pp. 291–300, Jun. 1993.
[19] D. C. Montgomery, G. C. Runger, and N. F. Hubele, *Engineering statistics*. [Hoboken, N.J.] : Wiley, c2011., 2011.
[20] M. Nouari, G. List, F. Girot, and D. Coupard, "Experimental analysis and optimisation of tool wear in dry machining of aluminium alloys," *Wear*, vol. 255, no. 7–12, pp. 1359–1368, Aug. 2003.
[21] yuhuaz@hrbust. edu. c. Zhang Yuhua1, yangshucai@hrbust. edu. c. Yang Shucai1, and fengchuang555@163. co. Feng Chuang2, "Research on the Tool Wear Mechanism of Cemented Carbide Ball End Mill Machining Titanium Alloy," *Mater. Sci. Forum*, vol. 836/837, pp. 318–325, Jan. 2016.

[22] S. Chinchanikar and S. Choudhury, "Predictive modeling for flank wear progression of coated carbide tool in turning hardened steel under practical machining conditions," *Int. J. Adv. Manuf. Technol.*, vol. 76, no. 5–8, pp. 1185–1201, Feb. 2015.
[23] H. Z. Li, H. Zeng, and X. Q. Chen, "An experimental study of tool wear and cutting force variation in the end milling of Inconel 718 with coated carbide inserts," *J. Mater. Process. Technol.*, vol. 180, no. 1–3, pp. 296–304, Dec. 2006.
[24] H. R. Krain, A. R. C. Sharman, and K. Ridgway, "Optimisation of tool life and productivity when end milling Inconel 718TM," *J. Mater. Process. Technol.*, vol. 189, no. 1–3, pp. 153–161, Jul. 2007.
[25] D. C. Montgomery, *Introduction to statistical quality control*. Hoboken, NJ : Wiley, c2013., 2013.

Chapter 6: Implementation and sustaining performance for collaborative robot

Implementation and sustaining performance for collaborative robot

This chapter describes the final recommended steps for implementing a collaborative robot following the same continuous improvement roadmap from Chapter 5 as well as the most recent safety standards available.

6.1 Establishing reliable methods

Chapter 5 described the relevance of the variability of the flight control element's stem dimensions prior to the machining process. The measurements for initial stem heights and flushness, as described throughout the last chapter, were performed using a digital dial gauge. The accuracy of the digital gauge used has a share on the total variation and can be put in perspective to other measurement techniques. This is of particular importance when going forward to establish statistical process controls across the production lines.

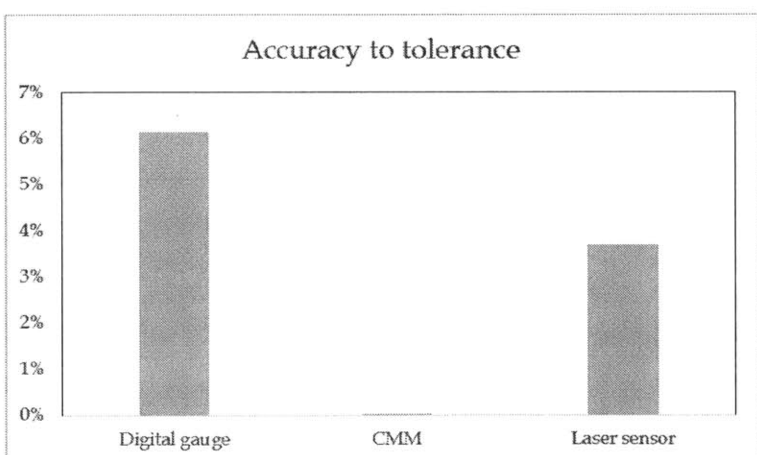
The variation on the measurements can be addressed by employing more accurate inspection methods and furthermore lead to higher process capability calculations. For that matter, precision to tolerance ratios are provided below for different inspection devices:

(6.1)

$$Accuracy\ to\ tolerance\ ratio = \frac{Inspection\ tool\ accuracy}{USL - LSL}$$

The accuracy to tolerance ratio for the digital gauge can be compared to that of a Coordinate Measure Machine (CMM) and a 2D laser sensor as shown in Figure 6-1:

Figure 6-1: Accuracy to tolerance ratio for inspection tools



It is noted that the difference in accuracy could lead to different values of Cpk. Also, it is important to consider that while the CMM is by far the most accurate instrument of these three, a customized probing methodology would have to be defined to ensure that the flushness is measured adequately. A laser sensor profile would also be suitable to obtain flushness measurements in a more detailed manner and would also be helpful for implementing further process monitoring controls.

However, considering the inspection method and the machining tool set up and calibration procedures currently in place for Stage 3, it is very unlikely that the defects rate would show an increase after the robot is implemented in comparison with the current state. One advantage of implementing a collaborative robot in this workstation is the low technical risk that derives from conserving the current standard procedures currently in place in combination with the capabilities to improve ergonomics that the robot brings with it. Henceforth, the robot is ultimately targeted to improve ergonomic conditions while preserving the quality conformance of the process.

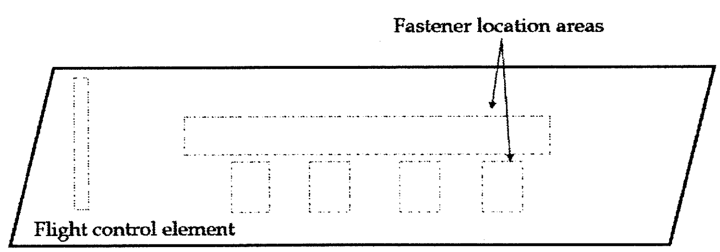
Once the optimal settings calculated in section 5.8 are tested in a production element, further monitoring tools and a statistical process control can be considered to eliminate the fully manual inspection task.

6.2 Continuously improving products and processes

After the robot is implemented to carry on the machining operation, an intermediate step towards automated inspection is establishing the proper monitoring tools. One of the concerns mentioned in section 5.6 was the suspected difference in mean for initial stem heights depending on their location within the flight control element. Considering that the Cpk resulted from a simulation using conservative approaches to tool wear, it does not seem unfeasible to move forward with a unique setting of force and speed. Leveraging the fact that full inspection would still be in place, a good tool suggested by the Advanced Quality Systems guide [1] is the defect concentration diagram.

By using a schematic of the control element top view, the quality inspector could capture the resulting flushness concentrated in different areas as follows:

Figure 6-2: defect concentration diagram



In case a unique force and speed setting was not sufficient to complete the machining task in one pass because of tool wear or significant stem height variability, patterns of poor flushness could be identified once enough data has been recorded.

Despite the unlikeliness of a defect being produced by the robot, as suggested by results of the simulation, this diagram could be used to gather data and further investigate if there are shifts of initial height means.

Complementarily, the likelihood and severity of a defective part can be assessed prior to the implementation of the collaborative robot in Stage 3 by performing a technical risk assessment. This assessment can in turn accelerate the implementation of the robot, since contingency plans could be laid-out in advance in case the workstation process capability seemed compromised. By following the steps indicated by the D1-9000 guide, a risk analysis for final implementation of the collaborative robot would be the following:

1. Assemble a cross-functional team, including: operators of Stage 3, health and safety, production leaders and managers, production systems engineering, industrial engineering, quality inspectors and the robotics development team
2. Gather the initial risk analysis scores and adjust them according to the test results
3. Revise the list of key characteristics that can potentially be affected by the robot implementation
4. Fill out the risk analysis template, as shown in Figure 6-3

Figure 6-3: Risk Analysis template

1 Candidate Key Characteristics	2 Potential Causes of Variation	3 Effect of Variation	4 Occurrence	5 Severity	6 Detectability	7 Risk Number
Material — elongation 6% minimum	Supplier material processing (chemical or heat treat)	Premature failure of part	2	6	6	72
Hole diameter 0.500 ± 0.005	• Force • Speed	Rework/scrap	2	2	2	8
0.500 step ± 0.005	• Wrong cutter • Bad setup	Difficult assembly/ shimming Part fatigue	3	8	8	192

Part or Process Name ______________________ Date ____________

Part or Process Number ________ ____________

Figure 1.7.2.3 Sample Risk Analysis Work Sheet

5. Pinpoint the key characteristics with the highest risk scores
6. Start a structure tree diagrams and cause-effect diagrams to breakdown the key characteristics to lower level characteristics. This exercise should also result in the identification of sources and effect of variation.

The Cpk value obtained in Chapter 5 could also serve as a baseline to estimate the effect of each source of risk to the overall workstation process capability. The D1-9000 document illustrates how the Cpk can be included in the risk assessment as following the occurrence rating index [1]:

Figure 6-4: Risk rating

Occurrence Rating

Rating	Approximate probability of failure	Associated Cpk	Comments
1	1/10,000	1.33	Remote probability of the characteristic varying outside of the specification limits. Process is in statistical control and is capable.
2 3 4 5	1/5,000 1/3,000 1/1,000 1/400	1.25 1.20 1.10 1.00	Low probability of occurrence of nonconformity. Process in statistical control, but not quite capable.
6	1/200	0.95	Moderate probability of occurrence. Generally associated with processes that have experienced occasional failures but not in major proportions. Process in statistical control but not quite capable.
7 8	1/100 1/40	0.85 0.75	High probability of occurrence. Generally associated with processes that have often failed. Process in statistical control but not capable.
9 10	1/20 1/10+	0.65 0.55	Very high probability of the characteristic varying outside of the specification limits.

This way, during the technical risk assessment session, the occurrence rating could be translated to the "associated Cpk" impact and compare to the baseline value.

It is recommended that prior to carrying out this technical risk assessment, a last phase of testing is performed as proposed in section 5.9. Following these recommendations will lead to a Cpk with more resolution, including tool wear and real stem height input variability.

After having completed this risk assessment step, further quality control tools might be easily integrated into the process to provide grounding for further continuous improvement projects. "X-bar" and "S" charts would be practical tools to establish, but only after enough evidence has been gathered to identify the different random processes with the assistance of the defect concentration diagram. It is not recommended to calculate natural control limits for stem heights or final flushness by pooling all fasteners within the flight control element. Once the different distributions have been identified, then control charts are a practical next step to improve the machining process and the inspection method (activities 44 and 45 from the ROM risk profile).

In terms of improving the machining process, the input tolerances for the collaborative robot are [2]:

- Force precision: ±10 N
- Torque precision: ±5 Nm

One of the initial concerns described in Chapter 5 was the capability of the robot to withhold enough downforce to carry out the machining operation. The initial experimental Cpk addresses that concern by demonstrating that the robot is capable of machining a full element with a force parameters that are below the safety limit (25 N) and above the theoretical required cutting force (<1). From the fundamentals of machining, the down force control should not be of great concern for process capability; but it is important to understand the effect of tool wear on the required force to machine.

By recalling the optimal value obtained for calculating the theoretical Cpk, the worst case scenario would be to increase the downforce parameter from this optimal value that is still more than beyond the safety threshold of 25 N recommended by the robot manufacturer. Fortunately the TS15066 document, recently released by ISO provides safety requirements related to force and speed parameters beyond 25 N as described in section 6.3

Need for additional force could derive from future requirements to reduce the cycle time, but the optimal machining speed is currently more than 100% faster than the minimum required to keep up with the current cycle time, which provides enough room for the expected 28% increase in production rates.

In regards to improving the inspection method, there are 2 different routes in which the inspection activities can be approached for further continuous improvement:

1) Reduced inspection through statistical controls
2) Fully automated inspection

The Aerospace Recommended Practice (ARP9013) points out that the measuring devices should be controlled per AS9100, which recommends that the measurement capability meets or exceeds 4:1 ratio between the product tolerance and the instrument accuracy to ensure the identification of non-conforming product [2].

Referring back to Figure 6-1, tolerance to accuracy ratio would be >16 for the digital gauge, >2000 for a CMM machine and >27 for a 2D laser sensor. The accuracy ratio of the instrument selected for inspection would drive the parameters of a statistical process control.

When evaluating a statistical sampling plan, reliability requirements need to be considered in the calculations. As dictated per the ARP9013 document, an inspection sampling plan should be laid-out based on the Average Run Length , which is the time it would take for the inspection technique to identify a shift in the mean of a random process. In simple terms, the reliability requirements for the flight control element indicate the minimum required probability of the part to perform its function, under given conditions, during a specified period of time. The ARP9013 [2] recommends to integrate the nonconformance probability into the reliability by deriving the latter from the probability of the part working given it conforms with engineering specifications, the probability of the part itself conforming to specifications, the probability of the part working given that it does not conform and the probability of the part not conforming. The nonconformance probability is therefore strictly related to the accuracy to tolerance ratio, meaning that the measuring device selected for inspection has a strong impact on the sampling frequency.

6.3 Further continuous improvement on ergonomics

Similar to the technical risk assessment, the ergonomic risk assessment could be performed prior to implementation. In theory, if a task is selected according to the ROM risk assessment tool and an observational risk assessment has now been performed, further risk identifications can be easily done and quantified by the same cross-functional team indicated in Step 1 of the technical risk assessment exercise. This way, the number of meetings are reduced, the same team is used to provide expectations on manufacturin, quality and safety performance.

Although the robot used throughout this project was tested by the manufacturer in accordance with: EN ISO 13849:2008 PL d EN ISO 10218-1:2011, Clause 5.4.3[3] additional risk identification activities must be performed before implementation. This risk assessment must target the peripheral hardware and processes under which the robot will be operating.

In February 2016, the ISO and RIA released an addendum (TS 15066)[4] that includes the technical specification supplements and safety requirements to guide the application of collaborative robots in the workplace. This addendum is complementary of the documents ISO 10218-1:2011 and ISO10218-1:2011 which establish the general safety requirements for industrial robots.

The TS 15066 [5] acknowledges that the operators can work in close proximity to the collaborative robot, while its actuators are powered. However, it indicates that a risk assessment is required to identify hazards and quantify risks of the workstation, i.e. the robot coupled with the peripheral components and tools. Therefore it is suggested to integrate the hazard identification exercise with the technical risk assessment proposed in section 6.2.

Key points to consider for elimination of hazards are [5]:

1) Outline restricted spaces and collaborative spaces
2) Identify influences on the collaborative workspace
3) Provide enough clearance around obstacles
4) Provide adequate accessibility to operators
5) Identify potential situations of contact between the robot and the operator
6) Consider access routes
7) Identify and minimize potential causes for trips and falls

In regards to ergonomics and human interface [5]:

1) Robot controls must be clear to the operator
2) Identify potential lack of concentration due to the collaborative task
3) Error/misuse of robot by the operator
4) Identify potential reflexive behaviors from the operators
5) Create training materials

When performing the hazard identification exercise, for this and further applications, the robot characteristics such as force, speed, loads, geometries and surfaces and quasi-static contact conditions should be initially considered. Additionally, the peripheral elements in the workstation such as the end-effector, workpiece, fixture designs must also be taken into account.

According to [4], collaborative operations can be achieved by any of the following:

1) Safety-rated monitored stop
2) Hand guiding
3) Speed and separation monitoring
4) Power and force limiting

The standard provides the specific safety requirements for each of the collaboration modes as well as further details on what needs to be considered when performing a risk assessment on each of these operation modes.

For the machining operation in question, the collaborative workstation can be delimited with power and force limiting. This approach allows contact between the robot and the operator, whether it is intentional or unintentional. Taking into account Annex A of this standard [4] provides the biomechanical limits to avoid injuries depending on the area of contact with the body. In this case, the robot force and speed parameters (for machining and to move in between fasteners) are orders of magnitude lower than the speed limits established for each body region in Tables A.2 and A.5 of this standard. These tables are to be used as a guide when designing parameters such as force and speed for the collaborative workstation, especially when considering power and force limiting as the collaborative mode.

6.4 Conclusions

Continuous improvement will remain a cornerstone of the tactics of commercial aircraft manufacturers to secure the substantial increase in aircraft deliveries coming up in the following decade. In these times where data analytics is becoming more crucial in the decision making processes, it is worthwhile to leverage the data input mechanisms in place at the factories to substantiate decisions not only on quality and productivity, but also in safety and ergonomics.

In broad summary, the proposal and execution of continuous improvement projects motivated solely on ergonomics is not an easy task, but action should not be delayed and resources should not be committed only to gathering information. The ROM risk profile obtained in Chapter 3 provides an immediate alternative to motivate improvement projects that might have stagnated by the lack of conventional ergonomic risk assessments. Although there is room for improving the model significance on some categories, it already points out several categories as risky with enough statistical significance. When prioritizing workstations, the recommended first step to give is using the data that is available to make improvements on those workstations where risky tasks are encountered. More granularity on the stressors can be obtained by putting in place a systematic method of capturing operators' discomfort, as proposed in Chapter 3. If the operators are already capturing their labor time, adding a stressor evaluation field to the same system should not come at a high price. Having this "live" input from the shop-floor would:

1) Provide specific input about specific stressors on specific activities, which the ROM does not provide
2) Save thousands of hours of observational risk assessments
3) Provide granularity via a live-tracking tool

On a secondary note, it is in the best interest of the industry to allow for technology to flow easier into the manufacturing processes. Continuous improvement is perfectly compatible with new technologies, especially when these have been developed and harnessed by highly specialized entities outside of the aerospace cluster. In this case, a collaborative robot was evaluated as the optimal level of technological intervention to solve a problem. For other types of tasks the optimal solution might be something else. The solution selection exercise allows for a quick quantification of the cost/benefit of all the options in a holistic manner, including safety, quality, productivity and time for implementation.

6.5 Chapter 6 references

[1] "Boeing Suppliers - Doing Business with Boeing." [Online]. Available: http://www.boeingsuppliers.com/. [Accessed: 02-Mar-2016].

[2] "Statistical Product Acceptance Requirements (ARP9013 Aerospace Standard) - SAE Digital Library." [Online]. Available: http://digitallibrary.sae.org.libproxy.mit.edu/content/arp9013. [Accessed: 11-Mar-2016].

[3] "UR10 industrial robot | Automate tasks up to 10 kgs." [Online]. Available: http://www.universal-robots.com/products/ur10-robot/. [Accessed: 12-Mar-2016].

[4] "3 Things You Need to Know About Collaborative Robots." [Online]. Available: http://cross-automation.com/blog/3-things-you-need-know-about-collaborative-robots. [Accessed: 12-Mar-2016].

[5] "ISO/TS 15066:2016 - Robots and robotic devices -- Collaborative robots." [Online]. Available: http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=62996. [Accessed: 13-Mar-2016].