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A COMPARISON OF DESIGN DECISIONS MADE EARLY AND LATE IN DEVELOPMENT

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Abstract

The occurrence rates and cost impact of design changes made early and later in the design process were studied, to test and quantify the 80-20 rule of design cost impacts, that early design decisions account for the majority of costs in a development program. Cost and schedule impact of decisions made throughout the development process was carried out at a large aerospace firm on two programs covering 7 years of development with 275 person-years effort. The underlying data used was the rate and cost of design changes made. We found no significant difference in the rate of occurrence of design change decisions made, but we found a significant difference in the cost impact of the design changes. Overall, early design change decisions cost 5 times more than later design change decisions. This difference is primarily due to the inability to determine if an early design decision is correct until later in development during testing.

Keywords: Requirements, Project management, Process modelling, Early design phases

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1 INTRODUCTION

The *80-20 rule* implies design decisions account for 80% of the product cost, as described in several works and as studied and reviewed by Ulrich and Scott (1993). Similarly Ullman (2015) concurred and found that 75% of the product cost is committed during design concept generation and further the freedom to change the design reduces as the development progresses. Studies within industry practice have shown that the opportunities for life cycle cost savings reduces as the design matures (Aerospace Industries Association, 2009). In this paper, we seek to refine the underlying understanding of these assertions by looking at past development programs within a large aerospace firm to establish the cost impact differences of design decisions and the occurrence rates of incorrect decisions, or *design defects*, over the development process. In combination, this analysis can show the relative impact of decisions made early versus late in development. We found a slightly higher occurrence rate of design defects in the early program phases than later phases. More significantly, we found that changes in design decisions made early require significantly more rework activities, nominally thirteen times more rework on average. Taken together, these observations indicate early concept design decisions have significantly higher cost impact. In the projects analysed, early design phase decisions accounted for 86% of the total potential rework cost. Therefore, the analysis confirmed the 80-20 rule with statistical significance.

2 RELATED RESEARCH AND STUDY SCOPE

In the literature, the 80-20 rule has been considered and supported at different industrial scales. In the defense industry, Mark et al (2006) considered entire weapons systems in general, whereas Obaid and David (2003) analyzed several fighter programs. Elsewhere, Tassey (2002) found similar design impact trends in the software community. While all these works report the high impact nature of design, there remains work to highlight where in design this high sensitivity exists. We seek here to provide a refined understanding of *occurrence* and *sensitivity*, how often correct or incorrect decisions are made at different points in design and their relative cost implications, given the inherent uncertain nature of understanding of outcomes in development.

Using the 80-20 heuristic as motivation, several authors have sought improvements to the design process. Ulrich and Scott (1998) studied design process improvements for coffee makers based on the 80-20 rule. Geoffrey et.al. (1994) used the 80-20 heuristic as motivation for adopting design for manufacturing and assembly (DFMA) methods. These works seek to understand in quantifiable detail the mechanics of design activities on the product development process.

Phase-gate design processes are often used in practice (Cooper, 1990, 2011), where the gate review process provides an opportunity to review and consider early potentially non-complying requirements. The gate review also allocates resources to the various stages of the developmental process (Cooper, 1998). Gate reviews are documented activities where decisions are discussed, critiqued and possible additional refined work activities defined. Therefore, gate review documentation provides data to study the impact of design decisions made before and after each gate review. Of the several gate reviews in a development process, if the 80-20 rule is correct, then the early concept freeze gate review can be considered a highly sensitive milestone. It is when the early design decisions are completed and subsequent activities are approved to instantiate the chosen design. Therefore, to study the 80-20 rule, we choose to study the impact of decisions made before and after the concept freeze. In summary, between decisions made before and after the concept freeze, we seek to understand the difference in cost impact of design decisions made.

Cost impact can be measured in terms of finances such as costs to develop, build and use the new design. Design process costs can be measured as work activities or time and materials measurements. In our study, cost is determined as the number of work activities and the additional cost is a result of rework activities.

An entirely separate consideration is the value of design decisions, whether design decisions made contribute to added future revenues. This is outside the scope of our work, which, as the works above, restrict to considering *cost* impacts of design decisions made.

Costs of design decisions can then be thought of in terms of differences between correct and incorrect decisions made, where a correct means the decision enables lower total cost to the firm. For our purposes, a design defect is the consequence of an incorrect decision made and this is recorded by missed requirements. We seek to understand the rate of occurrence of incorrect decisions made in the activities both before and after the conceptual design freeze. We also seek to understand the difference in cost sensitivity of decisions made both before and after the conceptual design freeze. Both of these factors contribute to the support of whether design accounts for 80% of cost.

To analyze this, we first review a typical corporate stage gate design process and clarify the relevant gates. Then, we consider a set of past projects case studies, and clarify design defects in the generated outcome designs, both those reworked and those defects that were never fixed. These sources of data provide the inputs for the analytical process as shown in Figure 1. Next, such outcome design defects will be traced to its root cause decision made. Further, the actual and 'what-if' rework activities are then analyzed to form a relationship and cost impact assessment. Finally, we will discuss the impact of our findings and provide opportunities for future work.

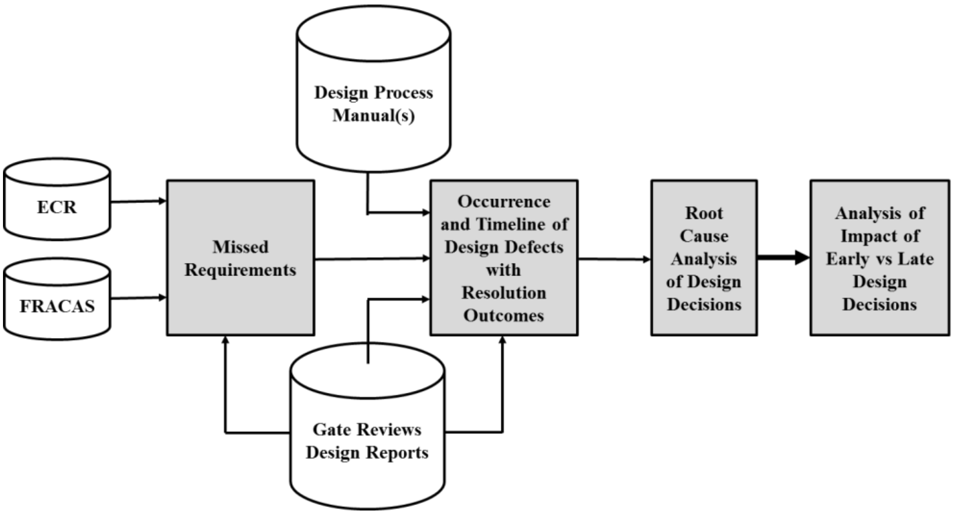

Figure 1. Data Sources and Analysis Flow

3 CORPORATE DESIGN PROCESS

We map our typical corporate design processes (Cooper 2001, Anderson, 2004, Hales 2011) to be consistent with the open and publicly documented DOD 5000-2P standard (Department of Defense, 2001, 2015). It has 4 major phases and 3 major milestones as shown in Figure 2. Milestone A is the end of the requirements analysis, while Milestone B marks the concept freeze and provides the go ahead for development. Milestone C freezes the design and checks for production feasibility. Our scope of study begins with Milestone A and ends after the initial deployment of the product.

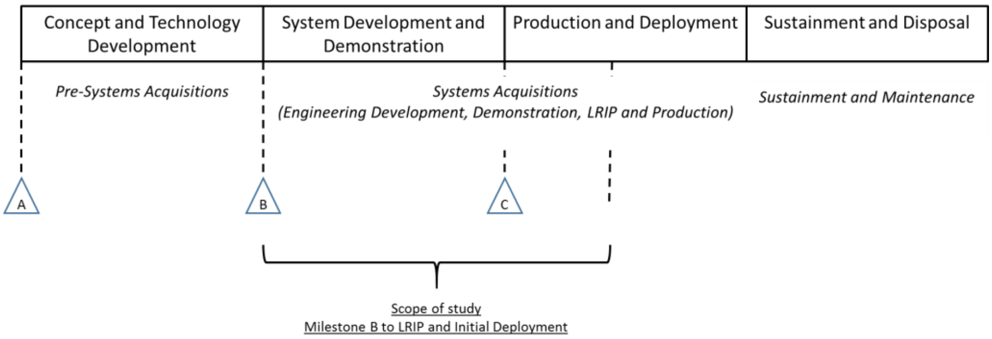

Figure 2. The DOD 5000-2P Process

Using the DOD 5000-P2 process, developmental stages are delimited with design technical reviews as gates (Department of Defense, 2001). The design reviews we study are in the following order; *systems requirements review* (SRR), *preliminary design review* (PDR), *critical design review* (CDR), and *production go ahead* (PGA). The periods between the gates we denote as *phases*: the activities before the concept is frozen (*Before Concept Freeze*, BCF), after the concept is frozen (*After Concept Freeze*, ACF), after the design is frozen (*After Design Freeze*, ADF) and after the production go ahead (*After Production Go Ahead*, APGA). These phases scope the extent of our analysis and is shown in Figure 3.

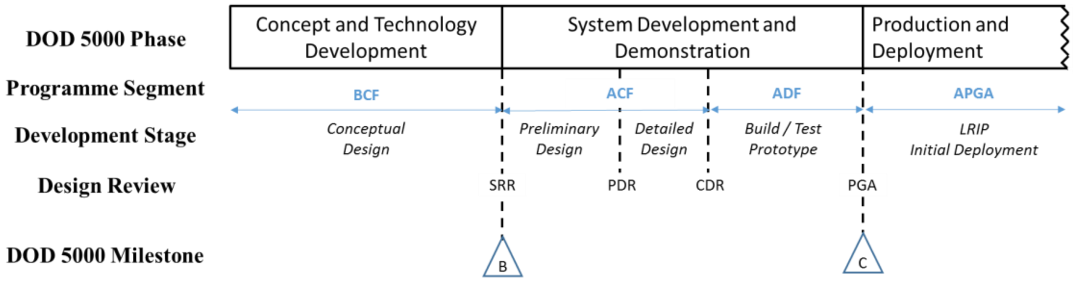

Figure 3. Corporate Design Process

4 CASE STUDIES IN THE LITERATURE

Before studying our industrial firm, we first studied the literature for other case studies on design defects. The case studies originate from various industries. We examined the overrun cost and schedule together with the root cause of the design defect as found in the literature and industry sources. Initial projected costs / time were used as the baseline, and reported additional cost / time were factored in normalised. This derived the percentage of total program cost / schedule slip attributed to the issue identified. The design case studies are summarized in Table 2, and the cost and schedule impact are presented in Figures 4 and 5.

Table 2. Case Studies of Design Defects

Case Study	**Issue**	**Root Cause**	**Reference**
Millennium Bridge	Resonance	Lateral vibration mode not considered in the design.	BBC, 2000
Chinook Mk 3 upgrade	Avionics uncertifiable	Unverifiable software operating parameters.	Burr, 2008
A400M	Performance requirements mismatch	Ill-defined work share program.	Brothers, 2014
A380	Wiring connection post assembly	Incompatible Design Tools.	Wong, 2006
F-22	Unstable industrial base	Development concept of the system architecture was not reviewed adequately.	Obaid, 2003
SH-2G(A)	Unable to operate in low light conditions	Inadequate requirements analysis.	Allard, 2005
S-80 Submarine	Unable to surface after submerging	Calculation error.	Govan, 2013
Citi Corp Center	Building could not withstand quarterly winds	Inadequate calculation verification process.	Vardaro, 2013
Boeing 787	Thermal runaway in batteries	Outdated design verification process.	Williard, 2013
Type 45 Destroyer	Failure of power generation system	System design with a single point of failure.	Batchelor, 2016

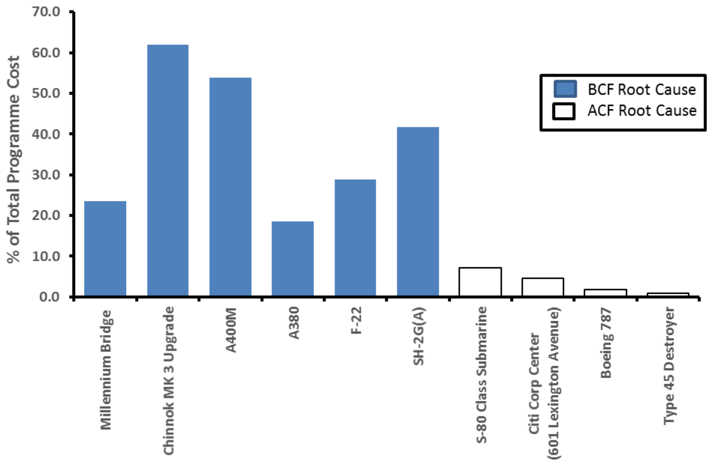

Figure 4. Cost Overrun Impact of Missed Requirements

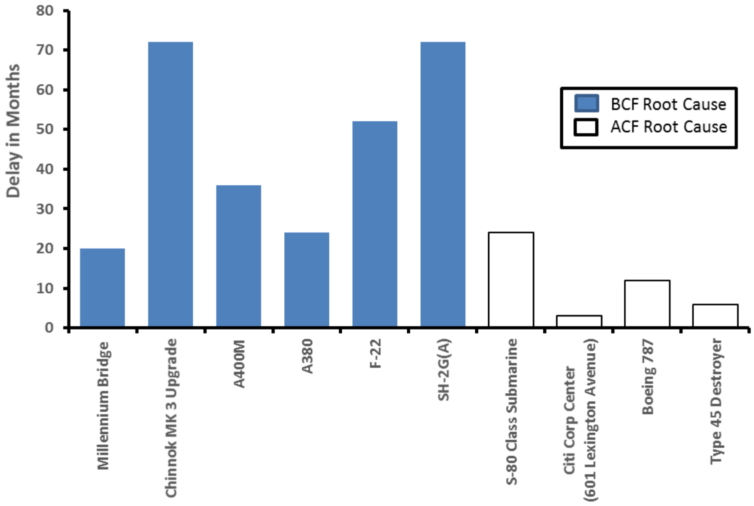

Figure 5. Schedule Impact of Missed Requirements

As can be seen in Figures 4 and 5, from the data presented in the literature the root causes of design defects originating from before concept freeze exhibit higher impact on cost and schedule than those of after concept freeze. Such literature case studies are anecdotal and provides motivation to investigate further. We do so here by examining a company’s design process and past results in detail.

5 DATA GATHERING AND ANALYSIS

We considered the development history of a large aerospace firm over the past 7 years. We select this timeframe as it covered two multi-year development programs of new unmanned aerial vehicles (UAVs). The programs were executed over 7 years of continuous development effort, representing 275 equivalent person-years of internal corporate effort. Both programs exhibited different forms of missed requirements late in the testing phase. A design defect was identified as an item entered in the *Engineering Change Request* (ECR) system. For each ECR, we conducted root cause analyses with the practicing engineers (via interviews with documentation reviews) to trace each design defect from onset detection through the ECR system, the Design Review documentation, the *Failure Reports System* (FRACAS) and gate reviews, to thereby identify the root cause design decision. We captured the activity and phase of the root cause design decision. An inter-rater-reliability assessment between analysts within the company was carried out to ensure the categorization of the program phase for each design defect. The Cohen’s kappa was 0.810, indicating good agreement.

In the programs studied, 264 ECRs, FRACAs, gate review and design reports were reviewed for a total of 211 requirements. From this, 58 design defects occurred resulting in missed requirements, and thus relevant to our study scope. The resulting corrective actions were tracked through the design process. Each design defect translated from one of our data sources. We analysed this data set of design changes for point of occurrence and for cost impact of rework activities between program segment via root cause analysis of the work activities. The insights generated from the analysis will then provide basis for improvement of standard work flows.

To do this, the necessary rework activities to fix each identified design defects (58 in total) were determined. To describe the various types of problems involved, the design defects are grouped by system type in Table 3. As shown, most design defects were associated with changes to the fuselage and avionics, though all major UAV systems experienced at least one design defect.

Table 3. Design Defect Identification by System Type

Design Defect ID	**Design Defect (System)**
4,5,6,34,39,40,41,44, 47,48,49,54,55,56,58	Airframe
9, 22	Electrical Power
13,14	Electrical System Installation
38,43,45,46	Engine
35,36	Exhaust
20,21	Fuel
1,2,12,23,24,25, 26,28,29,30,31,37	Fuselage
7,8,15,16,18,19,42, 50,51,52,53,57	Modular Avionics
10,33	Landing Gear
11,17	Navigation
3,27,32	Stabilizer

To study each design defect, the development process activities were analysed from the activity where the onset detection of the design defect occurred, and then traced back through the project schedule to the precedent activities. This is continued until the root cause activity was identified. The count of activities impacted were then summed. For example, if a design defect was detected in the after concept freeze (ACF) phase and the defect root cause was traced to the before concept freeze (BCF) phase, then the total number of activities required to address the design defect will include those within the program segments BCF and ACF. At the other extreme, if the root cause of the design defect was discovered at the point of detection, then rework activities are confined to the single activity only.

The root causes of design defects by development process tasks is shown in Figure 6. As can be seen, a large fraction of design defects were 'Requirements Definition' changes; the requirements defined turned out to be inconsistent. For example, a chosen payload was in excess of that possible given the chosen range.

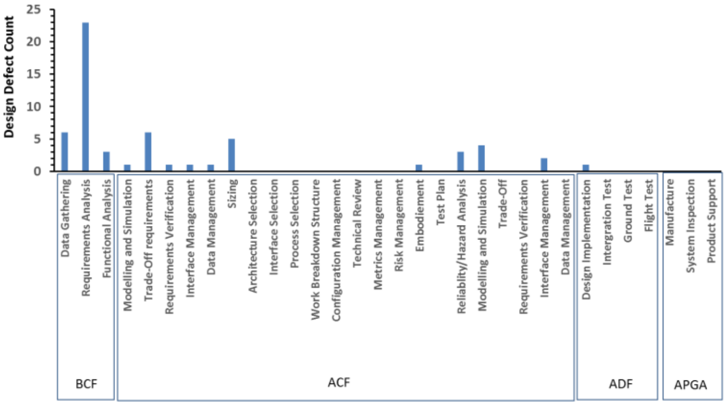

Figure 6: Design defects root causes by development process task.

Using this methodology, the required rework for all major design defects that arose is shown in Figures 7 and 8, for defects with root cause before concept freeze and after concept freeze respectively. First, each figure depicts the number of actual rework activities completed when the design defect was discovered. For comparison, each figure also depicts the number of rework activities that would have been required to fix the defect if it had been discovered immediately at the root program segment.

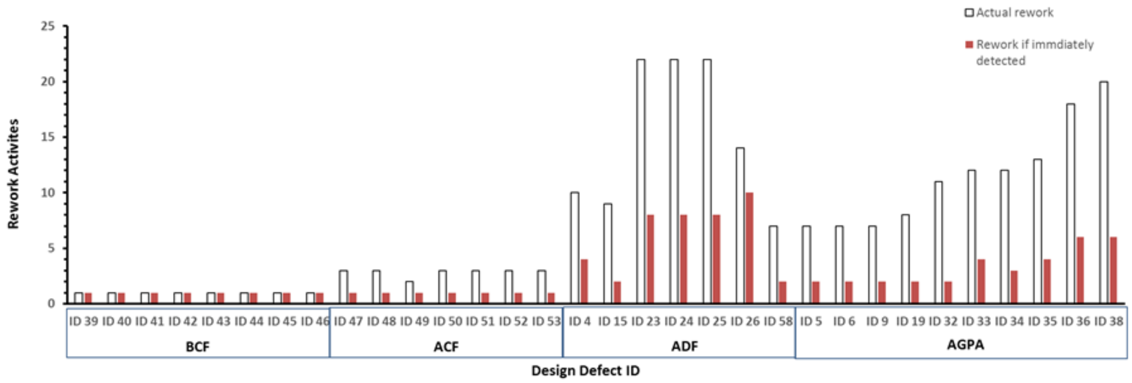

Figure 7. Rework activities required for the root causes that arose in BCF

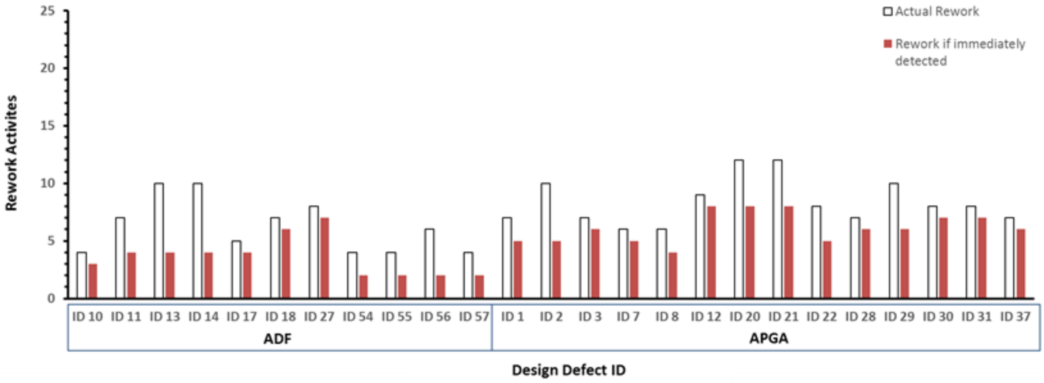

Figure 8. Rework activities required for the root causes that arose in ACF

From the figures, we can see that rework activities that arose from BCF root causes were significantly more than those of ACF root causes. The differences from before vs after concept freeze can be quantified. The average rework required difference from before vs after concept freeze can be computed from Figures 7 and 8.

The results as shown in Figures 7 and 8 indicate earlier decisions are costlier to change. From the overview illustrated in Figure 9, the average rate of increase of BCF multiplier rework activities between the BCF and ACF program is 2.9, while for BCF and ADF the multiplier is 15.1. For the multiplier between BCF and APGA, the multiplier value is 12.0 and finally the average multiplier across all program segments is 13.0.

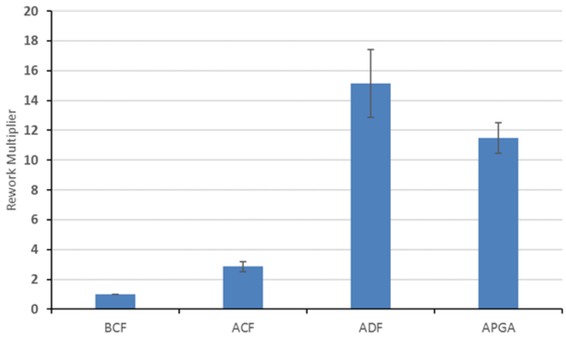

Figure 9. Increase of actual rework activities using BCF multipliers

A further observation from Figure 6 is that many early phase decisions could not be completely determined correct until late in the program, during the build and test phases. Fundamentally, this is the reason of the large rework activity levels. Few of the root causes before concept freeze could be detected before concept freeze, and so were incorrectly carried forward into the late phase testing. This resulted in high cost sensitivity of these early design decisions. As indicated in Figure 10, we observe the following from our data; 9 of design defects were not resolved (permanent non-compliance due to the high cost involved), 13 of the 49 design defects required re-certification on top of drawing changes.

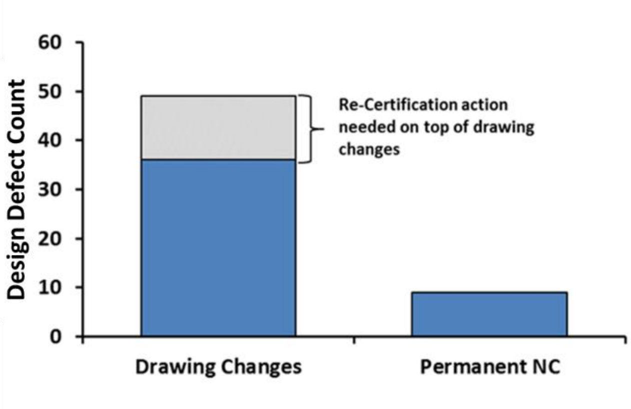

Figure 10: Design Defects Resolution Outcomes

In addition to cost impact, however, the occurrence rate of decision changes with relation to work activities need to be considered as shown in Table 4. Each program segment had a different rate of occurrence in poor design decisions that resulted in design defects. The BCF, ACF and ADF program segments had 59%, 28% and 22% chance of poor design decisions respectively, clearly showing early design phase decisions also have a higher error rate and are prone to being changed.

Table 4: Design Defect Occurrence Rate

Program Segment	**Activities**	**Activities with Defects**	**Defect Rate**
BCF	17	10	59%
ACF	75	21	28%
ADF	27	6	22%

The cost impact of changing any decision is the occurrence probability times the rework required. The analysis indicates design decision have different likelihood of error based on program segment. Further, with the ability to detect an incorrect early decision delayed until the later testing phase, the results showed that rework levels are 13 times higher on average for early phase decisions.

Theoretically, the cost of changing all design decisions made over the development process is the sum over all decisions of their change occurrence probabilities multiplied by cost impacts. Since the occurrence probability rates vary, the relative cost of design decisions before-versus after-concept-freeze is significant. We determine the design decision defect costs by summing up the total work activities across the program segments with the rework multiplier as tabulated in Table 5. As can be seen, the rework cost attributed from before the design freeze was 86%.

Table 5: Rework Activities Cost Contribution

	Segment Activities	**Rework Multiplier**	**Probability of rework**	**Cost Contribution**	**Percent Contribution**
BCF	17	13.0	0.59	147.0	33.5%
ACF	75	7.4	0.28	231.2	52.7%
ADF	27	2.9	0.22	44.1	10.1%
APGA	16	1.0	0.00	16.0	3.7%

6 CONCLUSION

At a major aerospace firm, the cost of changing design decisions made in the conceptual design phase were found to be on average 13 times larger than the cost of changing decisions made after the concept was fixed. Fundamentally, this difference was due to the inability to detect the need to change early design decisions until late in the program during system testing. We also found that occurrence rates of revised design decisions was higher earlier in the development process.

Considering the set of all design decisions made over the development process, the expected cost impact of changing any decision is the occurrence probability times the rework required. With the ability to detect an incorrect decision delayed until the testing phase, we determined that early design decisions account for 86% cost impact of all design decisions. This supports the 80-20 rule in terms of pre-and post-design freeze activities.

Future work would include repeating this study across different industries and scales, such as a meta study on various industrial companies. Interventive measures are also needed to reduce the occurrence rate of conceptual design changes. Particularly, large benefits would accrue when reducing the time needed to identify early phase design errors, rather than being unable to detect them until the latter testing phases of development.

REFERENCES

Aerospace Industries Association (2009), *S3000L: Intl. Proc. Spec. for Logistics Support Analysis* (LSA),

Allard, T. (2005), “Navy's $100M Chopper Can't Fly In Bad Light,” smh.com.au. N.P. 3 Dec. 2016.

Anderson J. (2010), *Fundamentals of aerodynamics*. Tata McGraw-Hill Education.

Batchelor, T. (2016), “Taxpayers Foot £1BILLION Bill After Mod 'Failed To Properly Test' Type 45 Destroyer Engine,” express.co.uk. N.P. 2017. 03 December 2016.

BBC (2016), “BBC News | UK | Millions To Repair Swaying Bridge.” news.bbc.co.uk. N.P. 3 December 2016.

Brothers, C. (2009), “Germany and France Delay Decision on Airbus Military Transport,” nytimes.com. N.P. 10 Oct. 2016.

Burr, T. (2008), *Chinook MK 3 Helicopters* (Rep. No. HC-512), London: National Audit Office.

Cooper, R. (1990), “Stage-gate systems: a new tool for managing new products.” *Business horizons*, 33(3):44-54.

Cooper, R. (2011), *Winning at new products: Creating value through innovation*. Basic Books.

Cooper, R. and Kleinschmidt, E. (1988), “Resource allocation in the new product process,” *Industrial Marketing Management*, 17(3):249-262.

Department of Defense (2015), *Department of Defense Instruction, Number 5000.02*. Department of Defense.

Department of Defense (2001), *Systems Engineering Fundamentals*. System Management College.

Geoffrey, B. and Winston, D. (1994), “Product Design for Manufacturing and Assembly,” *Computer Aided Design* Volume 26.

Govan, F. (2013), "£2 Billion Spanish Navy Submarine Will Sink to Bottom of Sea". Telegraph.co.uk. N.P. 10 Oct. 2016.

Hales, C. and Gooch S. (2011), *Managing engineering design*. Springer Science & Business Media.

Mark, V. (2006), *Historical cost growth of completed weapon system programs* (Vol. 343), Rand Corporation.

Obaid, Y., Stem, D., Lorell, M. and Lussier, F. (2005), *Lessons learned from the F/A-22 and F/A-18 E/F development programs*. RAND Corporation.

Tassey, G. (2002), *The economic impacts of inadequate infrastructure for software testing*. National Institute of Standards and Technology, RTI Project, 7007(011),

Ullman, D. (2015), *The Mechanical Design Process*. McGraw-Hill Education.

Ulrich, K. and Pearson, S. (1993), “Does product design really determine 80% of manufacturing cost?,” MIT Technical Report.

Ulrich, K. and Pearson, S. (1998), “Assessing the importance of design through product archaeology.” Management Science, 44(3):352-369.

Vardaro, M. (2013), “LeMessurier stands tall: A case study in professional ethics,” AIA Trust. (Online Case Study), http://www. theaiatrust. com/whitepapers/ethics/analysis. php.

Williard, N., He, W., Hendricks, C. and Pecht, M. (2013), “Lessons learned from the 787 Dreamliner issue on lithium-ion battery reliability”, *Energies*, 6(9):4682-4695.

Wong, K. (2006), “What Grounded The Airbus A380?” *cadalyst.com*. N.P. 3 Dec. 2016.

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