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Statistical Analysis of CubeSat Mission Failure

Abdulaziz Alanazi, Jeremy Straub
Department of Computer Science, North Dakota State University
1320 Albrecht Blvd., Room 258; Fargo, ND 58102; 701-231-8562
abdulaziz.alanazi@ndsu.edu, jeremy.straub@ndsu.edu

ABSTRACT

There are multiple common reasons for CubeSats' failure. These include power, mechanical, and communications issues. Some have suggested that the problem lies within the design and development process itself, in that universities and research institutions mainly focus on system and component level designs, while neglecting requirements' elicitation needed beforehand. A survey was conducted during the 14th Annual CubeSat Workshop at CalPoly, San Luis Obispo, to identify the challenges and needs of such groups and initial results from this survey and its analysis are reported in this paper. This survey was conducted with students in the U. S. and Europe, working on small spacecraft development and majoring in disciplines including computer science and mechanical engineering. The survey considered multiple factors prospectively associated with mission success or failure, including the possibility of adding or deleting components into/from the system design and system modifications' feasibility. Additionally, the respondents were asked the objectives of their CubeSat mission and whether their system design covered the entire system (e.g., structure, behavior, requirements, and system parametric). The problems identified by them related to tools, models, or both have also been reported. Finally, participants were asked whether they helped in reducing the system testing time or employed a CubeSat reference model. This paper concludes with a discussion regarding what has been learned from data analysis. Plans for future work are also discussed.

INTRODUCTION

In the last twenty years, small spacecraft have gained popularity in educational institutions. CubeSats have attracted educators' and researchers' interest due to their small sizes and masses The dimensions of a standard one unit CubeSat (1U) are 10 x 10 x 10 cm, with a mass of 1.33 kg.[1]. There are several modular sizes of CubeSats based on this, including 1U, 2U, 3U, and recently, 12U.[2]

What makes CubeSats highly popular is that they are not as expensive to build or launch as larger satellites. Building a larger satellite can cost millions of dollars, while building a CubeSat can be done for thousands or tens of thousands of dollars.[3] Government programs can provide free-to-developer launches and development and operations can use existing faculty and staff resource time and volunteer or low-cost student labor.

CubeSats, in particular, can be built for these low costs, because universities can use commercial-of-the-shelf parts (COTS) and open-source software.[3] Some COTS components may even be donated by vendors excited by their hardware's use in a space mission.

Teams that work on building CubeSats typically comprise students from different science and engineering disciplines including aerospace, software, mechanical, and electrical engineering. These students may be receiving academic credit or funded through university-level undergraduate research support programs. Thus, the labor cost may be minimal and is certainly much lower than the cost of professional aerospace engineers.

Another factor that contributes to CubeSats' high demand is that they can collect data in multiple locations, concurrently, as part of a multi-satellite network and communicate with other satellites and ground stations. Even basic satellite designs that use limited COTS parts, such as mobile phone hardware, low cost cameras, consumer radiometers, and basic RF beacons (which are commonly referred to as "Beebsats") can provide significant educational benefits to participating students.[4]

However while universities can swiftly design and build their CubeSats, with a team of students from different disciplines using COTS parts, this does not guarantee that the CubeSat mission will be successful. Statistics show that mission failure is frequent. For example, out of 270 CubeSats, 139 have failed in their mission between 2002 to 2016.[5,6] Reasons for failure include power failure, mechanical, communications failure and system design issues.

This paper is an early report in a project to attempt to identify design-attributable failures and develop processes and tools to prevent them in the future. In particular, to this end, it focuses on the identification of design decisions (or process failures) that lead to mission problems.

INVESTIGATING MISSION FAILURE

To investigate the causes of mission problems and failures in college and university projects, a survey was conducted regarding issues related to tools and models. The survey was sent out to 120 individuals identified at the CalPoly CubeSat Workshop; however, only 35 were returned fully completed.

Approximately 48% of respondents reported experiencing tools' failure, such as communication problems with simplex and duplex radios, VHF or UHF transceivers' failure, and power failure. Conversely, 24% of respondents thought that the major challenges for them were caused due to the models they use currently. This includes integration and analytical models (excluding flight software models). Additionally, 28% stated that the problems they have are due to both tools and models.

Of those responding, 57% reported that they have not considered techniques for reducing system testing time requirements, either because the testing is performed externally by vendors, or they have never used methods that can facilitate a reduction in testing time. required testing includes the testing of both hardware and software systems, including thermal, radiation, and vacuum testing. However, 43% respondents reported enjoying a reduction in testing time with the use of qualifications testing and requirements analysis.

Model-Based Systems Engineering (MBSE) has been proposed as a reference model and methodology to help schools meet their mission requirements[7]. MBSE includes different tools that facilitate the realization of verification and validation. Such tools include modeling, simulation, integration, and analytical models. However, only 35% respondents reported following one reference model for different CubeSat projects, while 65% have never considered using it.

STATISTICAL ANALYSIS

The principal objective of the analysis is to assess factors that can be associated with reducing the rate of CubeSat failures through the application of a system engineering approach. For this purpose, seven principal factors or critical system objectives were identified. These factors and their coding for data analysis are as follows:

1. Testing time reduction (variable name: TTR): coded as 0 if not occurring, 1 if it occurred
2. Design problems (variable name: DesPr): coded as 1 if problems were related to tools, 2 if related to models, 3 if related to both
3. Availability of model for modification (variable name: Mod): coded as 0 if not, 1 if yes
4. Ease of addition or deletion of components (variable name: AddDel): coded as 1 if easy, 2 if difficult
5. System design objectives met (variable name: SysMet): coded as 0 if not, 1 if yes
6. Mission objectives met (variable name: MMet): coded as 0 if not, 1 if yes
7. Whether one model was employed as a reference model for different missions (variable name: Mission): coded as 0 if not, 1 if yes

In addition, mission success or failure (variable name: Mission) was coded as 0 for failure and 1 for success.

Since the first seven factors or variables contributed toward possible mission success or failure, mission success constitutes a dependent variable (DV), while the first seven variables are independent variables (IV's).

All the IVs and DV's discussed above can be treated as being nominally independent of each other; they are not hierarchically related. Therefore, in order to ascertain whether each one of the IV's is related to another, chi-square tests of independence would be appropriate with mission success as the DV and one IV for each test of independence. In addition, it is possible that two or more of the IV's can jointly explain the success or failure of the mission, and for this, a logit or binomial regression model can be constructed with mission success as the DV and all the IV's.

The chi-square tests of independence were conducted first. These tests were done with two assumptions: each variable is categorical and independent of each other, and each level of each variable should have an expected value of at least 5. The first assumption was met, as discussed earlier, while the second assumption has been discussed for each test.

Chi-Square Tests

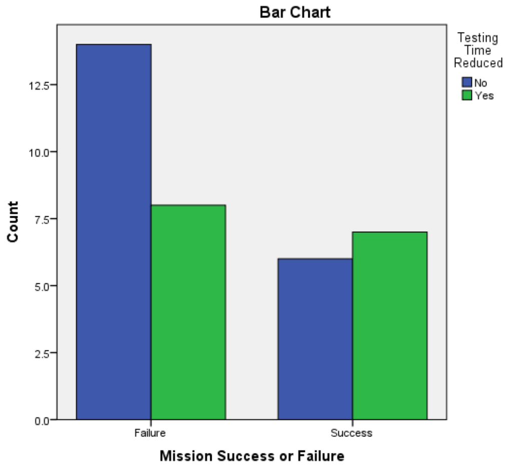


Figure 1: Testing Timer Reduction and Mission Success/Failure

Table 2: Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	1.020[a]	1	.313		
Continuity Correction[b]	.431	1	.512		
Likelihood Ratio	1.018	1	.313		
Fisher's Exact Test				.481	.255
Linear-by-Linear Association	.991	1	.320		
N of Valid Cases	35				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 5.57.
b. Computed only for a 2 x 2 table

From this, it can be observed that the p value of the Pearson $\chi 2$ test statistic is 0.313, which is higher than the 5% significance level ($p = 0.313$). Therefore, there is no significant relationship demonstrated between TTR and mission success/failure.

Figure 1 demonstrates that instances of reduction in testing time are higher for successful missions but are less for failed missions. The $\chi 2$ test result has been presented in Table 1.

Table 1: Mission Success or Failure * Testing Time Reduced Crosstabulation

Count

Mission Success or Failure	Testing Time Reduced		Total
	No	Yes	
Failure	14	8	22
Success	6	7	13
Total	20	15	35

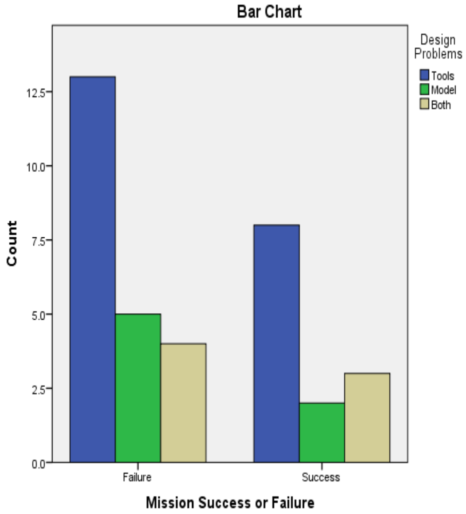


Figure 2: Design Problems and Mission Success/Failure

It can be observed that instances of problems with tools, models, and both were less for successful missions compared to the corresponding instances of problems for failed missions. The $\chi 2$ test result has been provided in Table 2.

Table 3: Mission Success or Failure * Design Problems Crosstabulation

Count

Mission Success or Failure	Design Problems			Total
	Tools	Model	Both	
Failure	13	5	4	22
Success	8	2	3	13

Total	21	7	7	35

Table 4: Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	.326[a]	2	.849	1.000	
Likelihood Ratio	.333	2	.847	.904	
Fisher’s Exact Test	.432			1.000	
Linear-by-Linear Association	.007[b]	1	.931	1.000	.546
N of Valid Cases	35				

a. 4 cells (66.7%) have the expected count of less than 5. The minimum expected count is 2.60.
b. The standardized statistic is .086.

Fisher’s exact test statistic would be more appropriate, since some cells had the expected counts of greater than 5. It can be observed that the test is not significant, since the p value is higher than the 5% significance level (p = 1.000). Therefore, there is no significant relationship demonstrated between the design problems faced and mission success/failure.

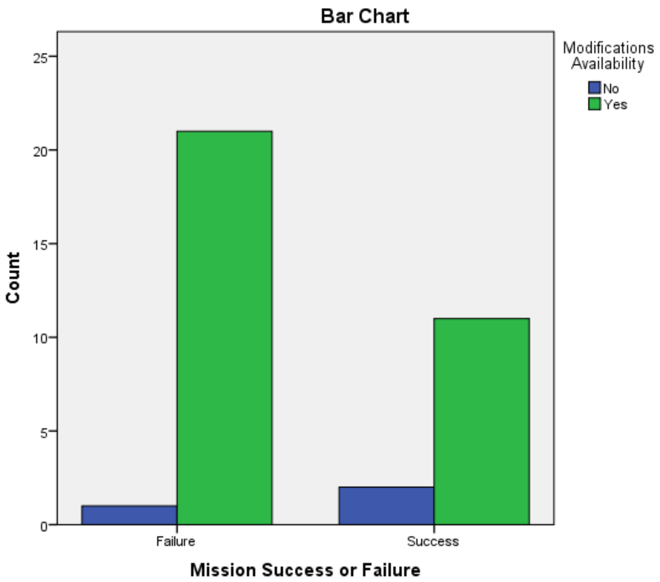


Figure 3: Availability of Modifications and Mission Success/Failure

It can be observed that a comparatively smaller number of models were available for modifications for successful missions compared to those that were available for failed missions. The χ2 test result has been presented below:

Table 5: Mission Success or Failure * Modifications Availability Crosstabulation

Count

Mission Success or Failure	Modifications Availability		Total
	No	Yes	
Failure	1	21	22
Success	2	11	13
Total	3	32	35

Table 6: Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	1.225[a]	1	.268	.541	.306
Continuity Correction[b]	.232	1	.630		
Likelihood Ratio	1.177	1	.278	.541	.306
Fisher's Exact Test				.541	.306
Linear-by-Linear Association	1.190[c]	1	.275	.541	.306
N of Valid Cases	35				

a. 2 cells (50.0%) have expected count less than 5. The minimum expected count is 1.11.
b. Computed only for a 2x2 table
c. The standardized statistic is –1.091.

It can be observed that the Fisher’s exact test statistic was not significant with a p value greater than 0.05 (p = 0.541), indicating that there is no significant relationship demonstrated between the availability of modifications and mission success/failure.

Figure 4: Ease of Addition or Deletion of Components and Mission Success/Failure

From the figure, it can be observed that both the ease and difficulty of addition/deletion of components was greater for failed missions as compared to successful missions. However, the relative ease of addition/deletion of components was greater for successful missions than for failed missions, since the difference between the green and blue bars is less for successful missions. The χ2 test result has been provided below:

Table 7: Mission Success or Failure* Add or Delete Components Crosstabulation

Mission Success or Failure	Add or Delete Components		Total
	Easy	Hard	
Failure	18	4	22
Success	10	3	13
Total	28	7	35

Table 8: Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	.122[a]	1	.726	1.000	.525
Continuity Correction[b]	.000	1	1.000		
Likelihood Ratio	.121	1	.728	1.000	.525
Fisher's Exact Test				1.000	.525
Linear-by-Linear Association	.119[c]	1	.730	1.000	.525
N of Valid Cases	35				

a. 2 cells (50.0%) have the expected count of less than 5. The minimum expected count is 2.60.
b. Computed only for a 2 x 2 table
c. The standardized statistic is .345.

It can be observed that the Fisher's exact test statistic was not significant with a p value greater than 0.05 (p = 1.000), indicating that there is no significant relationship between ease of addition or deletion of components and Mission success/failure.

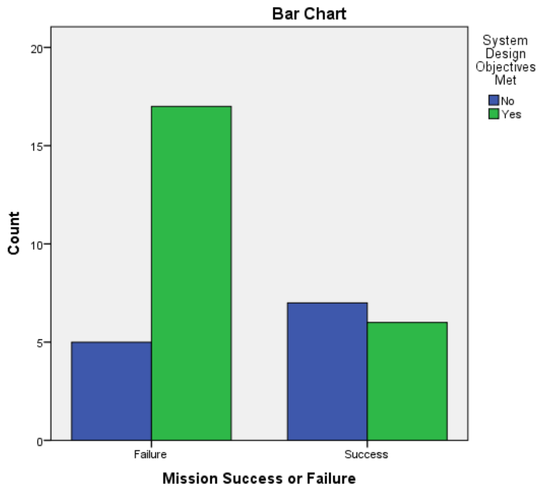


Figure 5: System Design Objectives and Mission success/failure

It can be observed from the figure that, in fact, the ratio of design objectives met to those not met was greater than 1 for failed missions (more system objectives were met than were not met), while the ratio was less than 1 for successful missions. The χ2 test result has been presented below:

Table 9: Mission Success or Failure* System Design Objectives Met Crosstabulation

Count

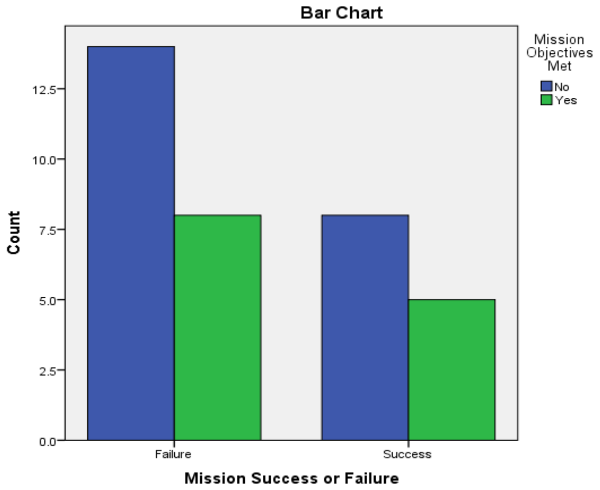
Mission Success or Failure	System Design Objectives Met		Total
	No	Yes	
Failure	5	17	22
Success	7	6	13
Total	12	23	35

Table 10: Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	3.512[a]	1	.061	.079	.067
Continuity Correction[b]	2.267	1	.132		
Likelihood Ratio	3.477	1	.062	.139	.067
Fisher's Exact Test				.079	.067
Linear-by-Linear Association	3.412[c]	1	.065	.079	.067
N of Valid Cases	35				

a. 1 cells (25.0%) have the expected count of less than 5. The minimum expected count is 4.46.
b. Computed only for a 2 x 2 table
c. The standardized statistic is –1.847.

It can be observed from the figure that the Pearson chi-square test statistic as well as the Fisher's exact test statistic were significant at the 10% level, with p values less than 0.1 (p = 0.06 and p = 0.079 respectively), indicating that there was a significant relationship shown between the system objectives met and mission success/failure.



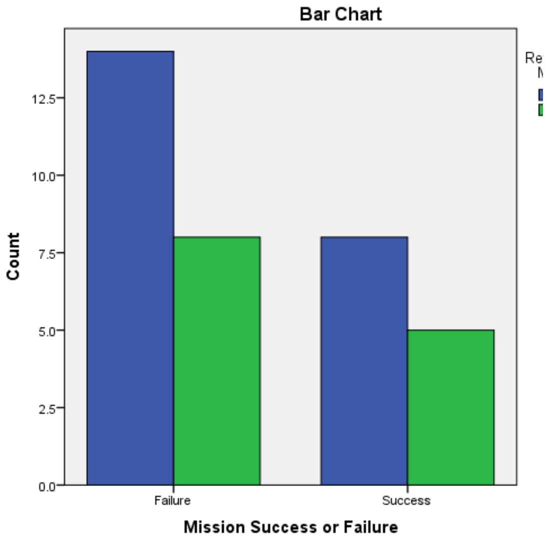


Figure 7: Reference Model and Mission Success/failure

Table 12: Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	.015[a]	1	.901	1.000	.591
Continuity Correction[b]	.000	1	1.000		
Likelihood Ratio	.015	1	.901	1.000	.591
Fisher's Exact Test				1.000	.591
Linear-by-Linear Association	.015[c]	1	.903	1.000	.591
N of Valid Cases	35				

a. 1 cells (25.0%) have the expected count of less than 5. The minimum expected count is 4.83. b.

Figure 6: Mission Objectives and Mission Success/Failure

It can be observed that the ratio of mission objectives met to those not met was higher for successful missions than for failed missions, since the difference between the bars was less for successful missions. The χ2 test result has been provided below:

Table 11: Mission Success or Failure* Mission Objectives Met Crosstabulation

Count

Mission Success or Failure	Mission Objectives Met		Total
	No	Yes	
Failure	14	8	22
Success	8	5	13
Total	22	13	35

b. Computed only for a 2 x 2 table;
c. The standardized statistic is .122.

It can be observed that the chi-square test was not significant (p = 0.9), indicating that there is no significant relationship demonstrated between mission objectives being fulfilled and mission success/failure.

It can be observed from the figure that one reference model was used less often in successful missions compared to failed missions. The χ2 test result has been given below:

Table 13: Mission Success or Failure * One Reference Model Crosstabulation

Count

Mission Success or Failure	One Reference Model		Total
	No	Yes	
Failure	14	8	22
Success	8	5	13
Total	22	13	35

Table 14: Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	.015[a]	1	.901	1.000	.591
Continuity Correction[b]	.000	1	1.000		
Likelihood Ratio	.015	1	.901	1.000	.591
Fisher's Exact Test				1.000	.591
Linear-by-Linear Association	.015[c]	1	.903	1.000	.591
N of Valid Cases	35				

a. 1 cells (25.0%) have the expected count of less than 5. The minimum expected count is 4.83.
b. Computed only for a 2 x 2 table

c. The standardized statistic is .122.

It can be observed that there is no significant relationship demonstrated between the use of one reference model and mission success/failure (p = 0.9).

The chi-square tests, therefore, demonstrated that only system objectives met formed a critical factor (at the 10% significance level) that contributed to mission success. While the above tests indicated whether each factor contributed individually to mission success, it was also decided that their combined impact would also be investigated, in some combinations or all together, whether or not they contributed to the same.

For this purpose a logit binomial regression model was constructed, because the DV entailed a binary variable. The results have been provided below:

Table 15: Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	11.045	6	.087

Table 16: Classification Table[a]

Observed			Predicted		
			Mission Success or Failure		Percentage Correct
			Failure	Success	
Step 1	Mission Success or Failure	Failure	19	3	86.4
		Success	3	10	76.9
	Overall Percentage				82.9

a. The cut value is .500

It can be observed that the model with one DV (mission) and all seven IV's was significant at the 10% level, since the p value of the Hosmer and Lemeshow goodness of fit test statistic was 0.087 (< 0.1), and the seven IV's together would be able to predict the success of the mission 76.9% of the time (absence of the IV's would enable the prediction of failure 86.4% of the time).

Table 17: Variables in the Equation

Step 1[a]	B	S.E.	Wald	df	Sig.	Exp(B)	95% C.I. for EXP(B)	
							Lower	Upper
TTR(1) DesPr DesPr(1) DesPr(2) Mod(1)	–.903	.868	1.083	1	.298	.405	.074	2.220
			2.078	2	.354			
	–1.701	1.201	2.005	1	.157	.183	.017	1.923
AddDel(1) SysMet(1) ObjMet(1) OneRef(1) Constant	–1.587	1.462	1.178	1	.278	.204	.012	3.592
	2.518	1.602	2.471	1	.116	12.401	.537	286.251
	.324	1.129	.082	1	.774	1.383	.151	12.641
	2.717	1.200	5.128	1	.024	15.132	1.441	158.904
	–1.739	1.179	2.175	1	.140	.176	.017	1.771
	–.291	.887	.108	1	.743	.748	.131	4.252
	.954	1.359	.492	1	.483	2.596		

a. Variable(s) entered on step 1: TTR, DesPr, Mod, AddDel, SysMet, ObjMet, OneRef

From the above table, it can be observed that only system objectives met forms a significant predictor in the model and that the odds of the mission being a success increase by 15 times when the objectives are satisfied compared to when they are not.

CONCLUSION

The overall analysis, therefore, indicates some important facts as summarized below.

Out of the seven factors identified, only system objectives met significantly contributes to mission success with 10% level of significant, and with p values less than 0.1 (p=0.06 and p=0.079 respectively): the likelihood of success increases by as much as 15 times when the objectives are satisfied.

As for testing time reduction, the data indicates that, in general, successful missions have reduced testing time compared to failed mission. Similarly, the data indicates that successful missions face less problems with tools, models, or both and such missions consist of comparatively lesser number of models available for modifications. In addition, it was observed that both ease and difficulty of addition/deletion of components were less for successful missions, and the ratio of mission objectives met to those not met was higher for such missions. In addition, successful missions were found to employ a lesser number of one reference model as compared to failed missions.

This initial work draws on a limited set of responses to a survey. Future work will include more detailed surveys that probe deeper in to the areas identified as being prospectively interesting by this initial study. Work will also focus on the development of tools and processes to facilitate future mission success.

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