FAILURES IN SPACECRAFT SYSTEMS: AN ANALYSIS FROM THE PERSPECTIVE OF DECISION MAKING

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ABBREVIATIONS

SE	Systems Engineering
SME	Subject Matter Expert
AD&C	Attitude Determination and Control
CPT	Cumulative Prospect Theory
sSE	Subsystem Engineer
EPS	Electrical Power Subsystem
ND	Normalization of Deviance

ABSTRACT

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Space mission-related projects are demanding and risky undertakings because of their complexity and cost. Many missions have failed over the years due to anomalies in either the launch vehicle or the spacecraft. Projects of such magnitude with undetected flaws due to ineffective process controls run into unwarranted cost, schedule overruns and account for huge losses. Such failures continue to occur despite the studies on systems engineering process deficiencies and the best systems engineering practices in place. To understand the reasons behind such failures, this work analyses some of the major contributing factors behind majority of space mission technical failures. To achieve this objective, we analyzed the failure data of space missions that happened over the last decade. Based on that information, we analyzed the launch-related failure events from a design decision-making perspective by employing failure event chain-based framework. By analyzing the failure events with this framework, we identify some dominant cognitive biases that might have impacted the overall system performance leading to unintended catastrophes.

The ability of any design team to achieve optimal performance is limited by communication and knowledge deficiencies between highly dissimilar subsystems. These inefficiencies work to *bias* each subsystem engineer to prioritize the utility provided by the subsystem they are responsible for. In order to understand how engineering design decisions are influenced by the presence of cognitive biases, the second part of this study establishes a mathematical framework for utility-based selection based on

Cumulative Prospect Theory. This framework captures the effect of cognitive biases on selection of alternatives by a rational decision-maker.

From the first study, *overconfidence* and *anchoring* biases are identified as the two dominant contributing factors that influenced the decisions behind majority of the failures. The theoretical models developed in the second study are employed to depict the influence of biased decision-making on utility-based selection of alternatives for an earth-orbiting satellite's power subsystem. Predictions from these models show a direct correlation between the decision-maker's biased preference structure and local change in utility curve depicting the (negative) influence of cognitive biases on decision-maker's choice(s).

1. INTRODUCTION

The objective of this thesis is to understand the reasons behind cost, schedule overruns and failures of space missions from Systems Engineering point-of-view. Systems Engineering (SE) encompass both technical and project-management processes, and deficiencies in either or both of them can lead to serious consequences especially in the case of complex, large-scale projects viz., space missions. In an organizational setting, cognitive biases of individuals and/or groups involved can influence individual as well as interactive decisions, and subsequently the project outcomes. To understand such influences, this thesis analyzes some of the failed space missions (due to technical lapses) from the perspective of design decision-making, and based on this information, the organizational *contributing causes* are inferred. A framework to explain the deviance in decision-making is demonstrated based on models for dominant cognitive biases coupled with human decision-making model based on Cumulative Prospect Theory (CPT). Finally, a satellite subsystem design case-study is presented along with the implementation of the aforementioned decision-making framework.

1.1 Systems Engineering

1.1.1 Systems Engineering Process

Systems Engineering is defined as "an interdisciplinary approach that focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing and disposal" [1]. The SE process is iterative in nature and as it progresses, systems engineers gain insights and realize the relationships between the requirements and the properties/outputs of the system(s). Due to the circular causation, where one system variable can be both the cause and effect of another, even the simplest of systems can have unexpected and unpredictable emergent properties [1].

Over the years, numerous systems engineering standards that describe many models of the systems engineering process have been developed. ISO/IEC 15288 *Systems engineering - System life cycle processes*, the lone international standard, establishes a common framework to describe the life-cycle of systems. The purpose in defining the system life cycle is to establish a framework for meeting the stakeholders needs in an orderly and efficient manner [2]. The six life cycle stages include concept, development, production, utilization, support, and retirement as depicted in Figure 1.1.

LIFE CYCLE STAGES	PURPOSE	DECISION GATES
CONCEPT	*Identify stakeholders' needs* *Explore concepts* *Propose viable solutions*	*Decision Options* *– Execute next stage* *– Continue this stage* *– Go to a preceding stage* *– Hold project activity* *– Terminate project*
DEVELOPMENT	*Refine system requirements* *Create solution description* *Build system* *Verify and validate system*	
PRODUCTION	Produce systems Inspect and test [verify]	
UTILIZATION	*Operate system to satisfy users' needs*	
SUPPORT	*Provide sustained system capability*	
RETIREMENT	*Store, archive, or dispose of the system*	

Fig. 1.1.: System life cycle stages (Source: [2])

SE processes comprise of Project management and Technical processes along with Enterprise and Agreement processes as shown in Figure 1.2.

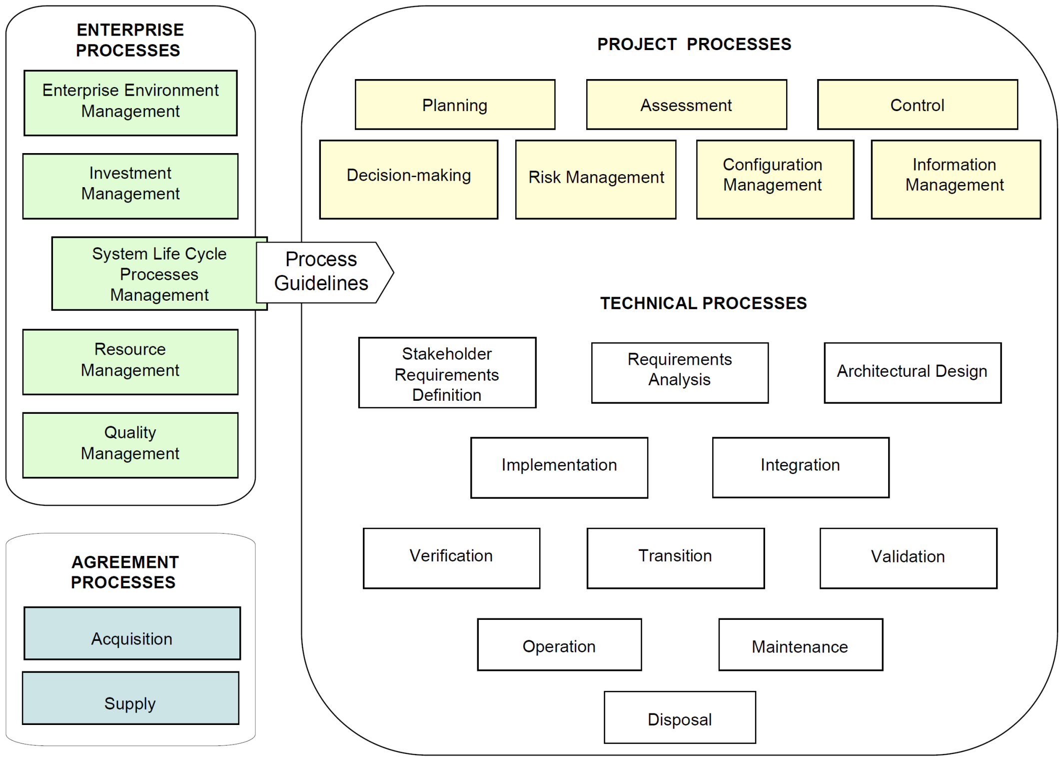


Fig. 1.2.: Systems Engineering processes (Source: [2])

Technical processes are used to establish requirements for a system, to sustain the system through its useful life and to support retirement of the system and consists of: stakeholder requirements definition, requirements analysis, architectural design, implementation, integration, verification, transition, validation, operation, maintenance, and disposal processes [1,2]. The Project Processes are used to establish project plans, control the execution and assess the progress until retirement of the product/service and consists of: planning, assessment, control, decision-making, risk management, configuration management, and information management processes [1,2]. The analysis presented in this work relates the deficiencies in project and technical processes by capturing the failures in technical processes from a decision-making stand-point. The

Enterprise and Agreement processes are business-oriented, involve multiple projects strategies and are not relevant to the nature of analyses presented in this work.

1.2 Decision-Making in Systems Engineering

According to [1], Systems Engineering includes both management and technical processes that depend on good decision-making. Decisions are made throughout the life cycle of every system whenever alternative courses of action exist. Decisions come from many sources and range from programmatic to highly technical. Milestones and decision gates mark the most formal decisions. As the system progresses from early concept definition throughout sustainment, decisions are needed to direct the focus of all personnel toward the desired result. Every decision involves an analysis of the alternative options for eventual selection of a course of action. Figure 1.3 depicts a typical decision-making process in SE context.

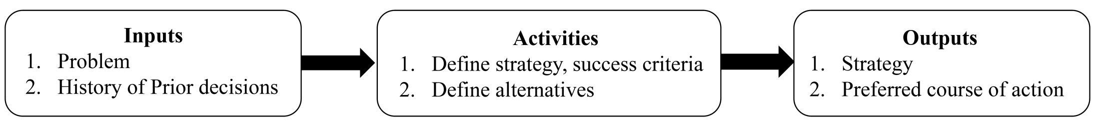


Fig. 1.3.: Decision-making process (modified and taken from [1])

1.2.1 Heuristics and Biases in Decision-Making

Studies have suggested that humans are susceptible to error prone judgments (and decisions) while undertaking tasks with hard deadlines and tight schedules [3,4] and it is well established that biases and heuristics play an important role in decision-making under uncertainty [5]. Teams involved in designing, developing, testing, and validating complex systems make numerous decisions over the course of a project. Several subject matter experts (SMEs), engineers and technicians often exchange information based on these decisions within their teams, with other teams and managers, and with third parties (external contractors, service providers etc.). These decisions include, but are not limited to, choices about feasibility studies, requirements definition, component selection and design, testing, validation and system life-time operations.

Such decisions should be objective and completely unbiased in nature. But it is well established that humans are prone to the biases that originate by being reliant on judgmental heuristics while making decisions under uncertainty [5]. Some common types of cognitive bias that are known to affect decisions include anchoring bias [5], optimism bias [6], confirmation bias [7] and outcome bias [8]. Presence of such biases can influence the outcomes of critical decisions and might lead to phenomena such as 'Normalization of Deviance' as discussed in the next section.

1.2.2 Normalization of Deviance

Normalization of Deviance in organizational setting is identified to be a phenomenon by which the unacceptable becomes acceptable in the absence of adverse consequences [9] and it is usually only with hindsight that people within an organization can realize that their seemingly normal behavior was, in fact, deviant [10]. Vaughan observed this 'deviant' organizational behavior during her study of NASA's culture prior to the Challenger disaster. The unacceptable behavior occurs as a summation of multiple decisions made that had no clear and immediate negative effects.

1.2.3 Gaps in Knowledge and Research Questions

So far, extensive project failure studies are carried out from a Systems Engineering perspective by identifying lapses in the *technical processes* (shown in Figure 1.2). In the SE literature, there is a lack of reasoning behind such failures from the *project processes* stand-point. Among the *project processes*, planning, assessment and control fall under project-specific processes and the rest are life-cycle processes [2]. To understand the human-behavioral patterns behind the causes leading to technical failures, this work presents two studies to analyze the failure reasons from a decision-making process stand-point that apply both inside and outside the project context.

The objective and the research question of the first study is **RQ-1**: *What are the major decision-related contributing factors behind space mission technical failures?*. In approach to answer RQ-1, we analyze space mission failures (during launch and while on-orbit) that happened over the past decade (2009-2019) to figure out the major failure categories. Based on this information, we study ten mission failures in the major failure category for which the post-failure investigation reports are available online. By breaking-down each failure event into its proximate and root cause(s), we infer the contributing factors from human decision-making perspective, taking cues from some of the keywords used to describe cognitive biases and heuristics. Finally, we present some common cognitive biases that are observed from the contributing factors.

With the contributing factors (social and behavioral) behind the failures being identified, the second study focuses on understanding how the presence of cognitive biases is a likely reason for propagation of errors that triggered the failure events. In doing so, we present a quantitative modeling technique based on decision-making under uncertainty to understand how different biases affect the failures. The second study answers the research question **RQ-2**: *How are engineering design decisions influenced due to deviations from rationality (such as presence of cognitive biases)?* and presents: a) an approach to identify some dominating cognitive biases that impacted the decisions behind some of the satellite mission failures b) modeling techniques for bias propagation to explain overconfidence in decision-making under uncertainty.

1.3 Thesis Structure

The failures analysis and biased decision-making studies in this thesis are organized as follows: Chapter 2 presents a review of previous studies done on understanding Systems engineering process deficiencies and human decision-making under uncertainty. Chapter 3 presents the study analyzing satellite failures, contributing and root causes for the failures, dominant cognitive biases behind the root causes and models for cognitive biases. Chapter 4 presents an engineering design case-study depicting the effect of biases as root causes for deviant decision-making. Chapter 5 summarizes the studies of this thesis, and provides directions for future research.

2. LITERATURE REVIEW

This chapter reviews the past literature on SE process deficiencies and engineering decision-making under uncertainty. Section 2.1 identifies a lack of focus on decision-making aspects behind technical failures in systems engineering literature. This sections reviews some large-scale complex projects failure analyses done from the perspective of SE process deficiencies. Section 2.2 presents literature review from design decision-making perspective and the effect of heuristics and biases on individual and group design-making processes.

2.1 Spacecrafts Systems Engineering Deficiencies

Each space mission is a challenging project to undertake which involves numerous complex systems that require high attention to detail, thin design margins followed by thorough testing and inspection procedures. Many missions have failed over the years due to anomalies in either the launch vehicle or the spacecraft. Such (failed) missions with undetected flaws even after rigorous testing and quality control, account for losses in the order of billions of dollars [11]. Understanding the reasons of failure not only benefits the satellite customers but also the tax-payers.

In the past, some studies have shown the statistics of spacecraft failures and analyzed the subsystem-wise failures contribution. Hecht and Fiorentino [12] classified the failure causes into seven categories: Design, Environment, Parts, Quality, Operation, other known, and unknown, and presented historical failure trends according to the causes. Similar studies along with subsystem-wise failure statistics are presented in [13, 14]. Several other studies [15–17] analyzed space mission failures from a Systems Engineering (SE) standpoint and attributed the failure causes to several lapses in the traditional Systems engineering process.

Sorenson and Marais [18] studied project failures across various industries, analyzed the causes by framing them in a "actor-action-object" structure. Johnson [19] discusses the role or organizational culture on mission outcomes, and highlights the importance of human-decision making and the role of social and psychological factors in failures. Causal analysis of failure events include categorizing the failure causes into three classes: proximate causes, root causes, and contributing factors. Johnson [19] points out that "the failure effects and proximate causes are technical, but the root causes and contributing factors are social or psychological" and he emphasizes the importance of performing research to better understand how humans make mistakes and the circumstances that increase our 'natural error rates.'

2.2 Space Mission Failures: Organizational Causes

Cases-studies on Challenger and Columbia space shuttle accidents have been extensively studied and some of the major causes behind the errors that triggered the failure events are found out to be cultural and organizational practices that are detrimental to the reliability of complex space systems. The major organizational causes of the Challenger space shuttle disaster [20] are regarded to be due to groupthink [21] and normalization of deviance [9]. Although the manufacturer of the O-ring is aware of the risk of O-ring malfunction under severe cold conditions, the launch was agreed upon during unfavorable weather conditions owing to normalization of deviance due to absence of adverse consequences till then. Adding to that, over-exaggeration of reliability of the shuttle (actual probability of failure is 1/50 compared to the quoted 1/1000), not providing launch accident escape system because of the incorrect assumption that the shuttle had high reliability [17, 20] resulted in the fatal loss.

The organizational causes of the Columbia space shuttle disaster [17,22] are found to be: a) original compromises that were required to gain approval for the Shuttle, b) years of resource constraints along with fluctuating priorities and schedule pressures, c) reliance on past success as a substitute for sound engineering practices, d) barriers that prevented effective communication of critical safety information, and, e) evolution of an informal chain of command outside the organizations rules. After such serious disasters, one tends to overestimate the occurrence probability of such an event. This type of cognitive bias is called the hindsight bias and is suggested to become an obstacle in the objective analysis of incidents, crashes, collisions or disasters [23].

To analyze the major causes behind space mission failures, we gathered publicly available data on the failure events of space missions that happened over the last decade (2009-2019), from [24–28]. Tables 2.1 and 2.2 present the spacecrafts launch data and mission success/failure details, respectively.

Table 2.1.: Spacecrafts launched during 2009-2019
(Sources: [24–28])

S.No.	**Launch date**	**Launch vehicle**	**Payload(s)**
1	08-Jan-18	Falcon 9 Full thrust	Zuma(USA-280)
2	25-Jan-18	Ariane 5	SES-14, GOLD, Al Yah-3
3	29-Mar-18	GSLC mk II	GSAT-6A
4	20-May-18	Long march 4c	Longjiang-1
5	11-Oct-18	Soyuz-FG	Soyuz MS-10/56S
6	27-Oct-18	Zhuque-1	Weilai 1/Future 1
7	14-Jan-17	SS 520	TRICOM 1
8	25-May-17	Electron	Test flight
9	18-Jun-17	Long march 3B/E	ChinaSat 9A
10	02-Jul-17	Long march 5	Shijian 18
11	14-Jul-17	Soyuz 2.1a/Fregat M	Corvus BC 1,2
12	14-Jul-17	Soyuz 2.1a/Fregat M	Mayak
13	14-Jul-17	Soyuz 2.1a/Fregat M	MKA-N

Table 2.1.: *continued*

S.No.	Launch date	Launch vehicle	Payload(s)
14	27-Jul-17	Simorgh	None
15	31-Aug-17	PSLV-XL	IRNSS-1H
16	28-Nov-17	Soyuz 2.1b/Fregat M	19 satellites
17	26-Dec-17	Zenit-3F/Fregat-SB	AngoSat 1
18	17-Feb-16	H-IIA 202	Hitomi
19	14-Mar-16	Proton-M/Briz-M	Schiaparelli EDM lander
20	23-Mar-16	Atlas-V 401	Multiple payloads
21	31-Aug-16	Long march 4c	Gaofen 10
22	01-Dec-16	Soyuz-U	Progress MS-04/65P
23	28-Dec-16	Long march 2D	Multiple payloads
24	28-Apr-15	Soyuz 2.1a	Progress M-27M/59P
25	16-May-15	Proton-M/Briz-M	Mexsat 1
26	28-Jun-15	Falcon 9 v1.1	Multiple payloads
27	04-Nov-15	SPARK	Multiple payloads
28	05-Dec-15	Soyuz-2-1v/Volga	Multiple payloads
29	27-Feb-14	H-IIA 202	Multiple payloads
30	01-Apr-14	Ariane 5 ECA	Amazonas 4A
31	18-Apr-14	Falcon 9 v1.1	Multiple payloads
32	15-May-14	Proton-M/Briz-M	Ekspress-AM4R
33	01-Jul-14	Soyuz-STB/Fregat	Galileo IOV FM4
34	22-Aug-14	Soyuz-STB/Fregat	Galileo FOC 1,2
35	01-Sep-14	Soyuz-2.1a	Foton M4
36	21-Oct-14	Proton-M/Briz-M	Ekspress-AM6

Table 2.1.: *continued*

S.No.	Launch date	Launch vehicle	Payload(s)
37	28-Oct-14	Antares 130	Cygnus CRS Orb-3
38	15-Jan-13	Rokot/Briz-KM	Kosmos 3 no.s
39	01-Feb-13	Zenit-3SL	Intelsat 27
40	05-May-13	M51	None
41	02-Jul-13	Proton-M/DM-03	3 GLONASS satellites
42	18-Sep-13	VS-30/Improved Orion	Scramspace
43	09-Dec-13	Long march 4B	CBERS-3
44	12-Apr-12	Unha-3	Kwangmyongsong-3
45	07-Mar-12	N/A	SkyTerra1
46	08-Apr-12	N/A	Envisat
47	01-Apr-12	N/A	AMC-16
48	23-Apr-12	VS-30/Orion	HiFire-5
49	01-May-12	N/A	EchoStar I,VI,XI,XIV
50	01-Jun-12	Zenit-3SL	Intelsat 19
51	06-Aug-12	Proton-M/Briz-M	Telkom-3, Ekspress MD2
52	23-Sep-12	N/A	GOES 13
53	08-Oct-12	Falcon 9 v1.0	CRS-1, Orbcomm-2 F1
54	08-Dec-12	Proton-M/Briz-M	Yamal-402
55	12-Dec-12	Unha-3	Kwangmyongsong-3
56	28-Jan-11	Black Brant IX	FIRE
57	01-Feb-11	Rokot/Briz-KM	Kosmos 2470

Table 2.1.: *continued*

S.No.	Launch date	Launch vehicle	Payload(s)
58	05-Feb-11	Black Brant IX	Polar Nox
59	04-Mar-11	Taurus XL 3110	Multiple payloads
60	22-Apr-11	Ariane 5ECA	Yahsat, New Dawn
61	20-May-11	Proton-M/Briz-M	Telstar 14R
62	27-Jul-11	LGM-30G Minuteman III	None
63	11-Aug-11	Minotaur IV lite	HTV-2b
64	17-Aug-11	Proton-M/Briz-M	Ekspress AM-4
65	18-Aug-11	Long march 2C	Shijian XI-04
66	24-Aug-11	Soyuz-U	Progress M-12M/44P
67	01-Sep-11	RIM-161C missile	None
68	08-Oct-11	Black Brant IX	PICTURE
69	01-Oct-11	N/A	Mars Express
70	08-Nov-11	Zenit-2M	Fobos-Grunt, Yinghuo-1
71	01-Nov-11	N/A	DirecTV10
72	23-Dec-11	Soyuz-2.1b/Fregat	Meridian 5
73	15-Apr-10	GSLV mk.II	GSAT-4
74	22-Apr-10	Minotaur IV lite	HTV-2a
75	20-May-10	H-IIA 202	Akatsuki
76	20-May-10	H-IIA 202	Waseda-SAT2
77	20-May-10	H-IIA 202	Hayato
78	20-May-10	H-IIA 202	Shin'en
79	21-May-10	Black Brant IX	DICE

Table 2.1.: *continued*

S.No.	Launch date	Launch vehicle	Payload(s)
80	10-Jun-10	Naro-1	STSAT-2B
81	14-Aug-10	Atlas V 531	USA-214
82	30-Aug-10	S-520	None
83	28-Oct-10	Ariane 5ECA	Eutelsat W3B, BSAT-3b
84	20-Nov-10	Minotaur IV/HAPS	Multiple payloads
85	05-Dec-10	Proton-M/DM-03	Glonass satellites 3 no.s
86	12-Dec-10	Black Brant IX	RENU1
87	25-Dec-10	GSLV mk.I	GSAT-5P
88	23-Jan-09	H-IIA 202	Raijin
89	23-Jan-09	H-IIA 202	Kagayaki
90	23-Jan-09	H-IIA 202	Kukai
91	23-Jan-09	H-IIA 202	Kiseki
92	30-Jan-09	Tsyklon-3	Koronas-Foton
93	24-Feb-09	Taurus XL 3110	OCO
94	24-Mar-09	Delta II 7925-9.5	USA-203
95	02-May-09	SpaceLoft XL	SL3, Discovery
96	21-May-09	Soyuz-2.1a/Fregat	Meridian 2
97	27-Jun-09	Black Brant IX	DICE
98	15-Jul-09	Space shuttle Endeavour	Multiple payloads
99	25-Aug-09	Naro-1	STSAT-2A
100	31-Aug-09	Long march 3B	Palapa-D

Table 2.2.: Type of orbit, launch, separation and payload success (S)/failure (F) details

Mission S.No.	**Orbit**	**Launch**	**Separation**	**Payload**
1	Low-Earth	S	F	N/A
2	Geo	Partial	S	Partial
3	Geo	S	S	F
4	Seleno	S	S	F
5	Low-Earth	F	N/A	N/A
6	Low-Earth	F	N/A	N/A
7	Low-Earth	F	N/A	N/A
8	Low-Earth	F	N/A	N/A
9	Geo	S	S	Partial
10	Geo	F	N/A	N/A
11	Low-Earth	S	S	F
12	Low-Earth	S	S	Partial
13	Low-Earth	S	S	F
14	Low-Earth	F	N/A	N/A
15	Geo	S	F	N/A
16	Low-Earth	F	N/A	N/A
17	Geo	S	S	F
18	Low-Earth	S	S	F
19	Martian Surface	F	S	F
20	Low-Earth	Partial	S	Partial
21	Low-Earth	F	N/A	N/A
22	Low-Earth	F	N/A	N/A

Table 2.2.: *continued*

Mission S.No.	Orbit	Launch	Separation	Payload
23	Low-Earth	Partial	S	Partial
24	Low-Earth	S	F	N/A
25	Geo	F	N/A	N/A
26	Low-Earth	F	N/A	N/A
27	Low-Earth	F	N/A	N/A
28	Low-Earth	S	F	N/A
29	Low-Earth	S	S	F
30	Geo	S	S	Partial
31	Low-Earth	S	S	F
32	Geo	F	N/A	N/A
33	Medium Earth	S	S	F
34	Medium Earth	Partial	S	Partial
35	Low-Earth	S	S	F
36	Geo	Partial	S	Partial
37	Low-Earth	F	N/A	N/A
38	Low-Earth	S	F	Partial
39	Geo	F	N/A	N/A
40	Suborbital	F	N/A	N/A
41	Medium Earth	F	N/A	N/A
42	Suborbital	F	N/A	N/A
43	Low-Earth	F	N/A	N/A
44	Low-Earth	F	N/A	N/A
45	N/A	S	S	Partial

Table 2.2.: *continued*

Mission S.No.	Orbit	Launch	Separation	Payload
46	N/A	S	S	F
47	N/A	S	S	Partial
48	Suborbital	F	N/A	N/A
49	N/A	S	S	F
50	Geo	S	S	Partial
51	Geo	F	N/A	N/A
52	N/A	S	S	Partial
53	Low-Earth	Partial	S	Partial
54	Geo	Partial	S	Partial
55	Low-Earth	S	S	F
56	Suborbital	S	S	F
57	Low-Earth	F	N/A	N/A
58	Suborbital	S	S	F
59	Low-Earth	S	F	N/A
60	Geo	S	S	Partial
61	Geo	S	S	Partial
62	Suborbital	F	N/A	N/A
63	Suborbital	S	S	F
64	Geo	F	N/A	N/A
65	Low-Earth	F	N/A	N/A
66	Low-Earth	F	N/A	N/A
67	Suborbital	F	N/A	N/A
68	Suborbital	S	S	F

Table 2.2.: *continued*

Mission S.No.	Orbit	Launch	Separation	Payload
69	Mars	S	S	F
70	Martian Orbit	S	S	F
71	Geo	S	S	Partial
72	Molniya	F	N/A	N/A
73	Geo	F	N/A	N/A
74	Suborbital	S	S	F
75	Venus	S	S	Partial
76	Low-Earth	S	S	F
77	Low-Earth	S	S	F
78	Heliocentric	S	S	F
79	Suborbital	S	S	F
80	Low-Earth	F	N/A	N/A
81	Geo	S	S	Partial
82	Suborbital	F	N/A	N/A
83	Geo	S	S	F
84	Low-Earth	S	S	Partial
85	Medium Earth	F	N/A	N/A
86	Suborbital	F	N/A	N/A
87	Geo	F	N/A	N/A
88	Low-Earth	S	S	F
89	Low-Earth	S	S	F
90	Low-Earth	S	S	F
91	Low-Earth	S	S	F

Table 2.2.: *continued*

Mission S.No.	Orbit	Launch	Separation	Payload
92	Low-Earth	S	S	F
93	Sun Sync	S	F	N/A
94	Medium Earth	S	S	Partial
95	Suborbital	F	N/A	N/A
96	Molniya	F	N/A	N/A
97	Suborbital	S	S	F
98	Low-Earth	S	S	Partial
99	Low-Earth	S	F	N/A
100	Geo	Partial	S	Partial

2.3 Heuristics and Cognitive Biases in Work-Space

It is well established that biases and heuristics play an important role in decision-making under uncertainty [5]. Further studies have suggested that humans are susceptible to error-prone judgments (and decision) while undertaking tasks with hard deadlines and tight schedules [3, 4]. Previous studies on behavioral economics and decision-making under uncertainty by Kahneman and Tversky [5, 29] pointed out that cognitive biases are resulted from the inability to make rational decisions due to bounded rationality. In [29], they pointed out that heuristic(s)-based approaches of cognitive information processing, especially, when there is a time constraint, constantly suffer from cognitive biases.

Murata *et al.* [23] presented a study based on five accidents to demonstrate the influence of heuristic-based biases, such as groupthink, confirmation bias, overconfidence biases, social loafing and framing biases on decision-making. Reason [30] enumerated judgmental heuristics and biases, bounded rationality and cognitive biases as potential risk factors of human decision-making errors leading to unfavorable or unexpected incidents. Dekker [31] suggested that analyzing accidents without hindsight bias but with foresight in consideration of processes, will aid in proper safety management. Therefore, it is important to understand how cognitive biases can influence critical decisions. However, these studies lack a description of quantitative model of how cognitive biases are related to deviant decision making which can trigger a number of unwarranted accidents.

While there is abundant data on systems failures, existing literature on SE process deficiencies contain satellite failure statistics categorized and analyzed from technical processes perspective and system/sub-system/component wise errors with little emphasis on lapses in project processes and errors that propagated through human decision-making lapses. This work presents an approach to understand how different decision-making errors affect the Systems Engineering technical processes in ways that result in project failures by: a) studying failed space missions to identify the contributing factors behind such failures from a decision-making perspective and, b) presenting modelling techniques for decision-making (based on utility-based selection) under uncertainty under the influence of the contributing factors identified.

3. DEFICIENCIES IN DESIGN DECISION-MAKING

When humans first went to space in the 1950s and 1960s, many space missions failed, leading to the development of processes and technologies to reduce the probability of failure [19]. The introduction of systems engineering, along with other related innovations such as redundancy and environmental testing, generally reduced system failure rates from around 50% to around 5 to 10% for space missions [1,2]. According to [17], a mission is a success if it meets its objectives, requirements, budget and schedule, and a failure otherwise.

Space mission-related projects are demanding and risky undertakings because of their complexity and cost. Many missions have failed over the years due to anomalies in either the launch vehicle or the spacecraft. Projects of such magnitude with undetected flaws due to ineffective process controls account for huge losses. Such failures continue to occur despite the studies on systems engineering process deficiencies and the state-of-the-art systems engineering practices in place. To further explore the reasons behind majority of the failures, we analyzed the failure data of space missions that happened over the last decade as detailed in the following sections.

3.1 Spacecraft Failures Analysis

To analyze the statistics of space mission failures, we gathered publicly available data about the failure events of space missions that happened over the last decade (2009-2019), from [24–28]. The data presented in Section 2.2 (refer to Tables 2.1 and 2.2) includes a total of 91 commercial, experimental and scientific-purpose launches by several countries. For the purpose of this study, we broadly classify failures into two categories: Launch vehicle-related failures and Payload-related failures. Launch vehicle-related failures are further categorized into payload-fairing separation failures and other failures which includes partial failures and failures due to other sub-system anomalies. Launches which resulted in a loss of performance without a significant mission loss are included under partial failures. Such cases attained mission success despite some launch issues. Payload failures are categorized into on-orbit and partial failures after separating the payloads lost during the launch phases (and before reaching the intended orbits).

Figure 3.1 highlights the launch vehicle-related failures statistics: 38 missions out of a total 91 have successful launches, and the remaining 53 missions have launch vehicle related anomalies. Out of the 53 launch anomalies, 8 missions failed due to fairing separation issues and 8 missions achieved partial success. A total of 37 missions failed at the launch stage due to other sub-system related issues. Figure 3.2 depicts the failure statistics of 100 payloads that are aboard the 91 missions: 44 payloads are lost during the launch and separation stages (before reaching the orbit), 32 payloads failed while being on-orbit and 24 payloads suffered partial failures.

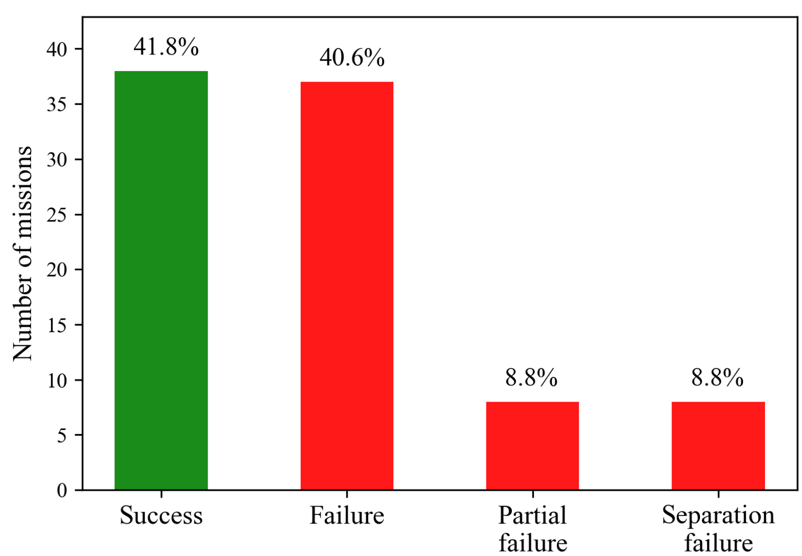


Fig. 3.1.: Launch vehicle related failure statistics in the last decade (2009 to 2019)

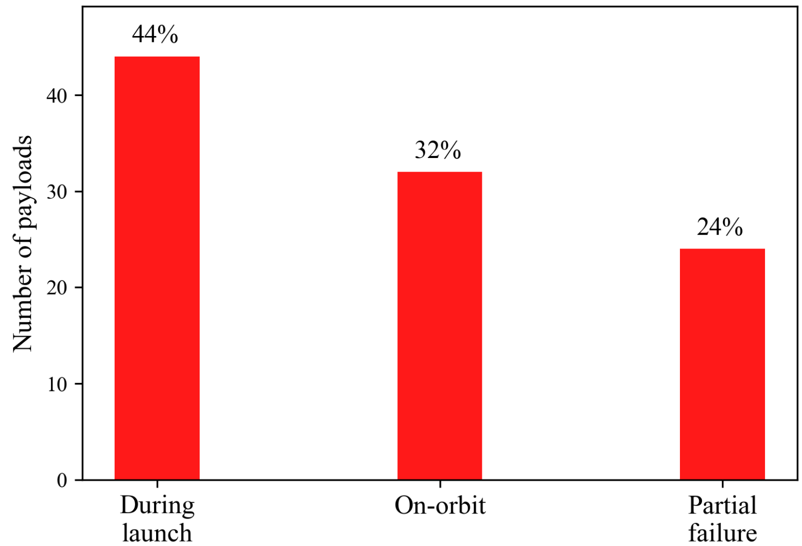


Fig. 3.2.: Payload failure statistics in the last decade (2009 to 2019)

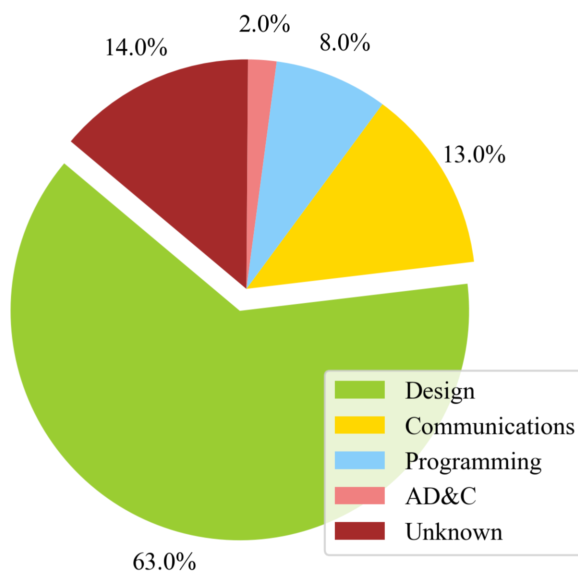


Fig. 3.3.: Break-down of space-mission failures (2009 to 2019)

All the failure cases are further analyzed and the category-wise statistics are shown in Figure 3.3. The "Design" category, which accounts for 63% of all failures, covers all the cases that failed due to design-related errors in power, propulsion, engine, structures and thermal subsystems. Very few cases with anomalies in Communications, AD&C (Attitude Determination and Control) subsystems are reported along-side some missions with programming errors. As apparent from the failure data, majority of the projects suffered from design related issues. Such design-related failure events are further studied to understand the human decision-making aspects behind some of the failure-causing design decisions.

3.1.1 Framework

Previous studies on mission failures have identified problems and patterns of causation in accidents [18]. While some studies [11–14] presented the failure statistics, others [15, 16] analyzed the problems from a systems engineering point-of-view and to the best of the authors' knowledge, none of the studies attempted to explore the failure events from a decision-making perspective. In this study, we present an approach to analyze the failures from a decision-making point of view by following the failure event chain based framework, as depicted in [19].

According to Johnson [19], 'culture' is an ambiguous term "that covers a lot of ground, including patterns of human knowledge, beliefs, behaviors, and social forms." To understand such human-behavioral patterns behind the causes leading to technical failures, he presented a failure event chain (shown in Figure 3.4) with contributing factors as the starting point towards system failures. Based on this, we analyzed a set of ten missions that failed catastrophically due to design flaws for which the failure-investigation reports are publicly available online. These missions had undetected design flaws that resulted due to management overconfidence, poor quality control, unskilled labor, inadequate design margins, uncontrollable manufacturing process etc., and are briefly discussed in the following section.

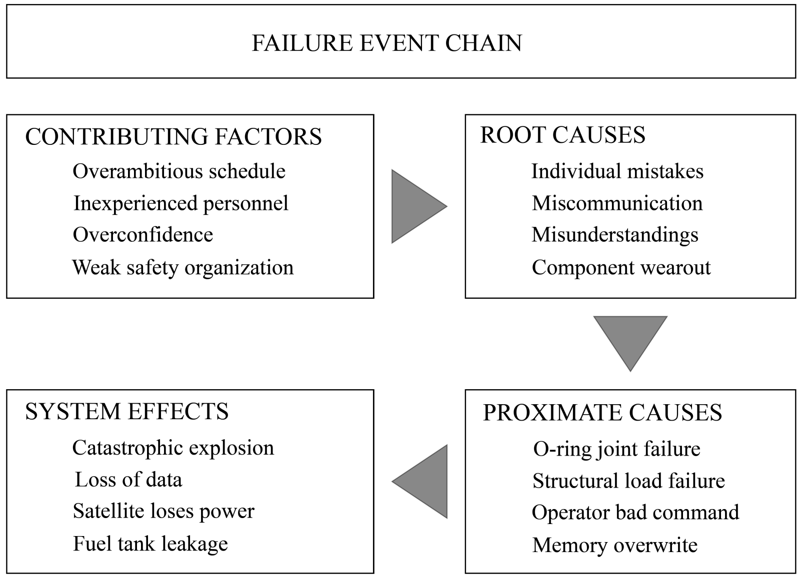


Fig. 3.4.: Failure event chain as depicted in [19]

3.1.2 Analysis of a Set of Failures

Acquiring detailed information on space mission failures is difficult, in general, and the organizations involved carry out investigations at their own discretion. From publicly available resources [24–28], we are able to extract failure-causation information of all the missions that took place over the last decade. Table 3.1 illustrates these failure events that include catastrophic failures during the launch stages which destroyed the launch vehicles and the payloads well before orbital-insertion. Every mission number corresponds to the mission details presented in Table 2.1.

Table 3.1.: Failure causes of the space missions
(Sources: [24–28])

Mission S.No.	Type of issue	Failure cause(s)
1	Separation	Payload adapter didn't separate

Table 3.1.: *continued*

Mission S.No.	Type of issue	Failure cause(s)
2	Programming	Satellites were placed on an off-nominal orbit and were corrected
3	Power	Loss of communication, power failure
4	Unknown	Unknown
5	Engine	Launch vehicle boosters failure
6	Design	Issue with third stage
7	Communication	Contact lost after 20 seconds
8	Programming	Terminated after error in ground tracking equipment
9	Programming	Payload inserted into wrong orbit; corrected after 16 days
10	Engine	Engine anomaly happened in the first stage
11	Engine	Later found to be fault in Fregat's first stage engine-spill of hydrazine
12	Structures	Failed to deploy solar reflector
13	Engine	Later found to be fault in Fregat's first stage engine-spill of hydrazine
14	Unknown	Unknown
15	Separation	Fairing didn't separate
16	Programming	Upper stage programming failure lead to loss of 19 satellites
17	Communication	Contact lost after launch
18	AD&C	Lost attitude control and snapped off solar array
19	Design	Upper stage of Briz-M exploded after separation

Table 3.1.: *continued*

Mission S.No.	**Type of issue**	**Failure cause(s)**
20	Engine	Early cut-off of Atlas-V booster engine due to an anomaly in the mixture ratio control valve assembly
21	Unknown	Unknown
22	Unknown	Unknown
23	Design	Satellites deployed in a lower orbit due to launch vehicle problem
24	Separation	Separation failure during launch; lost attitude control and communications soon after; declared total loss
25	Engine	Excessive vibration due to turbo-pump shaft coating degradation caused Proton's third stage engine failure
26	Structures	Vehicle disintegrated after helium tank support strut failure caused helium tank to break through second stage tanks
27	AD&C	After a minute into the launch, vehicle lost attitude control
28	Separation	One of the two satellites failed to separate from the Volga upper stage
29	Communication	One of the satellites (ITF-1) failed to communicate

Table 3.1.: *continued*

Mission S.No.	Type of issue	Failure cause(s)
30	Power	Amazonas 4A suffered a power-subsystem malfunction shortly after launch, which resulted in a permanent reduction in the satellites capacity and a reduced operational life
31	Separation	KickSat failed to separate
32	Structures	Turbo-pump structural support failure caused damage to the oxidizer inlet line; third stage thruster failed, as a result
33	Power	Permanent power failure of Galileo FM4 after it suffered a temporary power loss
34	Engine	"Spacecraft in incorrect orbit due to an interruption of the Fregats upper stage attitude control thrusters when its hydrazine propellant supply became frozen by a cold helium feed line incorrectly routed close to it"
35	Communication	Shortly after reaching orbit, the satellite suffered a communications problem and failed to raise its orbit
36	Unknown	Upper stage under performance resulted in lower than planned deployment orbit
37	Design	Rocket crashed near launch pad due to first stage failure
38	Separation	Loss of one satellite caused by Briz-KM's failure during separation

Table 3.1.: *continued*

Mission S.No.	**Type of issue**	**Failure cause(s)**
39	Engine	Loss of engine gimbal control due to failure of the first stage hydraulic power supply unit pump
40	Design	Test flight launch failure
41	Design	Incorrectly installed angular velocity sensors; first stage guidance failure lead to rocket crash
42	Design	Launch vehicle first stage failure
43	Design	Third stage shutdown 11 seconds too early
44	Design	Launch vehicle first stage failure
45	Structures	Initial deployment of the dish antenna failed; fully deployed after several attempts
46	Circuit	Satellite went to safe mode after the loss of the power regulator, blocking telemetry, telecommands and short circuit
47	Circuit	Another circuit failure on AMC-16 was experienced in early April 2012
48	Engine	Launch vehicle second stage failed to ignite
49	Power	Failure of multiple TWTAs and failure of solar array circuits which reduced design life
50	Structures	Initial deployment of second solar panel failed after launch; damaged after full deployment
51	Design	7 seconds into its third burn, Briz-M stage failed

Table 3.1.: *continued*

Mission S.No.	Type of issue	Failure cause(s)
52	Design	Satellite GOES-13 (East) suffered from a obstructed spinning motion of the filter wheel due to a lubricant build-up caused by motor vibration; satellite service restored on 18-October-2012
53	Engine	Orbcomm payload placed in a lower orbit due to first stage engine failure
54	Design	Briz-M stage failure on its fourth burn
55	Design	Satellite reached orbit but malfunctioned thereafter
56	Unknown	Unknown
57	Programming	Reached lower-than-planned orbit as the flight software caused upper stage malfunction
58	Unknown	Unknown
59	Separation	Fairing didn't separate
60	Structures	Failed deployment of New Dawn's C-Band antenna
61	Power	Tangled cable caused second solar panel deployment failure
62	Unknown	Test flight launch failure
63	Communication	Loss of contact approximately 20 minutes after launch

Table 3.1.: *continued*

Mission S.No.	Type of issue	Failure cause(s)
64	Programming	Loss of attitude control due to error in time-slot allocation for re-setting the gyroscopes of the upper stage control system
65	Structures	Loss of attitude control due to failure of second stage's vernier engine support structure
66	Engine	Gas generator fuel supply pipeline blocked by contaminants; third stage engine failure after launch
67	N/A	Intercept failed after the launch
68	Unknown	Unknown
69	Circuit	Connection problem between the power conditioning unit and the solar arrays
70	Design	Telemetry lost soon after the launch due to usage of cheap parts, design shortcomings, and lack of pre-flight testing; spacecraft stranded in low Earth orbit
71	Engine	Satellite's position maintaining propulsion system temporarily ceased to function
72	Engine	Failed to reach orbit due to third stage engine malfunction
73	Engine	Third stage failure
74	Communication	Loss of contact, nine minutes after launch

Table 3.1.: *continued*

Mission S.No.	Type of issue	Failure cause(s)
75	Unknown	During Cytherocentric orbit insertion, Akatsuki malfunctioned and failed to enter orbit. It managed to orbit around Venus five years later
76	Communication	Contact loss between Waseda-SAT2 and ground
77	Communication	Hayato affected by communications problems, lost contact with Shin'en on 21 May
78	Communication	Unknown
79	Unknown	Unknown
80	Separation	Exploded during first stage burn
81	Propulsion	During orbital insertion process, liquid apogee motor of Atlas V 531 failed to operate
82	Unknown	Failed to conduct high-voltage control experiments as planned
83	Propulsion	An oxidizer leak in the Eutelsat W3B's main propulsion system lead to total loss of the satellite after launch
84	Separation	Immediate deployment of NanoSail-D2 from FASTSAT failed, but, ejection was confirmed later
85	Design	Incorrect fuelling of upper stage led to mass being too large to achieve parking orbit
86	Unknown	Unknown
87	Engine	Disintegrated during first stage flight; destroyed after loss of control over liquid-fueled boosters

Table 3.1.: *continued*

Mission S.No.	Type of issue	Failure cause(s)
88	Communication	Following electromagnetic boom deployment, Raijin failed to respond to ground commands
89	Communication	Kagayaki failed to contact ground
90	Structures	Failed STARS tether deployment
91	Communication	Kiseki failed to respond to ground commands
92	Power	Loss of satellite signal in early December 2009 due to malfunction of power sub-system; declared a total loss in April 2010
93	Separation	Failed to reach orbit due to failed payload fairing separation
94	Communication	Decommissioned after 2 years; designed to last for 10 years
95	Programming	Failed to reach orbit due to premature payload separation
96	Programming	Propellant depletion during second burn in an attempt to compensate using Fregat when core vehicle second stage got shut down five seconds early
97	Unknown	Unknown
98	Separation	AggieSat 2 and BEVO-1 satellites failed to separate from each other
99	Separation	Failed to reach orbit due to failed payload fairing separation

Table 3.1.: *continued*

Mission S.No.	**Type of issue**	**Failure cause(s)**
100	Propulsion	Gas generator burn through; third stage failed during restart

For the purposes of this study, we selected ten missions from the above table for which mission investigation reports are available online and Table 3.2 illustrates the failure events data of these ten missions along with their launch dates, gathered from the respective references mentioned against each mission. These references include publicly accessible websites with information from the respective mission investigation reports and publicly released mission investigation reports.

We studied each failure event in detail, to identify the proximate cause(s), root cause(s) and the contributing factor(s). According to [17, 19], a *proximate cause* is defined as "a factor that directly led to the failure", a *root cause* is "a systemic factor that caused or created conditions leading to the failure" and a *contributing factor* is "something that worked to allow or make more likely the failure." In the following section, we present the approach used to isolate the proximate, root causes and contributing factors for the failure events of the ten missions considered here.

Table 3.2.: Spacecraft launch failure events

S.No.	**Launch date**	**Vehicle and Payload(s)**	**Failure event**	**Ref.**
1	16-May-2015	Proton-M/Block DM-03 with MexSat-1	"Third stage steering engine failed due to intense vibrations caused by an increasing imbalance in the rotor inside the engines turbo-pump."	[32]
2	02-July-2013	Proton-M/Block DM-03 with three GLONASS satellites	"Critical angular velocity sensors installed upside down causing the vehicle to swing wildly and, ultimately, crash."	[33]
3	01-February-2013	Zenit-3SL/Block DM-SL with Intelsat-27	"Poor manufacturing processes and quality control lead to the failure of Zenit-3SL first stage hydraulic power supply unit."	[34]
4	08-December-2012	Proton-M/Briz-M with Yamal-402	"Launch anomaly was due to a combination of adverse conditions which affected the operation of the Briz-M main engine during the start-up of the third burn."	[35]

Table 3.2.: *continued*

S.No.	**Launch date**	**Vehicle and Payload(s)**	**Failure event**	**Ref.**
5	06-August-2012	Proton-M/Briz-M with Telkom-3 and Ekspress-MD2	"Accident had been caused by a component of the pressurization system that was not manufactured to specifications."	[36]
6	24-August-2011	Soyuz-U with Progress M12-M	"A blocked duct due to a random production defect cut the fuel supply to the Soyuz-U's third-stage, causing its engine to shut down prematurely."	[37]
7	18-August-2011	Proton-M/Briz-M with Ekspress-AM4	"Inertial coordinate system on-board Briz-M upper stage failed due to a programming error between third and fourth firing and left the satellite in a wrong orbit."	[38]
8	04-March-2011	Taurus XL with Glory	"Payload fairing didn't separate as expected due to failed frangible joints."	[39]

Table 3.2.: *continued*

S.No.	Launch date	Vehicle and Payload(s)	Failure event	Ref.
9	05-December-2010	Proton-M/Block DM-03 with three GLONASS satellites	"Launch went wrong 10 minutes after take-off due to a miscalculation during the fueling of Block DM-03 upper stage, which received 1,582 kilograms of extra liquid oxygen above the maximum allowable limit."	[40]
10	24-February-2009	Taurus XL with OCO	"The OCO mission was lost in a launch failure when the payload fairing of the Taurus launch vehicle failed to separate during ascent."	[41]

3.1.3 Analysis Approach

For each mission in Table 3.2, we have studied the failure events, extracted the proximate, root causes and construed the contributing factors based on the definitions given above. We demonstrate our approach using the Proton-M launch failure that happened on 02-July-2013 (S.No. 2 in Table 3.2). From the mission investigation report details as mentioned in [33], we extracted the following statements with information about the failure causes:

1. "Each of those sensors had an arrow that was supposed to point towards the top of the vehicle, however multiple sensors on the failed rocket were pointing downward instead. As a result, the flight control system was receiving wrong

information about the position of the rocket and tried to correct it, causing the vehicle to swing wildly and, ultimately, crash."

2. "Trail led to a young technician responsible for the wrong assembly of the hardware."

3. "It appeared that no visual control of the faulty installation had been conducted, while electrical checks could not detect the problem since all circuits had been working correctly."

4. "Along with a human error, the investigation commission identified deficiencies in the installation instructions and in the mechanical design of the hardware, which both contributed to the problem. For example, the mounting plate lacked an arrow which would match the direction of an arrow on the DUS unit."

The *proximate* and the *root causes* as inferred from the above statements are:

1. *Proximate cause*: "Flight control system was receiving wrong information about the position of the rocket" and an attempt to correct it caused the failure, ultimately.

2. *Root cause*: The flight control system was receiving incorrect information about the rocket's position because "multiple (angular velocity) sensors on the rocket were pointing downward" which were "supposed to point towards the top of the vehicle."

With the proximate and root causes being known, we finally extracted the following statements with information about the contributing factors:

1. "Trail led to a young technician responsible for the wrong assembly of the hardware."

2. "It appeared that no visual control of the faulty installation had been conducted, [...]"

3. “Along with a human error, the investigation commission identified deficiencies in the installation instructions and in the mechanical design of the hardware, which both contributed to the problem.”

We followed a similar procedure to isolate the proximate and root causes of all the ten missions and the data is presented in Table 3.3.

Table 3.3.: Failures root cause analysis [42]

S.No.	**Proximate cause(s)**	**Root cause(s)**	**Information about contributing factor(s)**
1	Failure of third stage steering engine	Intense vibrations caused by an increasing imbalance in the rotor inside the engine’s turbo-pump	Usage of cheap materials caused rotor material degradation at higher temperatures and hence, the imbalance
2	Flight control system was receiving wrong information about the position of the rocket	Critical angular velocity sensors installed upside down	Installation by an unskilled technician with improper installation instructions document followed by poor inspection
3	Hydraulic oil supplied to the main engine gimbal actuators not pressurized properly	Abnormal performance of the pump due to manufacturing issues	Factors associated with a pump manufacturing process that proved difficult to control

Table 3.3.: *continued*

S.No.	**Proximate cause(s)**	**Root cause(s)**	**Information about contributing factor(s)**
4	Main engine failure during the start-up of the third burn	Accumulation of large volume of oxidizer gas at the engine inlet, exceeding the main engine specifications	Inadequate thermal requirements definition followed by adverse thermal conditions at the lift-off
5	Main engine shut-down by flight control system	Blocked pressurization line in the auxiliary propellant tank	Component of the pressurization system that was not manufactured to specifications
6	Premature shut-down of third stage engine	A blocked duct caused reduced fuel consumption in the gas generator of the third stage	Usage of defective fuel duct
7	Upper stage inertial coordinate system failed between third and fourth firing	Inertial reference frame lost as the intermediate gimbal ring got stuck at the gimbal limit	Time allotted for the delta rotation was incorrectly entered in the flight program

Table 3.3.: *continued*

S.No.	Proximate cause(s)	Root cause(s)	Information about contributing factor(s)
8	Payload fairing of the launch vehicle failed to separate	Failed frangible joints due to ’not-so tightly controlled’ manufacturing processes	Did not consider all flight environmental effects and the system performance margins were not updated accordingly
9	Launch fail due to extra mass of the propellant	Miscalculated the amount of fuel needed to be loaded into the rocket booster; exceeded the norm by 1-1.5 tons	Propellant filled-in according to old instructions and necessary pre-launch safety procedures were not carried out
10	Payload fairing of the launch vehicle failed to separate	Possible subsystem failures: Frangible Joints, Electrical and Pneumatic	Unable to determine a direct cause that lead to the fairing malfunction

3.1.4 Contributing Factors

Based on the information presented in Table 3.3, we identify the social and/or psychological contributing factors that increased the likelihood of error propagation through different phases of systems engineering. For the example mission described in Section 3.1.3, the following two statements provide details of the possible contributing factors (shown as bold text):

1. "It appeared that **no visual control of the faulty installation had been conducted**, while electrical checks could not detect the problem since all circuits had been working correctly."

2. "Along with a human error, the investigation commission identified **deficiencies in the installation instructions and in the mechanical design of the hardware**, which both contributed to the problem."

Such anomalies, mishaps, and eventual failures are possible results of lapses in team and/or human decision-making and are studied further as described in the following section.

3.2 Decision-Making Under Uncertainty and Cognitive Biases

According to [1], systems engineering includes both management and technical processes that depend on good decision-making and decisions are made throughout the life cycle of every system whenever alternative courses of action exist and, every decision involves an analysis of the alternative options for eventual selection of a course of action. Teams involved in designing, developing, testing, and validating complex space systems make numerous decisions over the course of a project.

Several SMEs, engineers and technicians often exchange information based on these decisions within their teams, with other teams and managers, and with third parties (external contractors, service providers etc.). These decisions include, but are not limited to, choices about feasibility studies, requirements definition, component selection and design, testing, validation and operations covering launch, deployment and re-entry phases. Such decisions should be objective and completely unbiased in nature. But, it is well established that humans are prone to the biases that originate by being reliant on judgmental heuristics while making decisions under uncertainty [5]. Some common types of cognitive bias that are known to affect decisions include anchoring bias [5], optimism bias [6], confirmation bias [7] and outcome bias [8]. These biases are briefly explained below:

1. *Anchoring bias*: The tendency to get "anchored" to a particular piece of information that one may have acquired for the first-time, or, to an expected result, when making decisions.

2. *Optimism bias*: "The tendency to overestimate the likelihood of positive events, and underestimate the likelihood of negative events". This bias is caused due to Representativeness heuristic, leads to overconfidence in results and a phenomenon called 'Normalization of deviance' [9].

3. *Confirmation bias*: The tendency to seek or interpret an evidence in ways that are partial to existing beliefs, expectations, or a hypothesis in hand which leads to 'overconfidence' in one's actions.

4. *Outcome bias*: The tendency to support a decision with favorable outcome over a decision with unfavorable outcome instead of the quality of the decision itself.

With this information about cognitive biases being known, we studied the contributing factors further in-depth, to identify any potential biases that might have initiated the anomalies or errors that ultimately lead to the aforementioned failures. Following from Section 3.1.4, the contributing factors are analyzed (as described below) by identifying the probable reasons and attributing some possible biases to explain the deviant behavior of the agents (managers, engineers, technicians etc.) and/or that of the firms involved in the mission.

1. *Contributing factor*: Lack of visual control of installations
   Reasons: Overconfidence and anchored to previous quality control procedures

2. *Contributing factor*: Improper/outdated/ambiguous hardware design, installation instructions
   Reasons: Lack of knowledge, overconfidence and anchored to previous designs and installation manuals

Following a similar procedure for the other nine projects, we inferred the possible biases that would have affected the decisions of the concerned individuals. Table 3.4

lists the contributing factors and the biases for corresponding root causes of the ten missions under consideration.

Table 3.4.: Contributing factors analysis [42]

S.No.	**Information about contributing factor(s)**	**Contributing factor(s)**	**Dominant Reasons**
1	Usage of cheap materials caused rotor material degradation at higher temperatures and hence, the imbalance	Usage of cheap materials, ineffective quality control	1. Anchoring bias 2. Normalization of deviance (Optimism bias)
2	Installation by an unskilled technician with improper installation instructions document followed by poor inspection	Improper technical manuals, unskilled technician, ineffective quality control	1. Anchoring bias 2. Overconfidence (Optimism bias)
3	Factors associated with a pump manufacturing process that proved difficult to control	Uncontrollable manufacturing process, ambitious requirements	Normalization of deviance (Optimism bias)
4	Inadequate thermal requirements definition followed by adverse thermal conditions at the lift-off	Inadequate requirements definition, inadequate safety margin	1. Anchoring bias 2. Overconfidence (Optimism bias)

Table 3.4.: *continued*

S.No.	**Information about contributing factor(s)**	**Contributing factor(s)**	**Dominant Cognitive Bias(es)**
5	Component of the pressurization system that was not manufactured to specifications	Component manufacturing specifications not met, poor quality control	1. Anchoring bias 2. Normalization of deviance (Optimism bias)
6	Usage of defective fuel duct	Production line defect, poor quality control	Overconfidence (Optimism bias)
7	Time allotted for the delta rotation was incorrectly entered in the flight program	Programming error, lack of program checks	Overconfidence (Optimism bias)
8	Did not consider all flight environmental effects and the system performance margins were not updated accordingly	Poor manufacturing process control, system performance margins not updated	1. Overconfidence (Optimism bias) 2. Normalization of deviance (Optimism bias)

Table 3.4.: *continued*

S.No.	Information about contributing factor(s)	Contributing factor(s)	Dominant Cognitive Bias(es)
9	Propellant filled-in according to old instructions and necessary pre-launch safety procedures were not carried out	Pre-launch safety procedures not carried out, outdated operational documentation	1. Overconfidence (Optimism bias) 2. Normalization of deviance (Optimism bias)
10	Unable to determine a direct cause that lead to the fairing malfunction	Poor quality control and inspection processes	Overconfidence (Optimism bias)

From Table 3.4, it is observed that *anchoring bias* and *overconfidence* are the dominant decision-making biases behind majority of the failure events. To study the effect of these biases on decision-making under uncertainty, we present a model based on Cumulative Prospect Theory (CPT) in the next section. The model is used to demonstrate the impact of cognitive biases on selection of alternatives in Chapter 4, with the help of a satellite power subsystem design case-study.

3.2.1 Model for Utility-Based Selection

Each stage in engineering design process involves multiple decisions that needs to be made. Decision making in engineering design is a field that has been extensively studied and tools have been developed that aid designers in making decisions at each step in the design process. Decision making in engineering design has been proposed and studied as a utility-based selection decision support problem that looks at decision making as a practical process based on mathematical axioms [43].

For a long time, expected utility theory [44, 45] prevailed as a dominant normative and descriptive model for decision-making under uncertainty which involves: a) assigning appropriate utility to each possible consequence, b) calculating expected utility of each alternative and c) selecting the alternative with the highest expected utility. The steps involved in a typical decision-making process can be represented by a flow chart as shown in Figure 3.5 where, A_i denotes the i^{th} alternative, X_{ij} denotes the j^{th} outcome of i^{th} alternative with probability p_{ij} and $U(.)$ is the utility function under consideration.

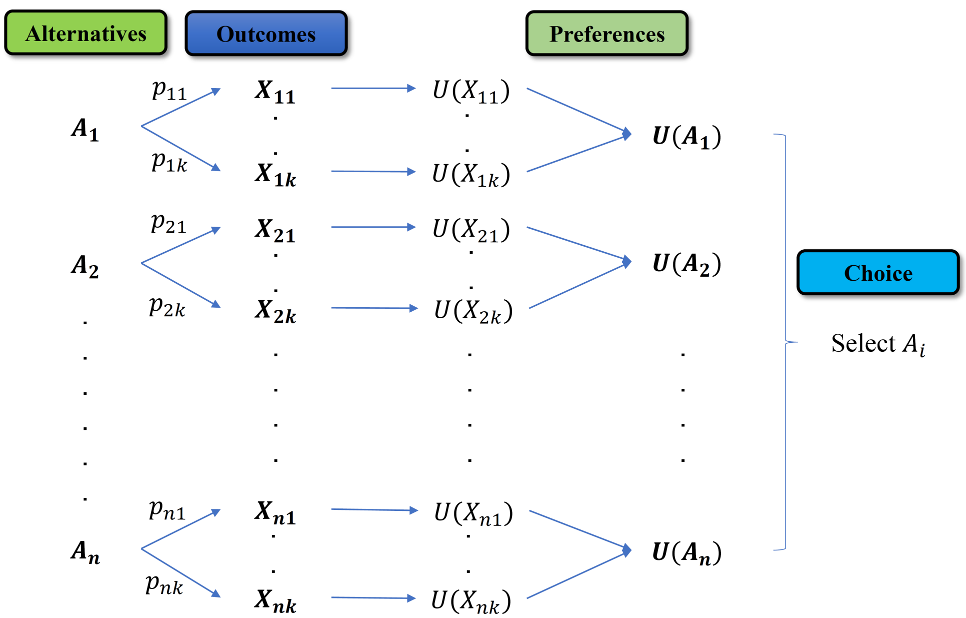


Fig. 3.5.: Typical decision-making process

It is well established that the expected utility theory does not provide an adequate description of individual choice and the major phenomena that violate the normative theory of expected utility maximization are framing effects, non-linearity of preferences in terms of probabilities, source dependence, risk seeking and loss aversion [46].

Decision-making under uncertainty modelling starts with the introduction of Kahneman and Tversky's *Cumulative Prospect Theory*. In the 1970s, Kahneman and Tversky developed *Prospect Theory* for decision-making under uncertainty [47]. In order to be consistent with first-order stochastic dominance, the theory was further developed by Tversky and Kahneman into *cumulative prospect theory* [46]. In the context of utility-based decision-making and selection, the key elements of CPT are:

- People behave differently on gains and on losses; they are not uniformly risk averse and are distinctively more sensitive to losses than to gains, and
- People tend to overweight low probabilities and underweight moderate to high probabilities

These elements translate into these technical features of the CPT used to assess utilities of alternatives under uncertainty: a) a *reference point* in wealth that defines gains and losses, b) a *value function* that is concave for gains and convex for losses, and, c) a *probability weighting function* that is a non-linear transformation of probability measure, which inflates a small probability and deflates a large probability. Based on these features, the CPT utility of an alternative A with random (uncertain) outcome X and reference point B is given by [48]:

$$U(A) = \int_{B}^{\infty} v_{+}(x-B)\frac{d}{dx}(-w_{+}(1-F(x)))dx - \int_{-\infty}^{B} v_{-}(B-x)\frac{d}{dx}(w_{-}(F(x)))dx \quad (3.1)$$

where,

$$\begin{aligned} U(A) &= \text{Utility of alternative } A \\ F(.) &= \text{Cumulative distribution function (CDF) of } X \\ v_{+}(.) &= \text{Value function for gains} \\ v_{-}(.) &= \text{Value function for losses} \\ w_{+}(.) &= \text{Probability weighing function for gains} \\ w_{-}(.) &= \text{Probability weighing function for losses} \end{aligned}$$

The value functions ($v_+(.)$, $v_-(.)$) mapping from $\mathbb{R}_+$ to $\mathbb{R}_+$ measure gains and losses respectively and the weighing functions ($w_+(.)$, $w_-(.)$) mapping from $[0, 1]$ to $[0, 1]$ represent the decision-makers weighting of probability for gains and losses respectively. Tversky and Kahneman [46] propose the following functional forms for these functions and are given as follows:

$$v_+(x) = x^\alpha \tag{3.2}$$

$$v_-(x) = \lambda x^\beta \tag{3.3}$$

$$w_+(p) = \frac{p^\gamma}{(p^\gamma + (1-p)^\gamma)^{1/\gamma}} \tag{3.4}$$

$$w_-(p) = \frac{p^\delta}{(p^\delta + (1-p)^\delta)^{1/\delta}} \tag{3.5}$$

The parameter values are estimated from experiments and are given as follows: $\alpha = \beta = 0.88$, $\gamma = 0.61$, $\delta = 0.69$ and $\lambda = 2.25$. With the decision-making model being set, the next section presents models for the dominant cognitive biases identified from Table

3.2.2 Modeling the Dominant Biases

It is well established that cognitive biases and heuristics impact decisions taken under uncertain conditions [5]. Previous studies on these biases have focused on their modelling aspect and impact on a single parameter judgment rather than on judgments involved in a complex project (spacecraft design, for example).

In this work, we set out to understand the decision-making lapses that triggered the failure events of some of the spacecrafts. From Table 3.4, it can be observed that anchoring bias and optimism bias are the dominant cognitive biases behind majority of such failure events. Decisions made with such biases can lead to unwarranted overconfidence and phenomena such as *Normalization of Deviance*, which is the tendency to accept risks as normal until a failure happens [9] in the absence of immediate failures. Some of the decision-making, belief and behavioral biases along with the ones modeled in the current study are presented in Figure 3.6. In this section, we present the two models for the most dominant decision-making bias - *overconfidence*, taken from literature assuming that the decision-maker's beliefs are Gaussian.

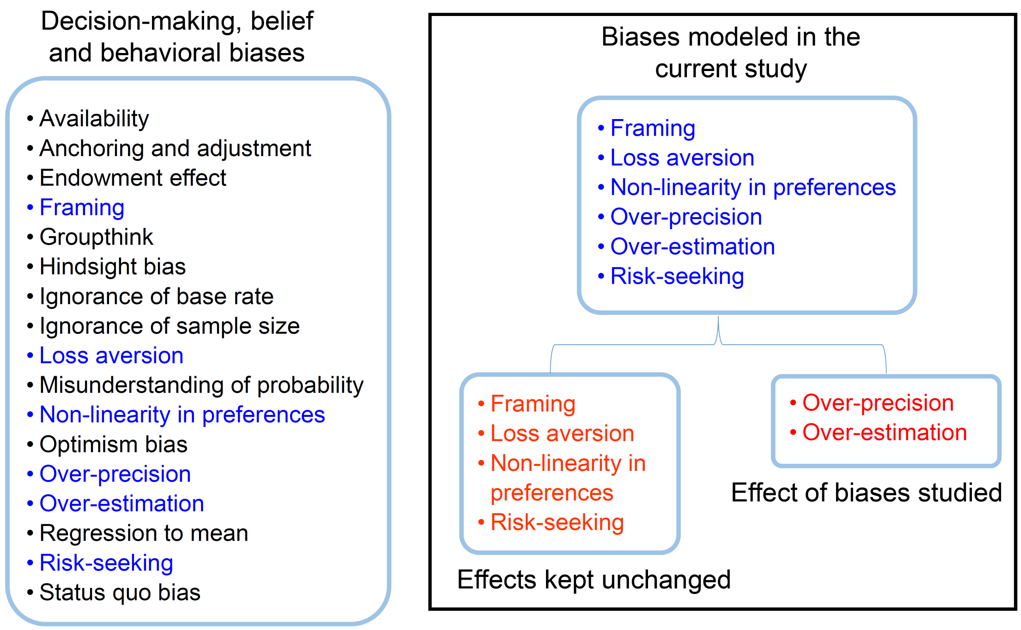


Fig. 3.6.: Biases modeled in this study

Overconfidence

According to [49], people use information about their ability to choose tasks and overestimation of ability raises utility by misleading people into believing that they are more able than they are in fact, and, moderate overconfidence (on one's ability) and overestimation of the precision of initial information leads people to choose tasks that raise expected output. In this work, we study how the perceived utility changes as the perception of the precision of decision-makers priors increases, following the modelling technique presented in [49]. An individual who underestimates the variance of ones priors (equivalent to overestimating the precision of priors) is more willing to choose the challenging task, which raises expected output and utility. In this work, we model the effect of overconfidence as a) the increase in precision of the individuals priors, keeping the mean of the priors constant and as b) the increase in mean of the individuals priors, keeping the variance of the priors constant. The likely reasons behind the over estimation of mean and precision of attribute performance are: a) lack of enough data about alternative performance and b) the performance curve interpolated from available data has different mean and standard deviation from the actual values.

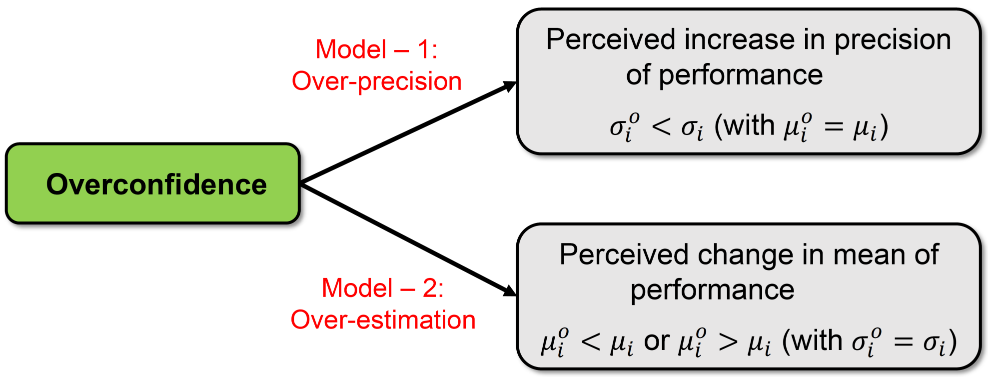


Fig. 3.7.: Models for dominant biases

Let the actual quality (performance) of an attribute of alternative A_i is given by $q(A_i) = N(\mu_i, \sigma_i)$ where, μ_i and σ_i correspond to the mean and standard deviation of the actual performance, and the quality as perceived by a biased decision-maker be given by $q^o(A_i) = N(\mu_i^o, \sigma_i^o)$ where, μ_i^o and σ_i^o correspond to the mean and standard deviation of the quality as perceived by a biased decision-maker. In this work, we employ two models of overconfidence bias (as shown in Figure 3.7) for the final decision-making model and are detailed as follows:

- Model-1: Overconfidence as increased precision of performance measure

$$\sigma_i^o < \sigma_i \text{ (with } \mu_i^o = \mu_i)$$

- Model-2: Overconfidence as increased mean of performance measure

$$\mu_i^o > \mu_i \text{ (with } \sigma_i^o = \sigma_i)$$

These models along with the CPT-based utility model are used to study the preference structures of the decision-maker as depicted in Figure 3.8. The decision-making model is employed for a satellite subsystem design case-study and the results are presented in Chapter 4.

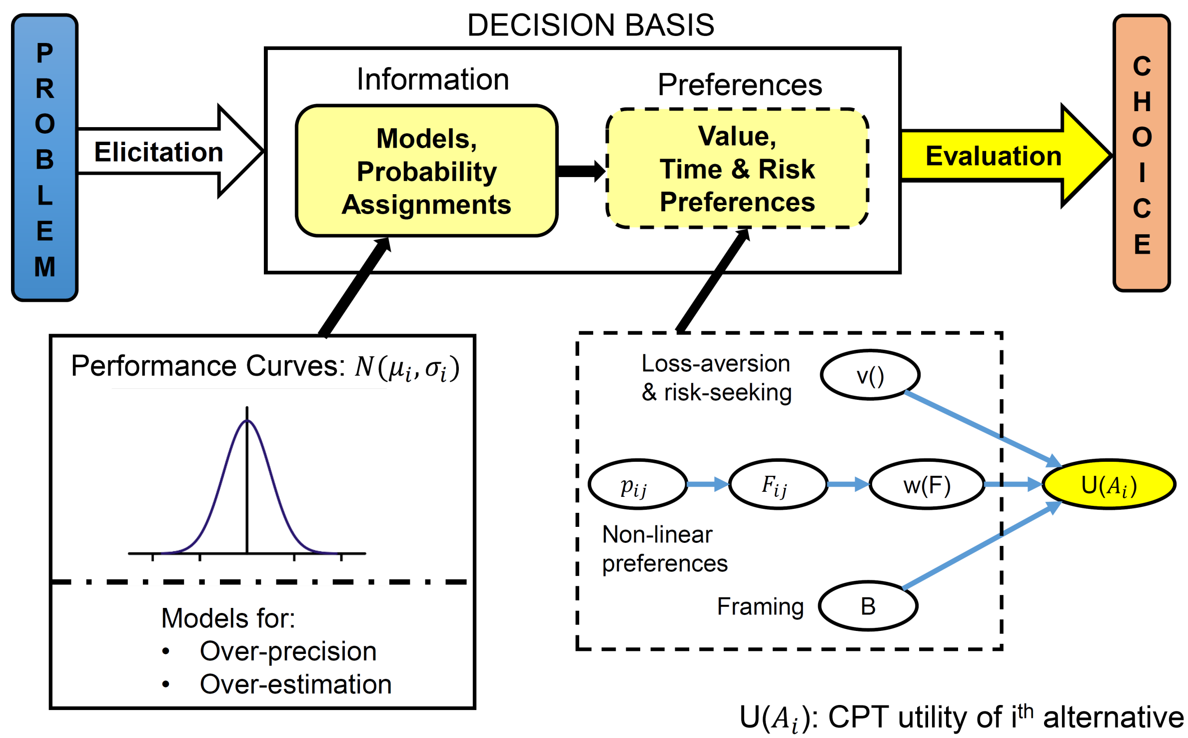


Fig. 3.8.: Flowchart depicting the overall decision-making model

4. CASE-STUDY: SATELLITE POWER SUBSYSTEM DESIGN

Space missions range widely from communications to planetary explorations and to proposals for space manufacturing. But, cost is a fundamental limitation to nearly all space missions. On the other hand, analysis and design are iterative, gradually refining both the requirements and methods of achieving them [50, 51]. Achieving broad mission objectives at a lower cost is the main reason behind design iterations and improvements.

A spacecraft can be decomposed as a system consisting of seven important subsystems [50]. They are: a) Attitude Determination and Control b) Telemetry, tracking and command c) Command and Data handling d) Power e) Thermal f) Structures and Mechanisms g) Guidance and Navigation. Other important systems are payload and propulsion. All the subsystems have to be designed reliably to meet the overall mission objectives which involves decision-making by several systems-level engineers and other subsystem-level engineers at every phase. Each Subsystem Engineer (sSE) is responsible for maximizing their system's utility to the overall system architecture and does not consider whether his/her actions benefit their fellow engineers. They are however aware of the goals their counterpart and the choices that they shall make to achieve these goals. To maximize their subsystem's utility, each sSE attempts to maximize a set of engineering objectives corresponding to a set of requirements for the spacecraft which are incentivized at the system level. Each sSE estimates the incentives at the system level by estimating the system level utility of a given objective.

4.1 Problem Setting: Power Subsystem Design

The Electrical Power Subsystem (EPS) is the most significant and highly interdependent subsystem in a spacecraft. The requirements for a power subsystem defines the design life of the spacecraft and thus the mission life. Payload mass and mission life dictates the power requirements which in turn affects the mass of power subsystem components which affects the total mass of the spacecraft which can demand more power to be produced at a given point of time. Such intricate inter-dependencies makes it a critical system, the design of which consists of subsystems with a myriad design characteristics which one should develop to meet mission-level requirements.

The power subsystem provides, stores, distributes and controls electric power for the equipment on the spacecraft and payload. It consists of a power source, energy storage, power conversion/distribution and power regulations and control equipment. These main components are presented in the form a flow chart as shown in Figure 4.1. With a higher-level objective of achieving mission requirements, this case-

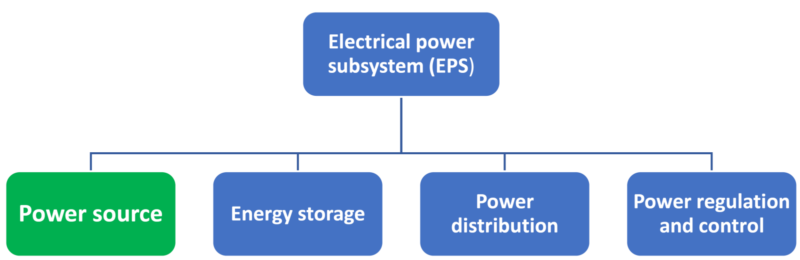


Fig. 4.1.: Hierarchy of Electrical Power Subsystem

study demonstrates the design of EPS by modelling the decisions involved in selecting a power source for the spacecraft.

The EPS lead seeks to maximize utility by optimizing mass of the power system, yearly degradation of the system performance, and system cost. The objectives largely concern the ability of EPS to deliver continuous power supply to all the supported subsystems over the mission life considering the aspects of degradation (due to shadowing, exposure to radiation etc.) and inefficiencies in power generation and transfer at minimum mass of the power generation and storage systems. For earth-orbiting satellites, solar photo-voltaic cells are commonly used to generate power. Solar panels with these solar cells provide the satellite with enough power required for operations over the design lifetime. The objective of the EPS sSE is to meet the power requirements over the mission life with minimum mass of the solar panels.

For the purpose of this case-study, the design objective along with subsystem requirements, constraints and available alternatives are presented below:

- *Objective*: Select a solar cell type for a communications satellite's power generation subsystem that meets the power demands of the satellite over the mean life time
- *Requirements*:
  - Power required during eclipse and daytime: 5000 W.
  - Mean satellite life: 10 years
- *Constraint(s)*: Mass of the subsystem $\leq$ 200 kg.
- *Alternatives*: The following five alternatives are available for solar cell material: Silicon (Si), Amorphous Silicon, Gallium Arsenide (GaAs), Indium Phospide (InP) and Multijunction (GaInP/GaAs).

The performance (quality) of solar cell materials is expressed in terms of the power conversion efficiency (denoted by η_{sc}). The performance data for the five alternatives mentioned above is taken from [50] and is tabulated below:

4.2 Modeling Techniques

4.2.1 EPS Modeling

The power source within EPS generates electrical power necessary for spacecraft operations over its lifetime. Among four different types of power sources for an earth-

Table 4.1.: Efficiencies of various solar cells

Alternative	**Range of η_{sc} (%)**
A_1: Amorphous Silicon	[5, 12]
A_2: Silicon	[14, 21]
A_3: InP	[18, 23]
A_4: GaAs	[18, 24]
A_5: Multijunction	[22, 26]

orbiting spacecraft, *photo-voltaic* solar cells are widely used that convert incident solar radiation directly to electrical energy [50, 51]. Key design issues for solar arrays include spacecraft configuration, required power level, operating temperatures, radiation environment, mission life, mass, area and cost. To design and size a solar array, the sSE must understand cell types and characteristics; solar-array design issues, types, sizing calculations, radiation and thermal environments. Mission life and power requirements are the two key design considerations in sizing the solar array. The system modeling equations to design a solar array that meets the End-Of-Life (EOL) power requirements are obtained from [50, 51] and are given below:

$$P = 1.658669 \times 10^{-4} \times (R_e + H)^{1.5} \tag{4.1}$$

$$\rho = \sin^{-1}(\frac{R_e}{R_e + H}) \tag{4.2}$$

$$\phi = 2\cos^{-1}(\frac{\cos\rho}{\cos\beta}) \tag{4.3}$$

$$T_e = \frac{\phi}{360} \times P \tag{4.4}$$

$$T_d = P - T_e \tag{4.5}$$

$$P_{sa} = \left(\frac{\frac{P_e T_e}{X_e} + \frac{P_d T_d}{X_d}}{T_d}\right) \tag{4.6}$$

$$P_O = \eta_{sc} \times 1368 \tag{4.7}$$

$$P_{BOL} = P_O \times I_d \times \cos\theta \tag{4.8}$$

$$P_{EOL} = P_{BOL} \times (1 - D_y)^L \tag{4.9}$$

$$A_{sa} = P_{sa}/P_{EOL} \tag{4.10}$$

$$M_{sa} = A_{sa} \times M_{pa} \tag{4.11}$$

$$C_r = \frac{P_e T_e}{60 \times DOD \times n_b \times \eta_b} \tag{4.12}$$

$$M_b = \frac{C_r}{SED} \tag{4.13}$$

$$M_{EPS} = M_{sa} + M_b \tag{4.14}$$

The variables and parameters used in these equations (along with the appropriate units) are given below:

Table 4.2.: Variables used in EPS modeling equations [50, 51]

S.No.	**Symbol**	**Description**	**Units**
1	H	Mean satellite orbit height from earth surface	Km.
2	P_e	Power requirement during eclipse per orbit	Watts
3	P_d	Power requirement during daylight per orbit	Watts
4	L	Mission life/duration	years
5	P	Satellite period	minutes
6	T_e	Length of eclipse per orbit	minutes
7	T_d	Length of daylight per orbit	minutes
8	X_e	Efficiency of paths from solar arrays through batteries to individual loads	-
9	X_d	Efficiency of paths from solar arrays directly to individual loads	-
10	ρ	Angular radius of earth	Deg.

Table 4.2.: *continued*

S.No.	Symbol	Description	Units
11	R_e	Radius of earth	Km.
12	α	Inclination of satellite orbit relative to equator	Deg.
13	β	Angle by which sun is out of satellite orbit-plane	Deg.
14	ϕ	Rotation angle covered by sun as it passes behind the disk of earth	Deg.
15	P_{BOL}	Power required at the beginning-of-life	W/m^2
16	P_{EOL}	Power required at the End-of-life	W/m^2
17	P_{sa}	Power to be produced by solar arrays during daylight to support the satellite requirements	Watts
18	P_O	Power output with sun normal to solar cell surface	W/m^2
19	I_d	Inherent degradation factor	-
20	η_{sc}	Efficiency of chosen solar cells	-
21	D_y	Performance degradation of chosen solar cell per year	-
22	M_{pa}	Mass per unit area of chosen solar cell	Kg/m^2
23	θ	Angle between solar array normal and sun line	Deg.
24	M_{sa}	Total mass of solar arrays required	Kg.
25	A_{sa}	Total area of solar arrays required	m^2
26	C_r	Battery capacity	W-hr
27	DOD	Depth-of-Discharge	-

Table 4.2.: *continued*

S.No.	Symbol	Description	Units
28	n_b	No.of batteries	-
29	η_b	Transmission efficiency between battery and load	-
30	SED	Specific Power density of battery couple	W-hr/Kg
31	M_b	Mass of the storage source for corresponding C_r	Kg.
32	M_{EPS}	Mass of EPS power source and power storage	Kg.

As shown in Figure 4.2, to obtain M_{EPS} as a function of quality (efficiency: η_{sc}) of the alternatives (solar cells, in this case), the constant values chosen for some of the model parameters are given in Table 4.3.

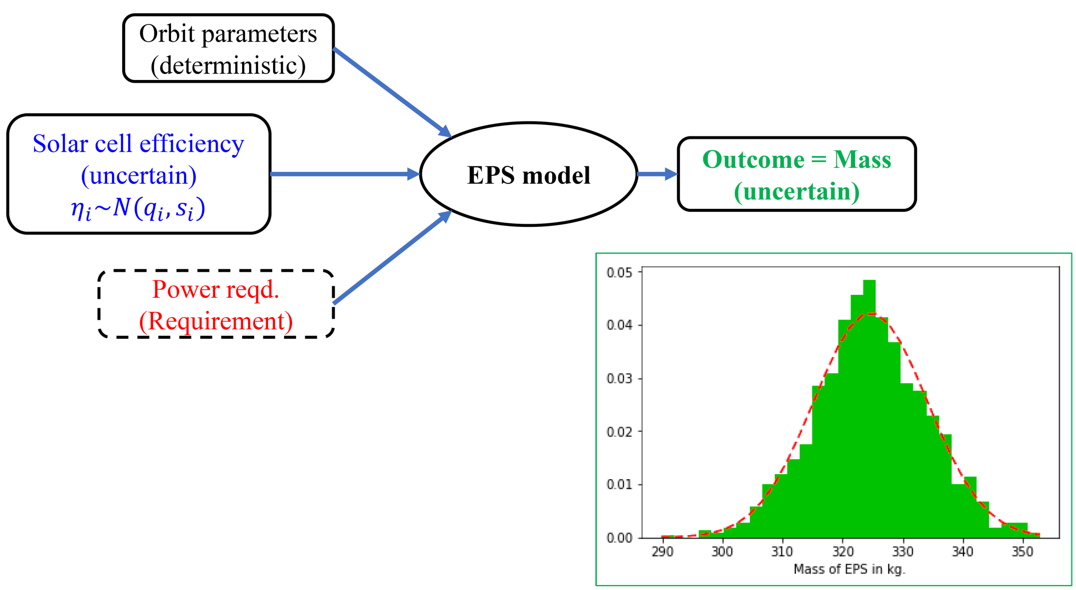


Fig. 4.2.: Input(s) and output(s) of EPS model

Table 4.3.: Parameter constants used in EPS modeling equations

S.No.	Parameter	Value chosen	Units
1	X_e	0.60	-
2	X_d	0.80	-
3	R_e	6378.14	Km.
4	α	10.00	Deg.
5	β	20.00	Deg.
6	I_d	0.77	-
7	D_y	0.02	-
8	M_{pa}	0.92	Kg/m^2
9	θ	23.50	Deg.
10	DOD	0.30	-
11	n_b	3	-
12	η_b	0.90	-
13	SED	40.00	W-hr/Kg

4.2.2 Biases

During the initial (proposal) phase of satellite development for scientific applications, a team led by a principal investigator and project manager is convened to put forward an estimate of how the goals of the project will be achieved through engineering means. However, in the process of successfully launching a satellite, all the necessary components to power, control, maneuver the satellite and transmit data must also be included in the satellite payload. Furthermore, the entire design is constrained by various factors, the most ubiquitous of which being *development cost* and *mass*. Both can be thought of as resources to be expended to achieve design goals.

In the requirements definition phase, the systems level representative proposes a requirement to the sSEs following the results of a system level requirements analysis which converts mission goals into functional requirements. These proposed requirements are then assessed by each sSE by performing a functional analysis of the subsystem and determining the allocations of systems level resources required to meet the requirements. The functional analysis considers estimates of engineering feasibility through preliminary sizing and concept design. These feasibility estimates are then used in trade off negotiations with project level personnel to secure allocations of key, system-level resources. These allocations take the form of project level cost, mass, and personnel resources as well as available power and thermal resources. The culmination of the proposal stage results in a basic architecture design with some sizing of key engineering features completed. From this point onwards, estimates and allocations propagate forward through the design process; once secured at the proposal stage, significant costs are associated with major changes in resource allocations or system architecture.

At the subsystem level, mass is a resource to be consumed in pursuit of meeting performance requirements and not an objective that provides utility directly. Generally, the launch vehicle and payload configuration selected for a satellite design dictates the maximum mass of the system. While the mass of the entire payload is capped, maximizing the utility obtained by the consumption of this mass budget is the goal of collaborative systems engineering.

Considering that the goal of a project team is to provide the most effective final product, ideally the various subsystems sSEs shall work together towards achieving a system level Pareto Optimal design while accepting the possibility of less than optimal subsystem performance. In reality, the ability of the design team to achieve this optimal performance is limited by communication and knowledge deficiencies between highly dissimilar subsystems. These inefficiencies work to *bias* each sSE to prioritize the utility provided by the subsystem they are responsible for.

As discussed previously, this work employs two models of overconfidence bias (as shown in Figure 3.7):

- Model-1: Overconfidence as increase in the precision of quality: $\sigma_i^o < \sigma_i$ (with $\mu_i^o = \mu_i$)

$$\sigma_i^o = k\sigma_i \text{ (where, the factor } k < 1) \tag{4.15}$$

- Model-2: Overconfidence as increase in the mean of quality: $\mu_i^o > \mu_i$ (with $\sigma_i^o = \sigma_i$)

$$\mu_i^o = m\mu_i \text{ (where, the factor } m > 1) \tag{4.16}$$

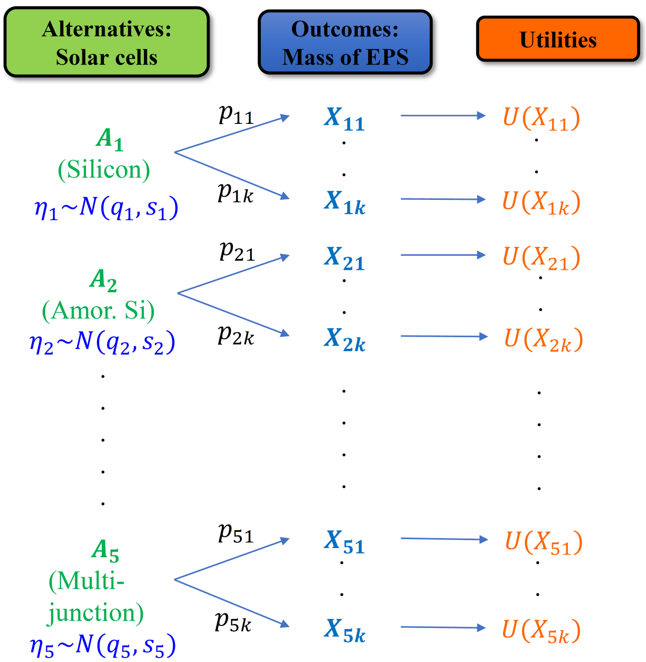
4.3 Results

4.3.1 Actual Preference Structure

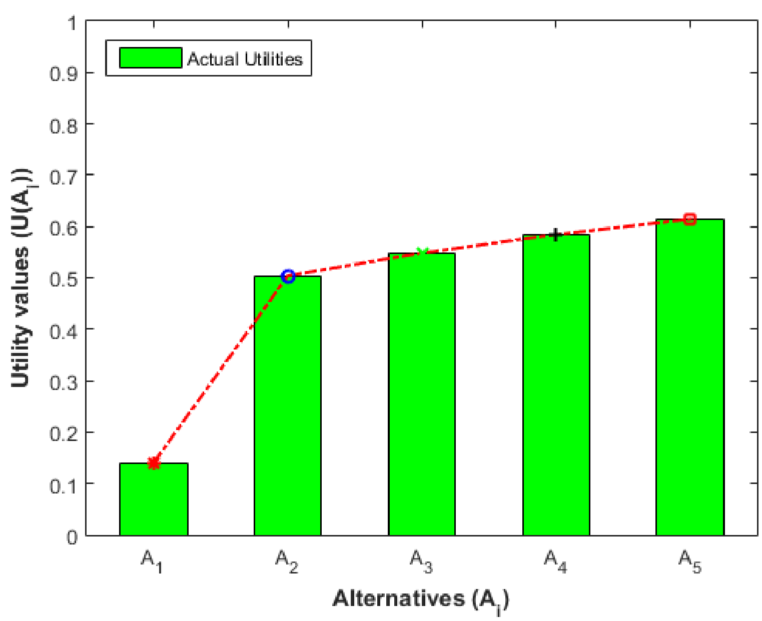
Figure 4.3(a) depicts the utility-based selection process given the performance curves of the alternatives (A_i, where, $i = 1, \ldots, 5$) and Figure 4.3(b) depicts the utility values (obtained by assuming the reference mass as 150 kg.) for the five alternatives. It can be observed that as the utility increases monotonically with mean quality, a rational decision-maker would choose the alternative with highest utility, which in this case turns out to be A_5: Multi-junction solar cells. The preference structure based on the actual utility curve is: $A_5 \succ A_4 \succ A_3 \succ A_2 \succ A_1$.

4.3.2 Effect of Overconfidence Bias

In this section, we present the preference structure of the EPS sSE who is biased and is more willing to choose the challenging task. To predict the effect of overconfidence, let us assume that the sSE is overconfident about the performance of fourth alternative A_4: GaAs solar cells i.e., he/she *believes* that using GaAs solar cells would yield lower mass of the solar panels while meeting the power and lifetime requirements. The likely reasons behind the over estimation of mean and precision of attribute performance are: a) lack of enough data about alternative performance and b) the performance curve interpolated from available data has different mean and standard deviation from the actual values.



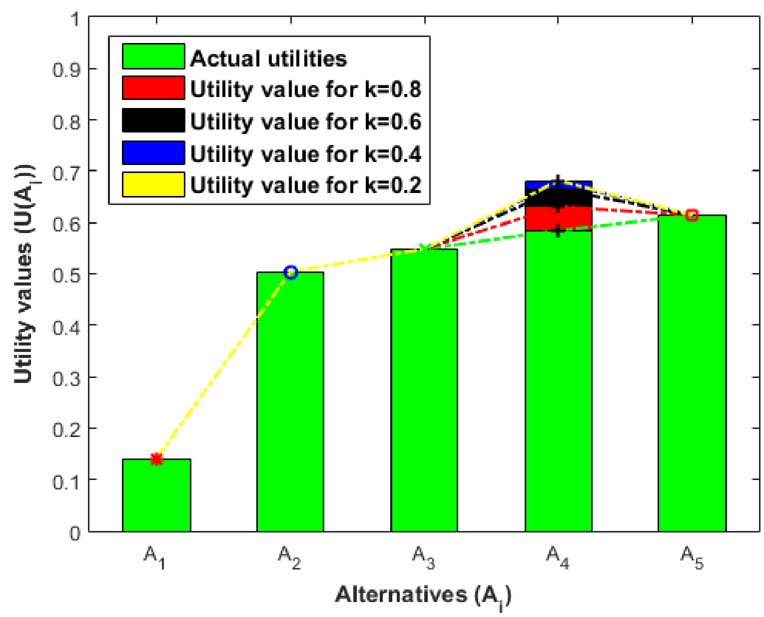
(a) Decision-making process for EPS power source selection



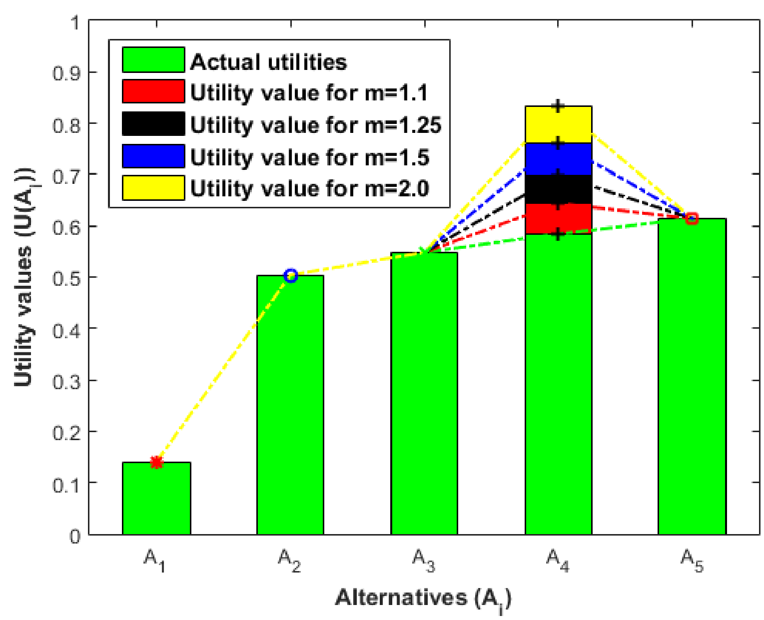
(b) Normalized utility values based on actual performance values of alternatives

Fig. 4.3.: Utility-based selection process with actual performance curves

Figure 4.4 depicts the variation in utility curve when the sSE is biased towards A_4. The local variation in utility values for the biased alternative based on the models of overconfidence is shown in Figures 4.4(a) and 4.4(b), respectively. Figure 4.4(a) captures the variation of decrease in factor k (refer to Equation 4.15) and Figure 4.4(b) captures the variation of increase in factor m (refer to Equation 4.16) on the utility values (which are a representation of the decision-maker's preference structure). The preference structure based on the biased utility curve is: $A_4 \succ A_5 \succ A_3 \succ A_2 \succ A_1$. These results demonstrate the model's ability to predict sSE's deviation from the best available alternative to other alternative(s) based on his/her overconfidence levels. In reality, such deviant decisions when made in succession can lead to sub-optimal system performance in some cases and system failures in other cases.



(a) Biased (overconfident about variance) utility curve



(b) Biased (overconfident about mean) utility curve

Fig. 4.4.: Utility-based selection process with biased performance curves

5. CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

In this work, we set out to understand the decision-making lapses that triggered the failure events of some of the spacecraft launch vehicles. From the first study, it is observed that anchoring bias and optimism bias are the dominant cognitive biases behind majority of the failure events. Decisions made with such biases can lead to unwarranted overconfidence and phenomena such as Normalization of Deviance, which is the tendency to accept risks as normal until a failure happens in the absence of immediate failures. We presented a systematic approach based on the failure-event chain to understand how behaviors influence the decisions behind some of the launch failures. This work forms a basis in studying more complex individual and group decision making phenomena such as Normalization of Deviance [9, 10] and Groupthink [21].

So far, studies on failures are carried out from a Systems Engineering perspective and not from a human decision-making perspective. This work presents an approach to identify some dominating cognitive biases so that techniques to mitigate the biases them could be developed. From the analysis of the ten case studies presented in Chapter 3, we note that two major types of cognitive biases manifest themselves as contributing factors of the mission failures. Overconfidence, in particular, optimistic bias and anchoring bias contributed mainly to majority of these failures. Such cognitive biases come into effect when making decisions under uncertainty, which might be due to lack of adequate data, resources, etc. Educating and raising awareness about the negative impacts of cognitive biases on engineering decision-making among the project staff is an important starting point to mitigate their effects and eventual consequences. The first part of this work presents a way to identify where and under what conditions overconfidence-based cognitive biases are likely to influence specific man-machine interactions. This way, safety interventions can be introduced to avoid such biases from becoming contributing factors behind accidents.

The second part of this work deals with development of theoretical model that captures the effect of cognitive biases on decision-making under uncertainty. The model presented in Section 3.2 is based on CPT and accounts for variations in beliefs about the quality of alternatives due to decision-maker's bias. Overconfidence in beliefs is captured by two factors k and m which correspond to variation in precision of beliefs and variation in mean of beliefs, respectively. Variation in these parameters correspond to variation in (over)confidence levels of the decision-maker, eventually affecting his/her preference structure. The effectiveness of this model is demonstrated with the help of a earth-orbiting satellite subsystem design case-study and is presented in Chapter 4. Some limitation of this mathematical framework are: a) achievement of different objectives is not systematically integrated in alternative-based decision-making, b) mathematical framework applicable only for utility-based selection problems, and, c) information about alternatives and their attribute performance parameters may not be readily available. Figure 4.4 depicts the change in utility values as a function of the overconfidence parameters. It can be observed that being overconfident about an alternative changes its utility value and hence force the decision-maker to choose an alternative that would result in sub-optimal system performance, eventually.

5.2 Future Work

This work only models the impact of cognitive biases that distorts the belief structure of decision-maker over the available alternatives and given that the models for these biases are known. Future studies on this topic can focus on other forms of biases such as biases due to limited data, misinterpretation of probabilities, heuristics such as availability etc. The model can further be extended to account for multiple biases over multiple attributes. Such models could be used to simulate and study the preference structures of decision-makers over time so that ways to mitigate such biases can be thought of well in advance. Further extensions of this work include: a) analysis of influence of biases over multiple attributes of alternatives, b) analysis of impact of factors such as incentives, peer pressure, time pressure, miscommunications etc., on decision-making under uncertainty, c) developing techniques to mitigate workspace biases.

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A. STATISTICS OF FAILED SPACE MISSIONS

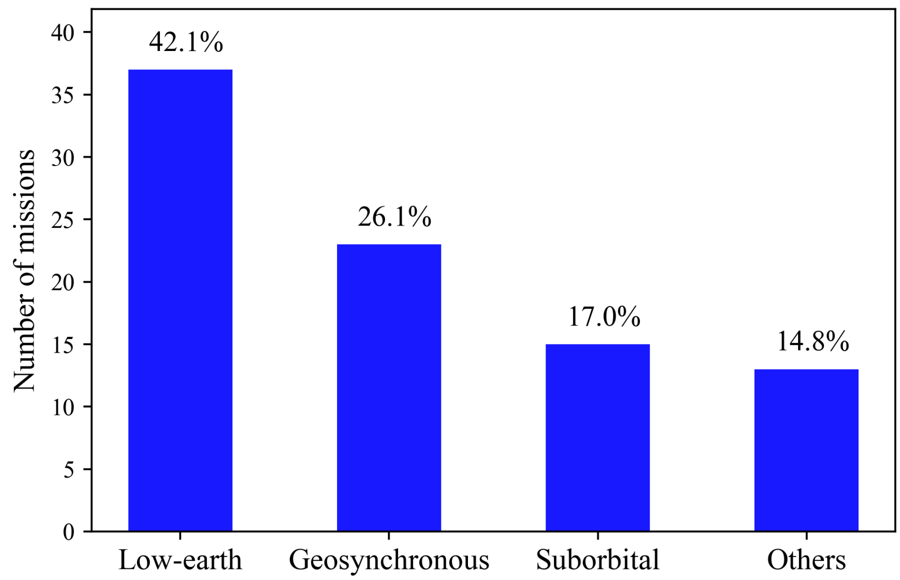

Fig. A.1.: Failed space mission statistics based on orbit type

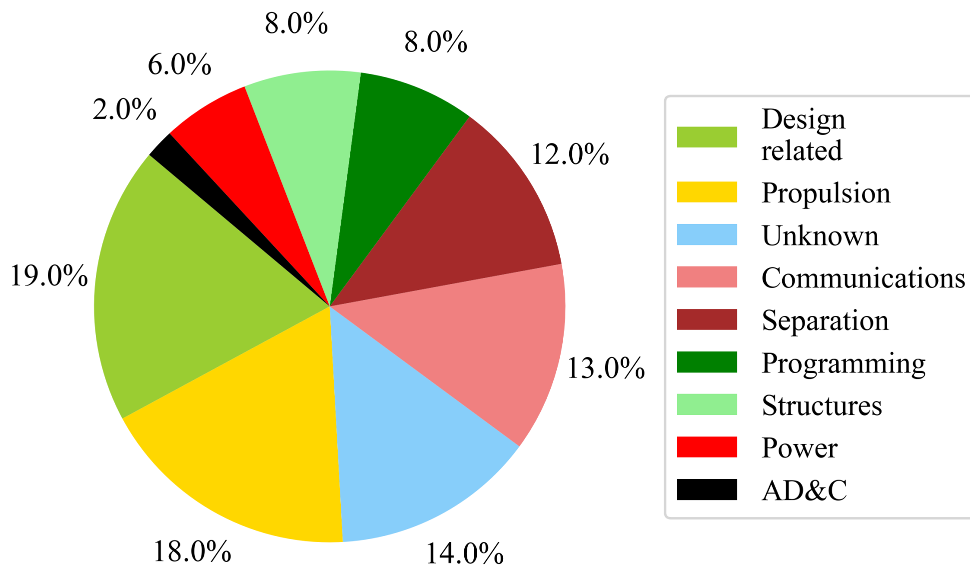

Fig. A.2.: Break-down of space-mission failures based on types of failures

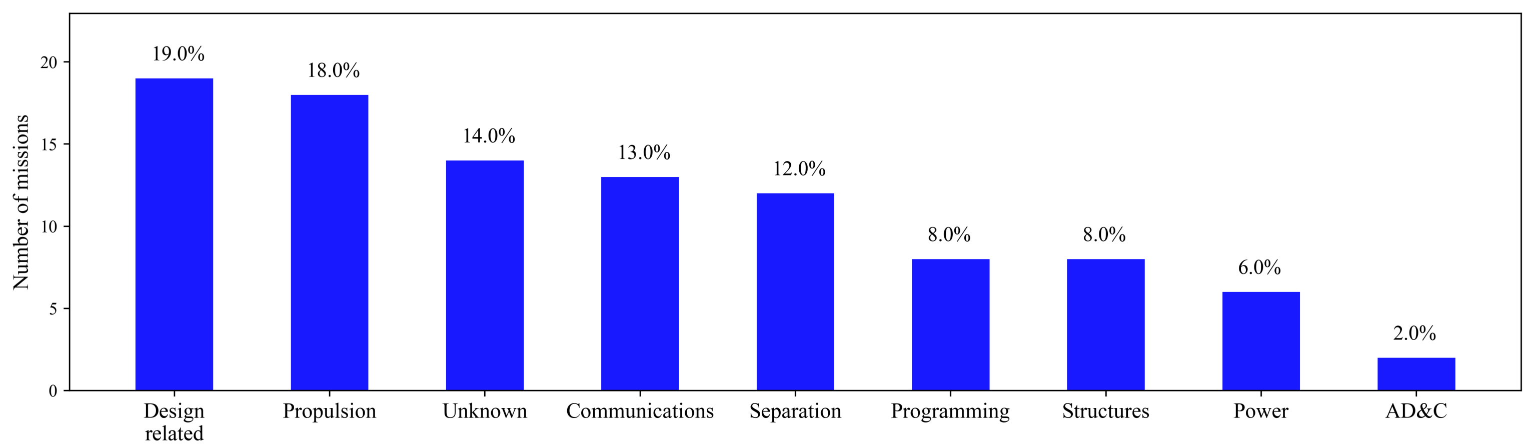

Fig. A.3.: Failed space mission statistics based on failure types