FORMALIZATION OF THE ENGINEERING SCIENCE DISCIPLINE

– KNOWLEDGE ENGINEERING

by

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Abstract

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Knowledge is the most precious ingredient facilitating aerospace engineering research and product development activities. Currently, the most common knowledge retention methods are paper-based documents, such as reports, books and journals. However, those media have innate weaknesses. For example, four generations of flying wing aircraft (Horten, Northrop XB-35/YB-49, Boeing BWB and many others) were mostly developed in isolation. The subsequent engineers were not aware of the previous developments, because these projects were documented such which prevented the next generation of engineers to benefit from the previous lessons learned. In this manner, inefficient knowledge retention methods have become a primary obstacle for knowledge transfer from the experienced to the next generation of engineers.

In addition, the quality of knowledge itself is a vital criterion; thus, an accurate measure of the quality of ‘knowledge’ is required. Although qualitative knowledge evaluation criteria have been researched in other disciplines, such as the AAA criterion by Ernest Sosa stemming from the field of philosophy, a quantitative knowledge evaluation criterion needs to be developed which is capable to numerically determine the qualities of knowledge for aerospace engineering research and product development activities.

To provide engineers with a high-quality knowledge management tool, the engineering science discipline Knowledge Engineering has been formalized to systematically address knowledge retention issues. This research undertaking formalizes Knowledge Engineering as follows:

1. Categorize knowledge according to its formats and representations for the first time, which serves as the foundation for the subsequent knowledge management function development.

2. Develop an efficiency evaluation criterion for knowledge management by analyzing the characteristics of both knowledge and the parties involved in the knowledge management processes.

3. Propose and develop an innovative Knowledge-Based System (KBS), AVD^{KBS}, forming a systematic approach facilitating knowledge management.

4. Demonstrate the efficiency advantages of AVD^{KBS} over traditional knowledge management methods via selected design case studies.

This research formalizes, for the first time, Knowledge Engineering as a distinct discipline by delivering a robust and high-quality knowledge management and process tool, AVD^{KBS}. Formalizing knowledge proves to significantly impact the effectiveness of aerospace knowledge retention and utilization.

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Chapter 1

Introduction

1.1 Research Motivation

Aerospace engineers have made great achievements throughout the last century of flight, such as the supersonic passenger plane, *Concorde*, and the electric aircraft, *NASA Helios*. Those achievements were gained based on the massive employment of new technologies. However, the management activities required to professionally prepare the underlying data and knowledge is often ignored during the development process of new technologies.

1.1.1 Current Issues

To scientific engineers, who are the users of the knowledge management tools, the aerospace research and product development process can be summarized by three stages: input, analysis and output. The output is the key to researchers, and it determines whether the entire research is successful. However, its quality entirely depends on the previous two stages, and is a natural outcome of the interactions between the analysis and input.

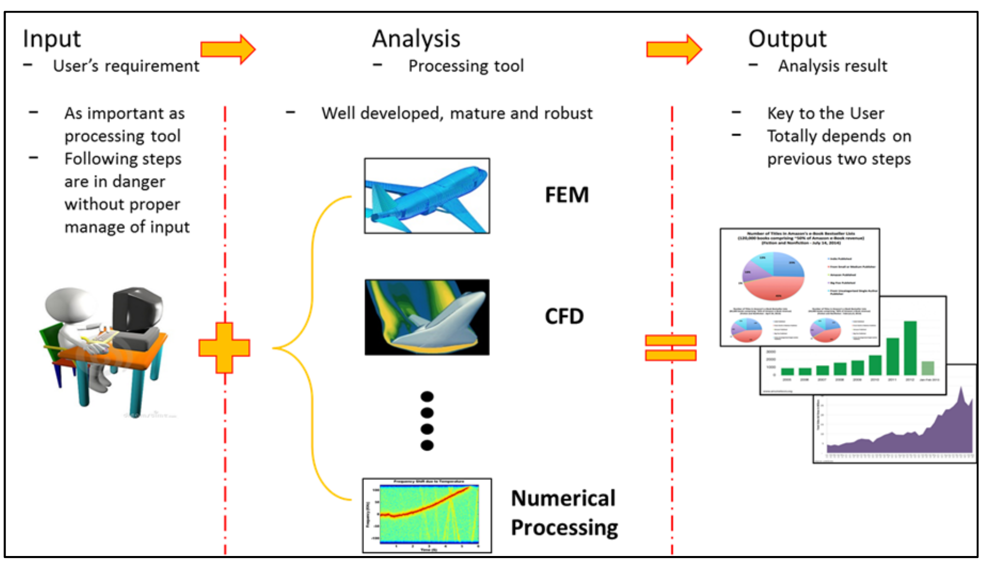


Figure 1-1 General Scientific Process

The analysis stage is the most developed, and researchers have created a great number of broadly used high-fidelity analysis toolsets, such as Comsol [(1)] and Abaqus [(2)]. In academia, these tools help researchers explore unknown fields and propose new theories; in industry, they help engineers optimize the current design and test innovative designs. These high-fidelity toolsets have already elevated many famous companies, such as Ansys, Inc.

> "Ansys, Inc. is an engineering simulation software (computer-aided engineering, or CAE) developer headquartered south of Pittsburgh in the Southpointe business park in Cecil Township, Pennsylvania, United States. One of its most significant products is Ansys CFX, a proprietary computational fluid dynamics (CFD) program." [(3).]

According to its FY 2014 report, the company revenue is $896M with total assets of $2.8 billion, employing more than 2,200 workers. Each year, there are millions of dollars of research funding being invested into developing those toolsets. While residing within the well-developed analysis stage, high quality data and knowledge management tools are necessary to help those software users to feed thus manage those analysis methods and calculating algorithms.

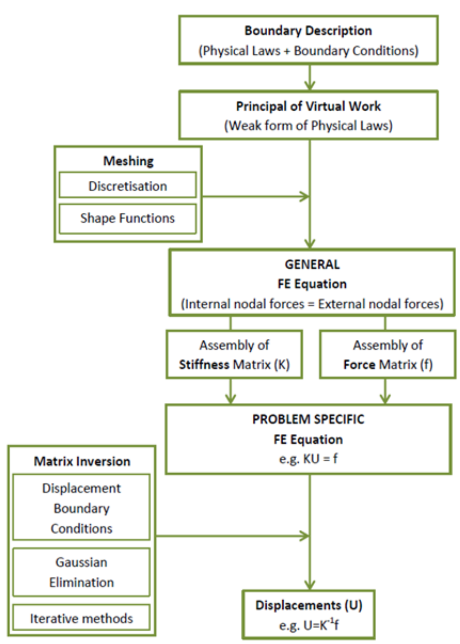


Figure 1-2 Regular FEA Process [(4)]

However, of the three stages, the input stage is often either underestimated or even ignored. The input is the starting point of the over analysis process, and it includes the engineers' current resources which are directly fed into the research process. It consists of knowledge accumulations, past experimental data, and research mission requirements. If the input information is flawed, the output results are no longer trustworthy, regardless of the quality of the actual analysis being conducted. For example, a regular FEA process, see Figure 1-2 [(4)], starts from the boundary description (physical laws and boundary conditions), which resembles the input stage of the normal aerospace research and product development process. If the physical laws and boundary conditions are not correctly represented, no matter how well the following analysis steps: principal of virtual work, meshing, general FE equation, assemble of stiffness/force matrix, problem specific FE equation and displacements, are conducted, the final FEA results cannot be solid, correct or accurate

1.1.2 Ideal Solution

To avoid those inherent risks, data and knowledge management toolsets have to be developed to help researchers organize and utilize available data and knowledge for both the input and analysis stages. The data and knowledge management toolsets will not only provide the basic storage function, which nowadays is usually implemented by books and hard drives, but also be able to prepare data and knowledge, and make them ready for use. An ideal solution for the entire research process is:

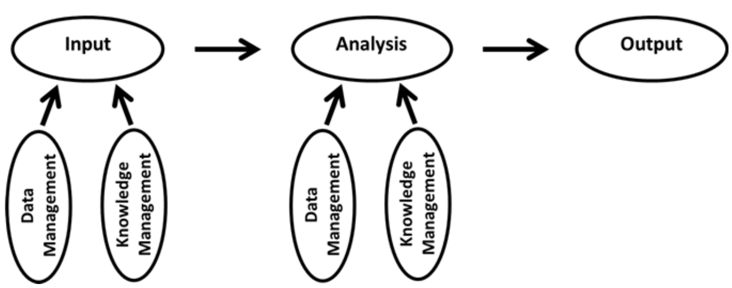


Figure 1-3 Ideal Research Process

Both *data management* and *knowledge management* work as support toolsets to help researchers manage data and knowledge during the input and analysis stages. With this approach, the quality of the output can be significantly improved in comparison. However, the topics *data management* and *knowledge management* are two large topics; consequently, this research focuses solely on developing an innovative *knowledge management* toolset.

In this dissertation, a new engineering science discipline, *Knowledge Engineering*, is proposed, and a knowledge management toolset and software, AVD^{KBS}, is developed.

1.2 Development History of Knowledge and Its Management Methods

Before we introduce the methodology of *knowledge engineering*, a review of the development history of knowledge and its management methods is necessary. Such understanding may offer us an overview of developing trends. It will demonstrate the necessity of formalizing knowledge management as an engineering science discipline adopted by the professional engineering community.

1.2.1 Introduction to Knowledge

Knowledge is obtained through the process of humans exploring nature, during which humans learn skills to make use of things in the environment to satisfy their needs [(5)]. Moreover, the continuous expansion of knowledge and its subsequent application help humans further explore the unknowns in this world. As a result, the history of human development is a history of knowledge generation, knowledge application and the knowledge accumulation process. The discovery and application of knowledge drove humans from originally living in caves and wearing leaves to the current prosperous civilizations. Such mechanism may continue to guide humans to interstellar travel in the future.

Figure 1-4 Knowledge Drove Human Society Developments

Knowledge, the most precious outcome from human life & exploration activities, has many definitions:

Oxford Dictionaries (6):

> facts, information, and skills acquired by a person through experience or education; the theoretical or practical understanding of a subject; awareness or familiarity gained by experience of a fact or situation.

Merriam-Webster (7):

> the fact or condition of knowing something with familiarity gained through experience or association; the fact or condition of being aware of something; the range of one's information or understanding; acquaintance with or understanding of a science, art, or technique.

From these definitions, data and information are closely related to knowledge, and they are both from the same family. The relationships of data, information and knowledge can be explained by the following example (8):

The average flyaway cost of a Curtiss P-40 Warhawk is $9.8*10^5$ dollars. The number $9.8E^5$ is a piece of data, describing the fact of the cost for a P-40. However, it cannot bring us more information, such as how the cost changes throughout the aircraft development history.

Then if we collect more flyaway cost data of aircrafts and organize them accordingly, they become information. It helps us understand the flyaway cost developing trend, which can be interpreted as: throughout the aircraft development history, the flyaway cost keeps rising. However, this information is only a general introduction and cannot be used to generally calculate the flyaway costs of other aircrafts; thus it is not a piece of knowledge.

Table 1-1 Selected Aircrafts and Their Average Flyaway Costs [8]

Aircraft	Average Flyaway Cost (Dollars)
P-40	$9.8*10^5$
F8U	$4.5*10^6$
F-4B	$5.1*10^6$
F-14A	$9.7*10^6$
F-15E/F	$3.6*10^7$

Finally, if we gather data on the *Year of Initial Operating Capability* of those aircrafts and put them with their *Average Flyaway Cost* data together, they can form a piece of knowledge on the relationship between the *Average Flyaway Cost* and *Year of Initial Operating Capability minus 17 Dec. 1903*. It is a linear function and can be expressed by Eqn. 1-1. This piece of knowledge can not only estimate the average flyaway cost of the aircraft developed in the past, but also be used to predict the cost of one which will be developed in future, see Figure 1-5.

$$Y = 85915 * 10^{0.027X} \tag{1-1}$$

X: Date of Initial Operating Capability minus 17 Dec. 1903

Y: Average Flyaway Cost

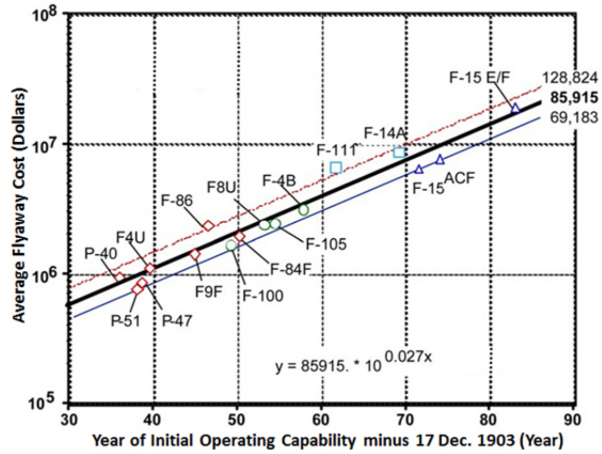


Figure 1-5 A Piece of Knowledge on the Relationship between Average Flyaway Cost and Year of Initial Operating Capability minus 17 Dec. 1903 (8)

As a result, the characteristics of data, information and knowledge can be summarized in Table 1-2.

Table 1-2 Characteristics of Data, Information and Knowledge

Stage	Item	Characteristics
1st	Data	Exact numerical descriptions of the object facts.
2nd	Information	Interpretation of data collections . Providing deeper understanding of the objects, such as background introduction, or developing trends.
3rd	Knowledge	Generated from interlinked information, unveiling the nature of the objects, and providing the deepest understanding. It includes aspects, such as principles, and theories, and can be used to guide the practices and lead to discoveries of more knowledge.

Before further analyzing knowledge, a comprehensive review of the development history of knowledge and its management methods is necessary to discover their developing trends and characteristics.

1.2.2 Development History of Knowledge and Its Management Method

The development history of knowledge and its management methods will be introduced according to the timeline of human society's development. It is divided into seven stages [9] [10] [11]: Paleolithic (2 million BC to 10,000 BC), Neolithic (10,000 BC to 3,300 BC), Bronze and Iron Ages (3,300 BC to 500 BC), Regional Empires (500 BC to 500 AD), and Middle Age (500 AD to 1350 AD), Early Modern Period (1350 AD to 1800 AD) and Modern Period (1800 AD to Present). In each stage, it introduces:

(i) Human activities: focus on the human achievements;

(ii) Knowledge discipline developments: focus on births of new knowledge disciplines;

(iii) Knowledge management methods: focus on developments of knowledge documentation media and representation methods.

Academic discipline can be defined as 'academic studies that focus on a self-imposed limited field of knowledge' [12]. Academic disciplines, instead of knowledge, are chosen to estimate the amount of knowledge because the pieces of knowledge are numerous and cannot be counted. On the contrary, academic disciplines are countable, and they offer reasonable indications for the amount of existing knowledge. As a result, they are chosen to measure the knowledge accumulations in each period. In conclusion, an overview will be drawn to show the relationship between knowledge and its management methods.

1.2.2.1 Paleolithic (2 million BC to 10,000 BC)

Human Activities. The human activities within the period about 2.6 million years ago were mainly the migration from Africa to the rest of the world, as well as the production of simple wooden and stone tools [9] [10] [11]. As ice decreased from the Ice Age, human ancestors migrated from Africa to Europe. About 100,000 to 15,000 years ago, a land bridge linking Siberia to Alaska provided a way for humans to migrate into North America.

Another important invention was the use of fire. It enabled humans to protect themselves from predators, increase their home ranges, cook food and deal with harsh winters.

(a) (b) (c)

Figure 1-6 Paleolithic Human Achievements: (a) Simple Stone Tool; (b) Pottery; (c) Master of Fire [13]

Other influential progresses in human history were: ceramic applications, mainly pottery objects or figurines made from clay were dated back to 27,000 years ago; Copper pendant was found in northern Iraq, which was believed to be dated about 10,000 years ago.

Knowledge Discipline Development. Two knowledge disciplines were born in the Paleolithic period: *mining engineering* and *art*.

Table 1-3 New Knowledge Disciplines Born in the Paleolithic Era

Knowledge Discipline	**Event**
Mining Engineering [14]	"The oldest known mine on archaeological record was the "Lion Cave" in Swaziland about 43,000 years old. Paleolithic humans mined mineral hematite to produce the red pigment ochre, which was considered as the origin of Mining Engineering".
Art [15]	"Sculptures, cave paintings, rock paintings and petroglyphs from the Upper Paleolithic dating to roughly 40,000 years ago have been found." They were considered the oldest form of art.

Knowledge Management Method. The documentation media during the Paleolithic era were natural objects provided by nature, like walls of caves. Humans drew paintings on them. However, the purposes of those picture expressions or the repeated signs are not clear to current researchers [16]. It is guessed that the paintings of animals were probably connected to magical rites to foster hunting, and the notches engraved on bones and stones were a way to count something, such as the lunar months, or the prey captured.

No formal writing system had been developed in this era, but symbols were broadly used. Those symbols were carved by simply processed tools [17], such as projectile points and knife blades, which were made of stones and animal bones. Tally sticks, made of wood or bones, were a famous example [18]. They were used to record the count of objects or the lunar months. Knotted ropes and similar materials were also used for tallies sticks.

Figure 1-7 Paleolithic Sculpture and Wall Carve [13]

1.2.2.2 Neolithic (10,000 BC to 3,300 BC)

In the Neolithic Era, the greatest development was the agriculture development, named as Neolithic Revolution [9] [10] [11], which featured the agriculture progress and animal domestication growth in the Near East. “Around 8500 BC, a permanent village consisting of rectangular mud-brick houses existed in Middle Euphrates Valley in Near East, and its inhabitants primarily hunted gazelle. Around 8000 BC, they began to domesticate sheep and goats, as well as growing einkorn, pulses and other cereal crops.”

Human Activities. Because of the huge food production, humans cultivated excessive amount of food, many of which were used for trading purposes. From 6500 BC, farming families began to trade with each other. Based on those developments, villages started to form, some of which evolving into a considerable size.

As villages grew and stayed together, towns and the states began to form, and those would then develop a complex economy and social structure. To satisfy the increasing communication requirements, a more sophisticated language and writing system was developed. Quite different cultures and religions were developed because of distinct background and environment.

Writing systems came into being with the typical examples of proto-writing, systems of ideographic and/or mnemonic symbols, like Jiahu symbols, carved on tortoise shells in Jiahu around 6600 BC.

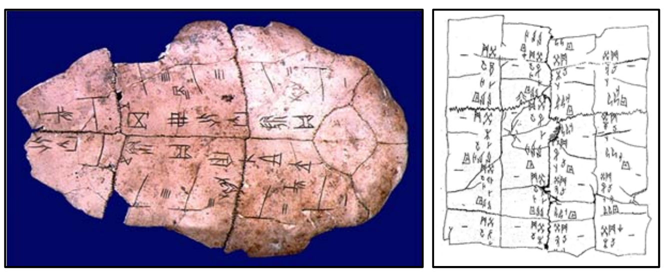


Figure 1-8 Neolithic Turtle Documentation Samples [13]

Knowledge Discipline Developments. From all of the cultural and technological advancements, Agriculture is the primary new discipline founded during the era.

Table 1-4 New Knowledge Disciplines Born in Neolithic

Knowledge Discipline	**Event**
Agriculture [19]	"By 7000 BC, small-scale agriculture reached Egypt. From at least 7000 BC the Indian subcontinent saw farming of wheat and barley, as attested by archaeological excavation at Mehrgarh in current Pakistan".

Knowledge Documentation Method. The documentation media did not change much over these times. Natural objects, such as turtle shells, wood and stones, were still the most common documentation media.

However, considerable progress was made concerning the writing system. Canadian researchers found that symbolism was used by cave painters of the Neolithic Age. 26 specific signs were used by these ancient humans as a graphic code shortly after their arrival in Europe from Africa. It demonstrated that the 'creative explosion' occurred tens of thousands of years earlier than scholars thought [20].

Another famous ideographic writing system was Jiahu symbols, which was carved in tortoise shells [21]. Archaeologists believed the markings were similar to some characters used in the modern world. A 2003 report in Antiquity described it "… *not as writing itself, but as features of a lengthy period of sign-use which led eventually to a fully-fledged system of writing. …*" [22]

1.2.2.3 Bronze and Iron Age (3,300 BC to 500 BC)

As the state-organized societies kept developing in Egypt and Mesopotamia, other preindustrial complex civilizations came into existence (9) (10) (11). Centralized political and social organizations were the typical characteristics of those complex society organizations, which were also featured by complex government bureaucracies and despotic leaders.

Figure 1-9 Bronze and Iron Age Civilization Rise and Transportation Progress [13]

Human Activities. The application of metal tools was the major progress in this era. The development of civilization and empires accelerated the economy, technology and culture developments. The most influential technical progress was the use of bronze for tools and weapons. Other improvements include the introduction of plows increasing the crop yields, as well as wheel applications, which significantly improved the development of transportation. The first iron production also began in this era, which were demonstrated by samples of smelted iron from Asmar, Mesopotamia and Tall Chagar Bazaar in northern Syria dated back between 3000 and 2700 BC.

Knowledge Discipline Development. Because of leaps in societal productivity, several new knowledge disciplines were born in the period.

Table 1-5 New Knowledge Disciplines Born in Bronze and Iron Age

Knowledge Discipline	Event
Mathematics [23]	"The earliest uses of mathematics were in trading, land measurement, painting, weaving patterns and the recording of time. More complex mathematics did not appear until around 3000 BC for taxation and other financial calculations."
Chemistry [24]	"By 1000 BC ancient civilizations were using technologies that formed the basis of the various branches of chemistry: extracting metal from their ores, making pigments for cosmetics and painting, and extracting chemicals from plants for medicine."
Astronomy [25]	"In early Bronze and Iron Age times, astronomy was born from the ancestors observing and predicting the motions of objects visible to the naked eye."
Medicine [26]	"The Egyptian Papyrus of Kahun (1900 BC) and Vedic literature in ancient India offered one of the first written records of veterinary medicine."
Hydraulic Engineering [27]	"Earliest uses of hydraulic engineering were used to irrigate crops and were dated back to the Middle East and Africa. One of the earliest hydraulic machines, the water clock was used in the early 2nd millennium BC."
Philosophy [28]	"Pulitzer Prize winning historian Will Durant dated the earliest philosophy writing, *The Story of Civilization: Our Oriental History*, as early as 2880 BC."
Literature [29]	*"The Epic of Gilgamesh* was one of the earliest known literary works. This Babylonian epic poem arose from stories in the Sumerian language."
Law [30]	"The history of law was closely connected to the development of civilization. Ancient Egyptian law was dated back to 3000 BC. It was based on the concept of Ma'at, characterized by tradition, rhetorical speech, social equality and impartiality."
Civil Engineering [31]	"The earliest practice of civil engineering may have commenced between 4000 and 2000 BC in Ancient Egypt and Mesopotamia when humans started to abandon a nomadic existence, creating a need for the construction of shelter."
Structural Engineering [32]	"Structural engineering was dated back to 2700 BC when the pyramid for Pharaoh Djoser was built by Imhotep."

Knowledge Documentation Method. The knowledge documentation media consisted of natural and simple man-made objects, like stones and metal.

In addition, four of these materials were broadly used for writing: metal, clay, wax and pottery [18]. Although the hardness of metals made them an inconvenient material for writing, the foils or sheets of soft metals like lead were usable. For example, lead sheets were used for curse tablets.

Clay was easy to be carved and could hold inscriptions almost permanently. Wax had many advantages: it offered a reusable surface, easily inscribed and erased; it was also combined with other materials like wood that gave it durability. Flat surfaces for writing were provided in forms of stone tablets, clay and wooden writing tablets, and wax-covered wooden tablets.

Since unglazed pottery could take inscription even after firing, unglazed pottery shards were used as a kind of scratch paper for tax receipts in Athens.

1.2.2.4 Regional Empires (500 BC to 500 AD)

After the rise of civilizations around the world, a great number of societies emerged in the Eastern Hemisphere [9] [10] [11]. It featured the great empires, “which provided large, secure areas for trade, providing the wealth and power necessary for basic economic development and political stability.” Those empires were based on significant commercial and technological developments, which provided a foundation in most regions for a sense of civilizational identity.

Human Activities. The regional empire period was characterized by the rise of powerful empires. The most famous empire around the world was Rome. The economy of early Rome was agrarian, whose most citizens were farmers. The republic in Rome rose in 505 BC, when the last king, Tarquinius Superbus, was expelled by L. Junius Brutus.

The Roman Empire gained more influence when Emperor Augustus (63 BC – 14 AD) founded the Principate in 27 BC, which was a monarchy system and was led by an emperor holding power for life instead of making himself dictator.

(a) (b) (c)

Figure 1-10 Rome Empire: (a) Colosseum; (b) Republic of Rome; (c) Territory [13]

At its peak, Roman dominated most of Western Europe and the shores of the Mediterranean, and its population was over one million. For a period of seven hundred years, Rome was the most important and powerful kingdm in the Western world.

Knowledge Discipline Developments. The prosperous economy and social development accelerated the knowledge discipline developments, and a considerable amount of new knowledge disciplines was born:

Table 1-6 New Knowledge Disciplines Born in Regional Empires

Knowledge Discipline	**Event**
Pharmacy [33]	"The earliest known compilation of medicinal substances was the Sushruta Samhita, an Indian Ayurvedic treatise being written in the 6th century BC."
Physics [34]	"Physics had its origins in Greece during the Archaic period, (650 – 480 BC), when Pre-Socratic philosophers like Thales proposed ideas verified by observations."
Geology [35]	"The study of the physical material of the Earth was dated back at least to ancient Greece when Theophrastus (372–287 BC) wrote the work Peri Lithon."
Biology [36]	"The formal study of biology was dated back to Hippocrates (460–370 BC). It was Aristotle (384–322 BC) who contributed most extensively to the development of biology."
Religious Studies [37]	"Interests in the general study of religion were dated back to at least Hecataeus of Miletus (550– 476 BC) and Herodotus (484–425 BC)."
Linguistics [38]	"The earliest known activities in descriptive linguistics were from Pāṇini around 500 BC, with his analysis of Sanskrit in *Ashtadhyayi*.."
Political Science [39]	"The antecedents of Western politics can be traced back to the Socratic political philosophers, Aristotle (384–322 BC). *The Politics and Nicomachean Ethics* by Aristotle analyzed political systems."
History [40]	"Greek historians greatly contributed to the development of historical methodology. The earliest known critical historical works were *The Histories*, composed by Herodotus (484–425 BC) who later became known as the 'father of history'."
Mechanical Engineering [41]	"In ancient Greece, the works of Archimedes (287–212 BC) deeply influenced mechanical engineering in the Western tradition."
Control Engineering [42]	"Automatic control systems were first developed over two thousand years ago. The first feedback control device on record was the ancient Ktesibios's water clock in Alexandria, Egypt around the third century BC."

Knowledge Documentation Method. An important progress in knowledge documentation media was made by the invention of paper [43]. Paper was invented by the ancient Chinese in the 2nd century BC during the Han Dynasty and spread slowly to the west via the Silk Road. After the defeat of the Chinese in the Battle of Talas, the invention spread to the Middle East. There were records of paper being made at Gilgit in Pakistan by 751 AD, in Bagdad by 793 AD, in Egypt by 900 AD, and in Fes Morocco around 1100 AD. Because of its light weight and easy documentation characteristics, paper became the most popular documentation medium.

In western civilizations, a paper like material, papyrus, was born and got broadly applications [18]. However, the early use of papyrus was soon replaced by parchment, which was made by treating animal hide around 500 BC. A wide variety of parchments from various animal skins, with different texture and quality were widely used for codices, religious and cultural texts. This was replaced by the increasing availability of paper.

In eastern civilizations such as India, the principal writing media were birch bark and dried palm leaves. The use of paper began only after the 10th century. However, birch bark and palm leaves continue to be used even today, such as wedding invitations and other cultural uses.

For the writing characters, Greek was born and it was the source for all of the modern scripts of Europe [44]. The most widespread descendent of Greek was the Latin script. It was wide spread via the central Italian people who came to dominate Europe with the rise of Rome. The Romans learned writing in about 500 BC from the Etruscan civilization, who used one of many Italic scripts derived from the western Greeks. Due to the cultural dominance of the Roman, the other Italic scripts have not survived.

The Italic scripts also inspired the development of English. English writing was not common until the 600 AD, when the Latin language and its writing system were brought to Britain by Augustine of Canterbury together with the Christian religion. The Britain rulers quickly adapted the script for their own language and produced literatures in English.

1.2.2.5 Middle Age (500 AD to 1350 AD)

In the Middle Age, there were three major developments in world history [9] [10] [11]: the expansions of civilizations, ‘complex societies featured by urban development, social stratification and symbolic communication forms’ [45], into new areas – in Asia, Africa and Europe, such as China, India, the Middle East and North Africa and Byzantium; the increasing influence of major world religions, such as the development of Islam; and the increasing international communications in the Eastern Hemisphere. In European history, this period coincided with the Middle Age, and then it was labeled by ‘medieval’.

Human Activities. Scholars often divided the Middle Age into three time periods: “an early phase; the central or high middle age; and a later period, when medieval patterns of culture began to decline.”

The general characteristics of the *Early Middle Age* were “the collapse of the centralized state, which had provided much of Western Europe with law and social order. “

In the *High Middle Age*, Europe saw great agricultural expansions, which provided a basis for large population growth. The international trade linked Europeans with many parts of the eastern Mediterranean, East Africa, East and Southeast Asia.

In the *Later Middle Age*, it began with significant changes: “the end of optimal hydrological and thermal conditions that had produced large harvests between 1000 and 1250 AD caused a great number of social disorders.”

Knowledge Discipline Developments. sociology and statistics are the new born knowledge disciplines during the Middle Age.

Table 1-7 New Knowledge Disciplines Born in Middle Age

Knowledge Discipline	**Event**
Sociolog [46] y	“Ibn Khaldun, a 14th century Arab Islamic scholar from North Africa, was considered the first sociologist; his Muqaddimah was the first work to advance social-scientific reasoning on social cohesion and social conflict.”
Statistics [47]	“The earliest writing on statistics appeared in a 9th century book entitled *Manuscript on Deciphering Cryptographic Messages* by Al-Kindi. Al-Kindi provided a description of how to use statistics and frequency analysis to decipher encrypted messages.”

Knowledge Documentation Method. During the Middle Ages, paper spread from China through the Middle East to medieval Europe in the 13th century, where the first water-powered paper mills were built. The dramatic increase in demand for paper and the printing techniques caused the dramatic cost reduction. Block printing became common in China by 1300 [43]. When paper became relatively easily available, around 1400, it gradually dominated the documentation medium.

After the collapse of the Roman authority in Western Europe, the literary development was confined to the Eastern Roman Empire and the Persian Empire [44]. Latin rapidly declined in importance. The primary literary languages were Greek and Persian.

The rise of Islam in the 7th century led to the rapid rise of Arabic as a major literary language in the region. Arabic and Persian quickly became the main language of scholarship. Arabic script was adopted as the primary script of the Persian language and the Turkish language. This script also heavily influenced the development of the cursive scripts of Greek, the Slavic languages, Latin, and other languages.

1.2.2.6 Early Modern Period (1350 AD to 1800 AD)

The Early Modern Period started after the Middle Age and lasted until the 20th century. The most significant contribution is the development of science and technologies [9] [10] [11]. In addition, capitalist economies was born.

The Renaissance was one of the two major revolutions in the Early Modern Period. It was initiated by the rediscovery of the classical world's scientific contributions, and it triggered the drastic economic and social development of Europe. It was considered so important in human history because it led to the Scientific Revolution in technologies.

Figure 1-11 Renaissance and Industrial Revolution Achievements [13]

The Industrial Revolution was the other major event in the Early Modern Period, and it was one of the most important changes in human history. It meant "a shift from an agrarian, handicraft economy to one dominated by machine manufacturing and division of labor."

Human Activities. In the Early Modern Period, the representations of technology developments were steam engines and machinery. These were crucial to the success of the Industrial Revolution, because they offered a capability of manufacturing goods more quickly and efficiently, exceeding previous human imagination. From then on, technology played a more and more important role in everyday life, becoming a dominant force in changing people's ways of lives.

Knowledge Discipline Developments. Pushed by the Renaissance and the Industrial Revolution, many new disciplines, especially science and engineering disciplines, were born during this period.

Table 1-8 New Knowledge Disciplines Born in Early Modern Period

Knowledge Discipline	Event
Material Science [48]	"A major breakthrough in the understanding of materials occured in the late 19th century, when the American scientist Josiah Willard Gibbs demonstrated that the thermodynamic properties were related to the physical properties of a material."
Electrical Engineering [49]	"Electricity has been a subject of scientific interest since at least the early 17th century. The first electrical engineer was William Gilbert who designed the versorium."
Computer Science [50]	"Wilhelm Schickard designed the first mechanical calculator in 1623, but did not complete its construction. Blaise Pascal designed and constructed the first working mechanical calculator, the Pascaline, in 1642."
Chemical Engineering [51]	"George E. Davis gave a series of lectures on molecule operations at the Manchester Technical School in 1887, and it was considered to be the earliest development in chemical engineering field."
Aerospace Engineering [52]	"The modern age of aviation began with the first untethered human flight on November 21, 1783, in a hot air balloon designed by the Montgolfier brothers."
Economics [53]	"Modern economic analysis began with Adam Smith (1723–1790). Smith described the physiocratic system "with all its imperfections.""
Ethnology [54]	"The term ethnologic was credited to Adam Franz Kollár who used and defined it in his *Historiae Ivrisqve Pvblici Regni Vngariae Amoenitates* published in Vienna in 1783."
Journalism [55]	"Johann Carolus's *Relation Aller Fürnemmen and Gedenckwürdigen Historien*, published in 1605 in Strassburg, was often recognized as the first newspaper."
Industrial Engineering [56]	"Efforts to apply science to the design of processing and production systems were made by many people in the 18th and 19th centuries."
Geology [57]	"Abraham Werner created a systematic classification scheme for rocks and minerals — a significant achievement for geology around 19th century."
Archaeology [58]	"Flavio Biondo, an Italian Renaissance humanist historian, created a systematic and documented guide to the ruins and topography of ancient Rome in the early 15th century for which he has been called an early founder of archaeology."

Knowledge Documentation Method. Due to printing technologies development, paper became the dominant documentation media. Books were published around the world, and more and more people gained access to knowledge.

In the 14th century renaissance emerged in Western Europe, leading to a temporary revival of the importance of Greek and Latin as a significant literary language. [44] At the same time, Arabic and Persian slowly declined in importance as the Islamic Golden Age ended.

The revival of literary development in Western Europe led to many innovations in Latin alphabet and the diversification of the alphabet.

1.2.2.7 Modern Period (1800 AD to Present)

The Modern Period witnessed "the apex of the European countries' wealth and power, which was contributed by their social and technological dominance over Eastern lands." [9] [10] [11] However, after World War II, two major nations, the United States and the Soviet Union, became the dominated power.

The 21st century features the highly interlinked economies across the world and developed communication technologies, which makes the world a smaller and smaller place. On the other hand, competition intensifies for natural resources among countries due to growing populations.

Human Activities. In the early Modern Period, science and technology were becoming increasingly international but major developments concentrated in Europe and the U.S.A..

> "The exploration of the earth's upper atmospheric regions and outer space represents an important part of global affairs in the second half of the 20th century. Many endeavors, like space travel which had been the subject of the science fiction genre, were accomplished.
>
> The development of new means of communication and information management created a revolutionary transformation of every aspect of human life. New modes of international communications, along with large international business organizations, produce more intense global cultural interactions. English increases in importance and is the most commonly learned second language."

Knowledge Discipline Developments. The development of information technology has been the main progress during the present era. The new born knowledge disciplines are:

Table 1-9 New Knowledge Disciplines Born in Modern Period

Knowledge Discipline	**Event**
Information and Communications Technology [59]	"The phrase ICT was created and used by academic researchers in the 1980s. It is a more specific discipline that stresses the role of unified communication and the integration of telecommunication."
Systems Theory [60]	"Systems theory as an area of study developed from the work of Ludwig von Bertalanffy and others in the 1950s, specifically catalyzed by the Society for General Systems Research."
Environmental science [61]	"Environmental science came alive as an active scientific investigation in the 1960s and 1970s, driven by (a) complex environmental problems, (b) the arrival of substantive environmental laws, and (c) the public concerns on environmental issues."
Agricultural Engineering [62]	"The first development in Agricultural Engineering was initiated at Iowa State University by J. B. Davidson in 1905, which applied engineering science and technology to agricultural production and processing."
Biological Engineering [63]	"The first development in biological engineering was made at Mississippi State University in 1967, focusing on the application of concepts and methods of biology to solve real-world problems related to the life sciences."
Petroleum Engineering [64]	"The field was initiated in 1914 within the American Institute of Mining, Metallurgical and Petroleum Engineers (AIME). Since then, the profession has evolved to solve increasingly difficult oil mining situations."
Software Engineering [65]	"Programming languages started to appear in the 1950s. Major languages such as Fortran, ALGOL, and COBOL were released in the late 1950s to deal with scientific, algorithmic, and business problems."

Knowledge Documentation Method. Because of the development of computer technologies, a completely new documentation medium has been born: the electronic documentation medium, and it includes hard drive, ROM and RAM. Although the paper documentation medium is still popularly used, electronic documentation is becoming more and more important. Electronic documentation media utilize the keyboard as the man-machine interface, electrical storage devices, and the screen for displaying data, information and knowledge.

The writing systems keep evolving due to the development of new technologies over the centuries. The computer and the mobile phone have altered the written ways. For example, characters can be formed by the press of a button, rather than making the physical motion. In addition, written communication can be delivered with little time delay, such as email and SMS. Writing is more often seen as an authoritative means of communication, such as legal documentation and government announcement.

Summarized from the above review, the development history of knowledge and its management methods can be categorized into three eras according to the types of knowledge documentation media: the natural objects dominated period, the paper like material dominated period and the electronic media dominated period. In each period, the time span, the new born knowledge disciplines and the knowledge developing speed are concluded within the following table:

Table 1-10 Summary of Knowledge and Its Management Methods Development History

Period	**Time Span (Year)**	**Number of knowledge disciplines (Discipline)**	**Knowledge generation rate (Discipline/Year)**
Natural object	200,200	25	$1.25*10^{-4}$
Paper	1,740	17	$9.77*10^{-3}$
Electronic	75	5	0.07

1.3 Problems with Current Knowledge Management Methods

The development history of knowledge and its management methods is summarized in Figure 1-13. This figure is not drawn in a linear time scale in order to illustrate the highly non-linear or accelerated knowledge development pattern. It can be observed that the knowledge developing speed is still accelerating. If it was plotted in a linear time scale as in Figure 1-12, the details of knowledge development in the later periods could not be shown.

In Figure 1-13, there is a line standing for the amount of non-academic knowledge which is mainly documented in human brains. Most of this knowledge is closely related to human daily life and satisfies the living requirements. For example, the knowledge of walking and eating is taught to each person at the very early ages and passed from generation to generation. However, it is never formally documented in any academic discipline. Taking this kind of knowledge into consideration, it gives a complete overview of the development history of knowledge, including academic and non-academic knowledge.

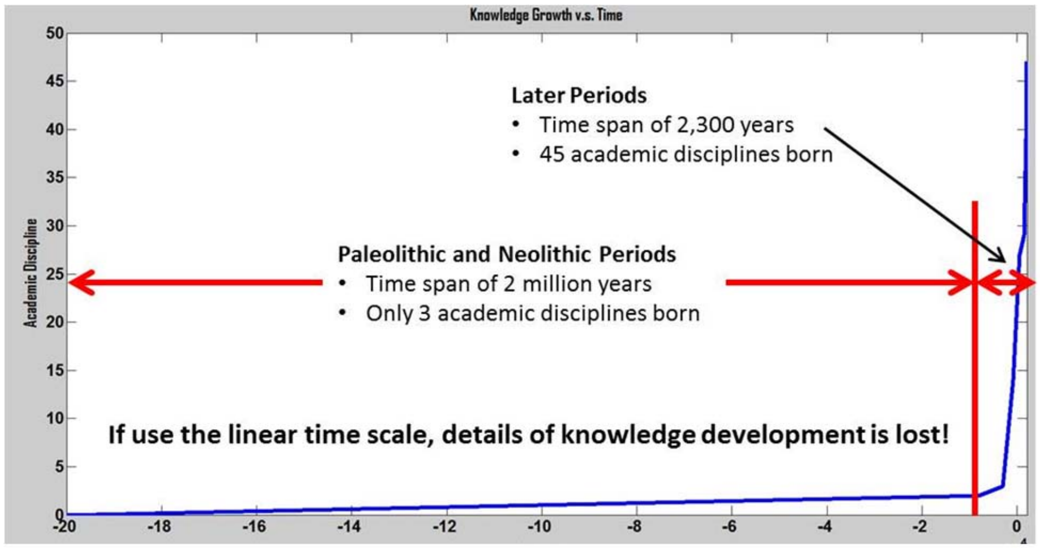


Figure 1-12 Knowledge Disciplines Development throughout Human History - Linear Time Scale

Based on the knowledge development history and review produced above, the requirements for knowledge management methods are:

1. Efficient knowledge management methods are needed to accelerate new knowledge discoveries. In the periods when natural objects were used as the main knowledge documentation media, from 200,000 BC to 200 AD, the time span is 200,200 years and the new born knowledge disciplines were 25. For the whole period, the knowledge generation rate was 1.25E-4 discipline/year; Then in the periods when paper like materials were used as the main knowledge documentation media, within a time span of 1,740 years, 17 new knowledge disciplines were born, so the knowledge generation rate was accelerated to 9.77E-3 discipline/year. Later during the electronic knowledge documentation media period, the time span is 75 years and 5 new knowledge disciplines are

born, so the knowledge generation rate is further increased to 0.07 discipline/year. As a result, the generation of new knowledge can be accelerated as the knowledge management methods improve. This can be, in part, attributed to the fact that the progress in knowledge documentation media, from natural objects documentation media to paper-like materials and electronic documentation media, helps people learn and transfer knowledge much more easily. As a result, it helps more people become educated, leading to more research activities and resulting in more discoveries of knowledge.

2. Efficient knowledge management methods are needed to handle the huge amount of latent or existing knowledge. Currently, a huge amount of knowledge already exists, and it is still growing at a high speed. As a result, people are easily overloaded by reaching their natural band-width. Existing knowledge disciplines keep developing. For example, Art has evolved into 6 sub disciplines and 47 research fields [66]. In addition, the current age resembles an information explosion era. Until August 2005, there had been over 70 million web servers. As of September 2007, there were over 135 million web servers [67] [68]. According to Sifry's Alerts, the number of blogs doubles roughly every 6 months, with a total of 35.3 million blogs by April 2006 [69]. All of those statistics demonstrate the dramatic growth of knowledge around the world. However, our knowledge management methods have not changed much in contrast. They are still natural objects, such as stones and walls; paper like materials, such as books and journals; and electronic media, such as hard drives and ROMs. More advanced knowledge management methods are needed to help humans deal with the overwhelming amount of knowledge.

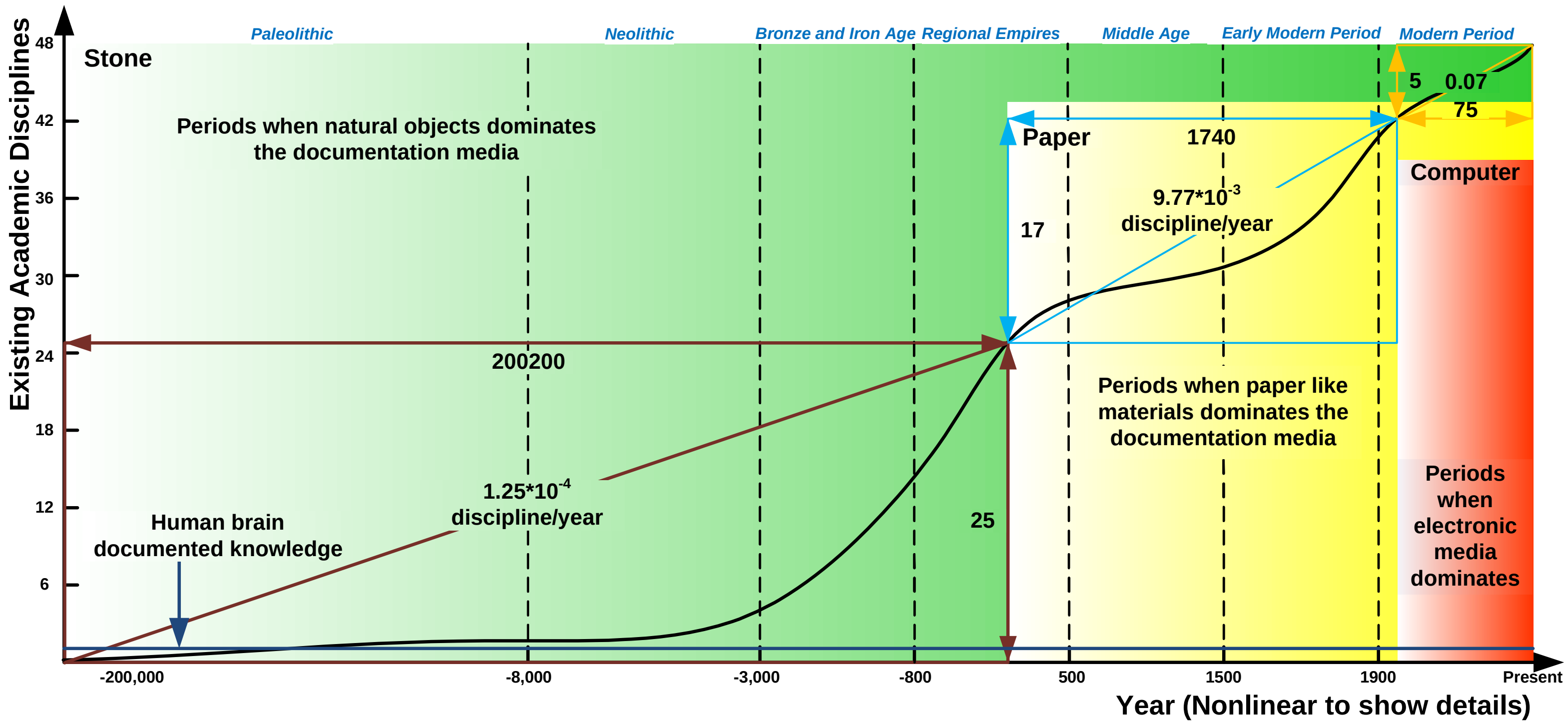


Figure 1-13 Knowledge disciplines development progress throughout human history

Current knowledge management methods can not satisfy the requirements because of the following reasons:

1. Knowledge preservation is intermittent. The experts, who master cutting-edge knowledge do retire and eventually pass away. As a result, successor engineers will not have a chance to inherit the intelligence fortune from the older generations, and the knowledge will be lost temporarily or even permanently. For example, in Boeing, "…*more than half of the Boeing work force will be eligible for retirement within the next decade. That is approximately 80,000 employees' cumulative corporate wisdom walking out the door*. …" [70] These types of situations will result, as a fact, in significant knowledge loss.

2. Knowledge accessibility is difficult. Knowledge cannot be easily transferred because of current knowledge management methods, such as knowledge recorded in reports and books. As a result, research groups around the world do not learn from others and only work independently, and their research efficiencies are quite low. For example, four generations of flying wing aircrafts were developed in isolation [71]. Researchers are not even aware of the existence of past flying wing design knowledge.

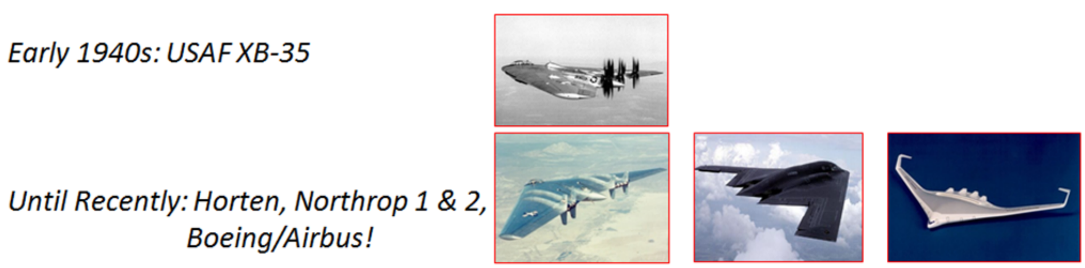


Figure 1-14 Isolated Evolutions of Flying Wing Design [71]

3. Knowledge applications are inconsistent. Past knowledge is usually obtained from different methods or by different researchers. Minor differences may exist in content, but the current knowledge management methods cannot help users

discover them. In addition, for the same knowledge, interpretations from different experts can be different and even contradictory because of different understandings. Both of the above reasons lead to inconsistent results during knowledge application processes.

4. Knowledge storage cost is high. Because of the human resources, space and maintenance requirements of conventional knowledge management methods, the cost of keeping knowledge can be very high. "… *In Princeton University, the Firestone Library currently has more than 70 miles (110 km) of bookshelves, and is served by about 370 maintenance staff members. It is only one of its libraries. …*" [(72)] The cost includes not only the investments in hardware, such as buildings and shelves, but also the investments in maintenance and service, such as staff wages, resulting in a large cost-overhead.

To deal with those deficiencies, a new knowledge management method is needed. Before we introduce our novel knowledge management methodology, there is a necessity to introduce the *Artificial Intelligence* technologies on which our knowledge management toolset is based.

1.4 Research Contribution Summary

The original research contributions from Chapter 1 are as follows:

1. A pragmatic assessment of data and knowledge management, during the research and product development processes points to a staggering weakness of the process routinely employed. While the majority of the research and engineering community nowadays tend to focus on developing high-fidelity analysis tools, the importance of data and knowledge management to the success of research and the product development processes is generally underestimated., overall resulting in insufficient understandings to expose this apparent weakness.

2. Through surveying the development history of knowledge and its management methods, this chapter does conclude the necessity of developing a new knowledge management method which should be much more efficient than existing methods, such as books, journals and hard drives.

Chapter 2

Introduction to Knowledge, Artificial Intelligence and the Knowledge-Based System

After justifying the necessity of developing a more efficient knowledge management method in Chapter 1, it is necessary to review the research in knowledge and obtain a profound understanding about it at first.

2.1 Epistemology

Epistemology, as a terminology, was proposed by Scottish philosopher James Frederick Ferrier (73). It is a branch of philosophy which explores the nature and scope of knowledge. The main research areas include:

1. Knowledge definitions: what knowledge is.
2. Knowledge sources: how knowledge is obtained.
3. Knowledge evaluations: how knowledge is assessed.

2.1.1 Knowledge Definitions

The discussion on knowledge definitions has existed for thousands of years. In ancient times, Plato (74) argued that the knowledge is the truth-bearer.

However, this classic concept was challenged by American philosopher Edmund Gettier. He argued that the true beliefs could be categorized into poorly-justified true beliefs and well-justified true beliefs (75). Only the well-justified true beliefs can be considered knowledge. This means that there are cases in which one belief is justified and true, but cannot be considered knowledge, because their justification processes are not conducted correctly. For example, the justification processes may lead to the truth only by luck.

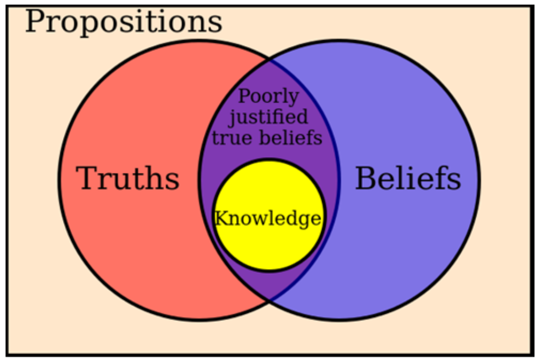


Figure 2-1 Edmund Gettier's Definition of Knowledge(75)

Although Edmund's definition was a breakthrough for the classical characterizations of knowledge, other researchers proposed additional criteria to define knowledge more accurately. Robert Nozick used four criteria to define knowledge (76):

1. P, a belief;
2. S (a person) believes that P;
3. If P were false, S would not believe that P;
4. If P is true, S will believe that P.

After all of those four conditions are met, the S's belief in P can be defined as knowledge. Nozick believes the counterfactual conditions (condition 3 and 4) provide an improved clarification of knowledge which he names the "*tracking theory*" of knowledge.

Compared to previous researchers' work, then AVD working definition of knowledge will be introduced in later sections.

2.1.2 Knowledge Sources

Knowledge can be obtained through the following sources (77):

1. Language
2. Sense perception
3. Emotion
4. Reasoning

5. Intuition
6. Memory

Language. It refers to knowledge obtained through communications [77]. People usually learn knowledge used in daily life through communicating with others, such as how to use the new bus check-in system. However, the language learning method is often filled with problems, such as misunderstandings, ambiguity and subjective interpretations.

In addition, language also plays an important role in documenting and transferring knowledge. As a result, some researchers claim that language is part of the knowledge itself and not just a description of it.

Sense Perception. It refers to knowledge obtained through sensory organs [77]. The human body has five senses: sight, touch, scent, taste and sound. Those senses help humans gain knowledge about concrete things in the world. For example, children can learn that leaves are usually green through sight.

However, prior experiences might be required before sense perception learning can happen. For instance, people can only judge the improvements or new features of products based on the pre-acquisition of their background knowledge.

Emotion. It refers to the knowledge obtained through emotional feelings [77]. Darwin believed that emotions are purely physiological, so it is universal. Learning via emotion helps humans gain social and cultural knowledge, such as the traditions of festivals. However, emotion has sometimes been regarded as an unreliable method of learning, and it may become an obstacle for learning because of irrational emotional influences.

Reasoning. It refers to the knowledge obtained through the deduction from given starting points or premises [77]. It is closely linked to logic and is unrelated with senses and emotions. Most scientific and engineering knowledge is gained through reasoning, such as the *Theory of Relativity*. Reasoning can be classified into two categories: inductive reasoning and deductive reasoning. Inductive reasoning is the process of concluding general knowledge from many particular cases; while deductive reasoning uses a general principle to predict a particular case.

Intuition. It refers to the knowledge obtained without rational deductions, which is contrary to the reasoning based learning. Intuition is characterized by learning knowledge without understanding it, and it is associated with nature. For example, we have an intuitive capability to eat and drink.

However, because intuition based learning is to know something through an immediate awareness, some researchers argue that it is impossible to tell the differences of people's capabilities in intuition learning. For example, some people are considered more intuitive than others, who can make quicker and more accurate instinctive decisions.

Memory. It refers to the knowledge obtained through retrieving past experiences. Contrary to the sense perception learning, a memory learning refers to the process of learning knowledge from things which are not currently happening. Interpretation of new situations can be heavily influenced by memories. As a result, memory is a method which helps people gain knowledge and handle new situations. However, the memory learning is often regarded as unreliable. For example, it is subjective or heavily influenced by emotions.

These knowledge learning methods will be used as a basis to propose one of the AVD knowledge evaluation criteria, which will be discussed in later sections. Moreover, the knowledge used to construct the AVD knowledge base is engineering knowledge, which is mainly obtained through the reasoning based learning. It is the most reliable method of gaining knowledge. The obtained knowledge is always justified by experiments and simulations, and reviewed by thousands of peers and demonstrated thus validated & calibrated via hundreds of projects.

2.1.3 Knowledge Evaluation

Knowledge is obtained from different sources through various approaches, so it is necessary to have a criterion to differentiate its qualities. Considering knowledge covers a broad range, including engineering, science, and laws, some researchers propose criteria using very general scales. Ernest Sosa (78) uses the AAA criterion to evaluate knowledge: Accurate, Adroit and Apt.

2.1.3.1 AAA

- Accurate evaluates the correctness of knowledge. If an application of knowledge leads to the right result, the knowledge is accurate.
- Adroit evaluates the capability of the knowledge manifesting the user's skills. If an application of knowledge is based on the user's skills instead of external factors, such as luck, the knowledge is adroit.
- Apt evaluates both the accurate and adroit of knowledge. If the knowledge is both accurate and adroit, it is apt.

For example, a student is doing a multiple-choice problem. If the knowledge he/she uses leads to the right answer, it is accurate. However, there is a case: although the answer is right, the student uses a dice to make the selection. Then the knowledge is not adroit, because it does not demonstrate the student's skills for the problem. At last, if the student uses the knowledge learnt in class and makes the right selection, the knowledge is apt because it leads to the right answer and demonstrates the student's skills.

2.1.3.2 CERC

In addition, some researchers include many other factors, such as evaluator backgrounds and application guidelines, into the overall knowledge evaluation processes.

Montserrat Prats Lopez [79] proposes a four-step evaluation criterion: Consciousness, Evidence, Reasoning and Criteria (CERC).

Consciousness is the evaluation factor related with the evaluator's background. The evaluator's prior knowledge inevitably influences the evaluation process. For example, for the same piece of history knowledge, an evaluation from a historian is probably closer to its true value than one from an engineer.

Evidence is the base from which the knowledge is deduced. It can be experiments, observation facts, past experiences and established theories. Those evidences contribute to knowledge qualities. For instance, the knowledge deduced from experiments has a higher quality than one summarized from observations.

Reasoning is the bridge connecting the knowledge with its foundations, and it explains how a knowledge conclusion is made. It has many methods, such as logic deductions and mathematical reasoning. For example, in engineering fields, researchers use strict mathematical deductions to develop new knowledge based on simulation and experiment results.

Criteria are related with the knowledge application areas, and they determine the application value of the knowledge. Different application fields have different requirements for knowledge, so even for the same piece of knowledge, it shows different values in different application fields. For example, in a company, the value of knowledge is determined by the amount of profits it can bring to the company; while in research organizations, the value of knowledge is determined by its innovativeness and benefits to the society.

After reviewing other researchers' work, an AVD knowledge evaluation criterion will be proposed in the following section.

2.1.4 AVD Knowledge Definition and Evaluation

The KBS research at the AVD Laboratory focuses on the management of aerospace engineering knowledge utilized during the early conceptual design stage. As a result, the aerospace knowledge can be defined as valuable guidelines stemming from past project activities and research efforts, overall carrying value to be used to guide current and future aerospace technology developments and decision-making processes.

The AVD knowledge evaluation process is defined to stem from three principal aspects: *acquisition, storage* and *application*. For each of those sub-attributes, the knowledge piece is divided into evaluation categories at first; then for each evaluation category, it will be further characterized into several subcategories and be quantitatively measured by evaluation parameters with physical meanings; At last, an evaluation index, the *efficiency index*, is proposed to systematically organize those parameters into a single parameter to offer a clear indication of the overall quality of the knowledge.

<u>*Acquisition*</u> evaluates the quality of knowledge based on its sources. The knowledge piece can be obtained from various sources, such as languages, sense perceptions and reasoning. In addition, they are derived from different periods. Some have evolved more than one hundred years and have been demonstrated thousands of times, while some have just been born and have not been put into any practice. All of those factors influence the qualities of knowledge. As a result, the acquisition aspect is categorized into two categories: (a) *source* and (b) *evolving periods*.

In the (a) *source category*, knowledge sources are divided into *observational sources* and *correlational sources*, and both of them are quantitatively measured by the parameter *accuracy* (%). In the (b) *evolving periods* category, knowledge evolving periods are characterized by *time length* subcategory, and are quantitatively measured by the parameter *accumulation* (years).

Storage evaluates the quality of knowledge based on its documentation methods. Knowledge is documented in many media, such as stones, bamboo, papers, books and hard drives. Some are easier to transport, like books and hard drives; while some are more difficult or even impossible to move, such as stones or walls of caves. As a result, the storage aspect is measured by *medium* category. In the medium category, knowledge storage media are evaluated by (a) *space* and (b) *weight* subcategories, which are quantitatively measured by parameters (a) *storage density* (GB/cm^3) and (b) *storage cost* ($/GB).

Application evaluates the quality of knowledge based on its utilization fields. The knowledge application can be classified into (a) *transfer* and (b) *retrieval*. The transfer refers to the knowledge utilized in education, and retrieval refers to the knowledge utilized in all of the other activities, such as work.

In the (a) *transfer* category, knowledge application is characterized by the *completeness* subcategory, which is quantitatively measured by the parameter *completeness* (%); In the (b) *retrieval* category, knowledge application characteristics are described by *relevance* and *correctness*, which are quantitatively measured by parameters *relevance* (1/0) and *correctness* (%), respectively.

The details of the *AVD knowledge evaluation criterion* will be further explained in Chapter 4. Table 2-1 compares the AAA, CERC and *AVD knowledge evaluation criterion*.

Table 2-1 Knowledge Evaluation Methods Comparison

Item	**AAA**		**CERC**		**AVD Evaluation Criterion**	
Evaluation Aspects	✓	Accurate Adroit Apt	✓	Consciousness Evidence Reasoning Criteria	✓	Acquisition Storage Application
Evaluation Category	✗	None	✗	None	✓	Source, Evolving Period Medium, Representation Method Transfer, Retrieval
Evaluation Subcategory	✗	None	✗	None	✓	Observational, Correlational, Time Length Space, Weight Completeness, Correctness, Relevance
Evaluation Parameters	✗	None	✗	None	✓	Accuracy, Accumulation Storage Density, Storage Cost Completeness, Relevance, Correctness
Evaluation Index	✗	None	✗	None	✓	Efficiency Index

2.2 Artificial Intelligence

Artificial Intelligence (AI), as a branch in computer science, aims to analyze and build intelligent agents, mimicking the human ways of solving problems. It was formally founded by John McCarthy, Marvin Minsky, Allen Newell and Herbert Simon at Dartmouth College in the summer of 1956 [80].

Figure 2-2 AI Birth conference at Dartmouth College in 1956 Summer, from Left: Trenchard More, John McCarthy, Marvin Minsky, Oliver Selfridge, and Ray Solomonoff [80]

Its objectives contain thinking humanly, which includes reasoning activities such as learning and decision-making; and acting humanly, which includes rational movements, such as autonomous navigation.

The idea of artificial intelligence can be traced back to ancient Egyptian myths, such as the Talos of Crete [80]. However, its real development started after the birth of computers. The tree search model, *The Logic Theorist*, was developed by Allen Newell et al [81] in the late 1950s to solve problems through mimicking human problem solving skills. It was considered the first AI program. Afterwards, the research of AI went through a prosperous period, during which the development of the LISP language and the General Problem Solver (GPS) were the achievements. Government organizations, such as DARPA, also provided huge amounts of funding to support the research, expecting the "*… machines will be capable, within twenty years, of doing any work a man can do. …*" [82]. The early peak in AI development was the birth of *expert systems*, which could provide suggestions like a real expert. They had extensive applications in industries, including forecasting the stock market, aiding doctors with diagnoses and predicting mine locations. However, the development of AI slowed down in the 1980s because of technical constraints. After the birth of *fuzzy logic*, AI began its recovery and gained more applications. It was put into use in war during Desert Storm in the 1990s as missile guidance systems. More recent examples are the IBM chess player *Deep Blue* and quiz answerer *Watson*.

The main topics in AI research are [83]:

1. *Representing*: aims to solve issues related with representing objects from the real world in an electronic way.
2. *Searching*: aims to solve issues concerning finding a path to achieve a goal through a sequence of actions within an environment.
3. *Learning*: aims to solve issues associated with obtaining knowledge from past experiences.
4. *Planning*: aims to solve issues regarding making a plan of what actions should be taken to achieve a goal in more general problems.

5. *Reasoning*: aims to solve issues regarding making logical judgments given the availability of collected information.

2.2.1 Representing

In order to make the smart agent be able to perceive, think and act, a method needs to be developed to help it "understand" the problem. This is the issue which is solved by the AI representing technologies. It figures out methods to represent the problem from the real world and make it understandable to an AI agent.

The representation methods can be categorized into syntactic representation and inferential representation in general [84]. The syntactic representation is the way in which the knowledge is stored in an explicit format and can be directly used, while the inferential representation is the way in which the knowledge is retrieved. The information representation can be divided into four levels. [84] [85]

1. Implemental Level. It clarifies the representing structure and searching mechanisms of the representation languages. From the syntactic aspect, the main concern is the structure of knowledge, such as how to organize the components of knowledge in order to put them into the computer, and whether they are compatible with the representation language.

   From the inferential aspect, the main concern is the searching mechanism. It determines whether the required knowledge is available and how to locate it.

2. Logical Level. It specifies the logical properties of representation languages, which are the denoting and reasoning functions. From the syntactic aspect, there are two main concerns: the first one is the meanings of the representation language, like what specific representation terminology means; the other one is the capability of the representation language, like what kinds of knowledge can be represented by the language.

From the inferential aspect, the main concern is the robustness of the inferential mechanism. The requirement is if the input is true, the searching mechanism should lead to the right result.

3. Epistemological Level. This specifies the necessary primitives in certain types of representations and the according inferential mechanism. The first concern is the primitives. For example, the essential knowledge primitives for the aircraft design are quite different from ones for the ship design. The second concern is the inferential mechanism. Different types of knowledge need different inferential mechanisms. For example, researchers in conceptual design are likely to use inferential mechanisms different from those who do research in detail design.

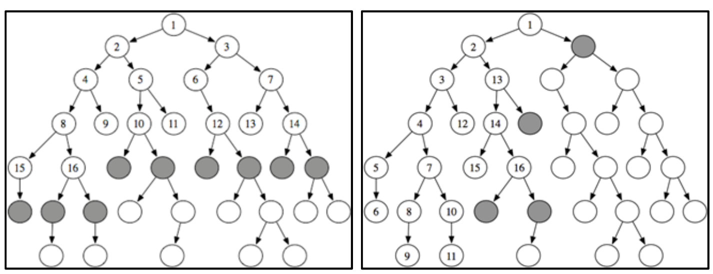
4. Conceptual Level. This level discusses the functions the primitives should have in order to satisfy the representation requirements. For example, if we want to express the relationship between two objects, should the relationship be an “is-a” relation? Or should it be a “has-a” relation? Or should it be “lead-to” relation? Or is there anything missing? All of the above should be considered in the knowledge representation development process.

2.2.2 Searching

Searching refers to the process during which the searching mechanism leads the intelligent agent from the current state to the destination state. There are generally two categories: the classical search and the beyond classical search. In the classical search, the problems are usually in an observable, deterministic and known environment; while in the beyond classical search, those environments can be either unknown or nondeterministic. [83]

Classical Search.

There are two categories in classical search: the uninformed search and the informed search. The uninformed search is the kind of problems in which all of the information is provided at the beginning. The intelligent agent is searching in a completely known environment. A typical example would be the search in the knowledge base because the knowledge base is a completely known environment, and locating and retrieving the stored knowledge is an uninformed search process. The methods used in the uninformed search are: breadth-first search, uninform-cost search, depth-first search, and bidirectional search. The breadth-first search is the search process in which the initial state is expanded first, and then all of those states will be expanded if the final state is not included in those states. The expansion stops if the final state is found. The uniform-cost search is the search process taking the expansion cost into account. Instead of expanding all of the current states, the uniform-cost search will expand the state with the minimum cost, which is determined by the cost function. The depth-first search is the search process during which the expanded state is always at the deepest level, and the expansion process stops until it cannot go any further or it meets the goal state. The bidirectional search is the process in which the search starts from both the initial and goal states, and they come toward each other until they meet.



(a) (b)

Figure 2-3 (a) Breadth-first Search and (b) Depth-first Search [83]

In the informed search, the intelligent agent receives extra information during the search process. It includes best-first search and A* search. The best-first search is the search process during which the expanded state is selected based on the search strategy function. A* search is the search process during which two cost functions are taken into account. The first function calculates the cost from the initial state to the current state, and the second function determines the cost from the current state to the destination state. Then the state with the minimum sum of the two costs will be chosen as the expanding state.

Beyond Classical Search.

There are mainly two kinds of beyond classical search methods: *local search* and *nondeterministic search*. Local search contains hill-climbing search, simulated annealing search and local beam search. Hill climbing search is the search process during which the current state continues moving towards the state with a higher value, so it will reach a state with at least a local peak. The simulated annealing search is the search process during which the next state is chosen among randomly selected states, and it moves towards the one with the highest value. The simulated annealing search prevents the confinement to local peaks. Local beam search is the search process in which a certain number of states are selected and expanded instead of only one. Among those expanded states, the same amount of new states will be selected for the next expansion.

In the nondeterministic search, the AND-OR search is broadly used. AND-OR search is a search process during which the next action is determined by the result consisting of ANDs and ORs. OR is the selection of the available actions; AND is the according outcome from the environment. The combination of ANDs and ORs lead the intelligent agent through the search process.

2.2.3 Learning

Learning refers to the process of the intelligent agent gaining new knowledge from the provided information. It is closely related to statistics, focusing on deducing fitting models. Learning provides a method to optimize the intelligent agent performances based on collected data and experiences. It is an alternative or even the only solution to problems under many situations, such as when the human expertise does not exist, like navigating on Mars, or when the solutions need to be adapted to particular cases, like user biometrics.

There are generally two types of machine learning: supervised learning and unsupervised learning. (83) (86)

Supervised Learning.

Supervised learning is the learning process during which the intelligent agent is offered examples of input-output pairs, and it develops a function linking input and output, which is the desired knowledge. Supervised learning has two categories: classification and regression. For classification, the learning output is a set of finite discrete values. Typical applications include spam email filtering; credit scoring, determining low risk or high risk; weather prediction, determining sunny, cloudy or rainy.

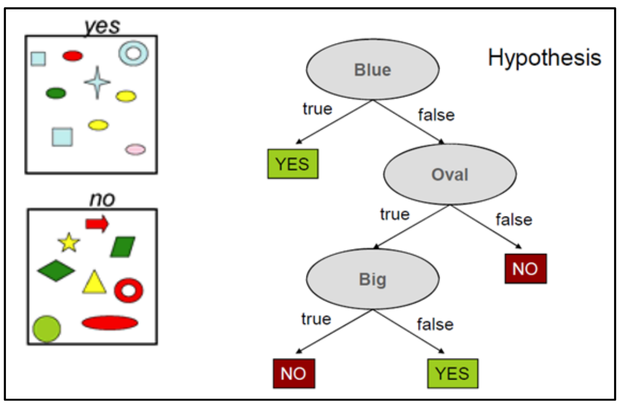
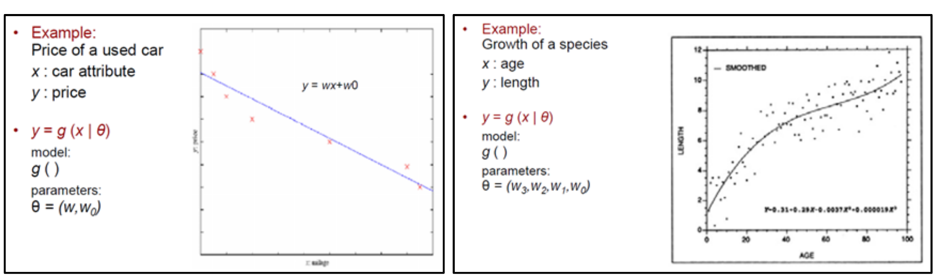


Figure 2-4 Example of Classification Training Sets and Determination Process (87)

Regression is the learning process during which the learning output is a set of continuous values. Typical applications include cost estimation, like energy consumption, and



(a) (b)

Figue 2-5 Regression Examples: (a) Linear and (b) Polynomial (87) trend predictions, like the stock market.

Unsupervised Learning.

Unsupervised learning is the learning process during which the intelligent agent is only offered examples of input, and no output is provided. The intelligent agent gains knowledge from identifying patterns within the input. The methods are clustering and dimensionality reduction. Clustering aims to detect objects with similar characteristics in the input examples, and a typical application is: image clustering, like face detection.

Dimensionality reduction is the process of reducing the number of input features based on the similarities. It chooses a subset of the original features, and transforms the input based on that.

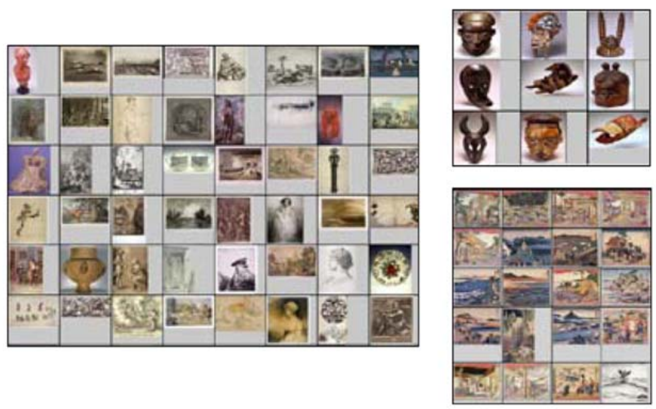


Figure 2-6 Image Clustering Example (87)

2.2.4 Planning

Planning aims at making a plan consisting of a series of actions to accomplish the task. A planning problem is similar to a searching problem, but there is a big difference between the two. (83) (88) In the searching problem, the research object is data structures; while in the planning problem, the research object is logical sentences. As a result, the planning problem is actually a more complicated high-level searching problem, and it needs to generate a logical sequence to accomplish the task.

The planning techniques are categorized into: state-space planning and plan-space planning. In the state-space planning, the agent works with states and their related operators, and it needs to find a plan to form a path to go from the start state to the goal state. The state-space planning can be divided into: progressive planning and regression planning based on starting states. In progressive planning, the agent starts from the initial state and the general process is that it determines all of the operators that are applicable to the starting state. Then it chooses an operator to apply. After that, it determines the content of the new state and available operators. The process will be repeated until it meets the final state. On the contrary, in regression planning, the agent starts from the goal state. At first, it selects the operator that will lead to a new state satisfying some of the goal state requirements; then it implements the operator and it will repeat the step until the current state matches the start state.

(a) (b)

Figure 2-7 Planning Techniques Applied in NASA Projects: (a) Deep Space 1; (b) MAPGEN [80]

In the plan-space planning, the agent works at the level of plans instead of states, and it aims at finding a satisfying plan through the space of plans.

Those planning techniques have been applied in several of NASA projects. The Autonav system in Deep Space 1 is used for autonomous navigation. In the MAPGEN, the planning and scheduling system is used for daily command sequence generation for the Mars Exploration Rover mission.

2.2.5 Reasoning

(87)Reasoning is the technique which helps the intelligent agent make decisions through logical judgments. According to its application environment, it can be divided into reasoning under a deterministic environment and reasoning under an uncertainty environment. (83) (89)

In the deterministic environment, the environment information is known and no unexpected thing happens. The methods are propositional logic and first order logic. Propositional logic is a simple logic method, and its syntax is quite clear and directly related to facts, so it is easy to be understood. However, its semantics only include “true” and “false”, so it has a limited expressive power, and it is difficult to express other meanings, like cause-effect relationship. First-order logic is a much more powerful method, and it assumes the world consists of objects, which are considered as elements. It uses functions to correlate one object to others in the same kind, such as father of, best friend of, and more than; It employs relations to express the relationships between objects from different kinds, like red, round, and prime. Functions and relations work together to help the agent make logical judgments.

In the uncertain environment, the problems are usually either partially observable, such as the strategies of other players, or uncertainty during the process because of external influences. In order to handle those situations, probability is used. Bayesian network is a graphical method used to express those probabilities. It represents a set of random variables and their dependencies via a directed acyclic graph. The intelligent agent can make its decision based on the probabilistic relationships.

2.2.6 Research Conclusion

Based on the above discussions, an overview of Artificial Intelligence (AI) development can be illustrated, see Figure 2-8. If Artificial Intelligence is considered as a tree, its life is supported by the *soil*, which is the hardware and methodologies, such as parallel processing, neural computing and fifth-generation computer systems. The *roots*, which make the tree stable and support its further development, are programming languages, such as LISP, PROLOG and smalltalk, and technologies, such as learning techniques, searching techniques, reasoning techniques, cognitive sentences and formal logic. The *branches* of the tree represent its broad applications, such as machine translation, speech recognition, voice processing, image processing, visual processing, intelligent robots, and knowledge-based systems. Although humans are also capable of accomplishing those tasks, artificial intelligence technologies can complete them in a much faster and mistake-proof manner.

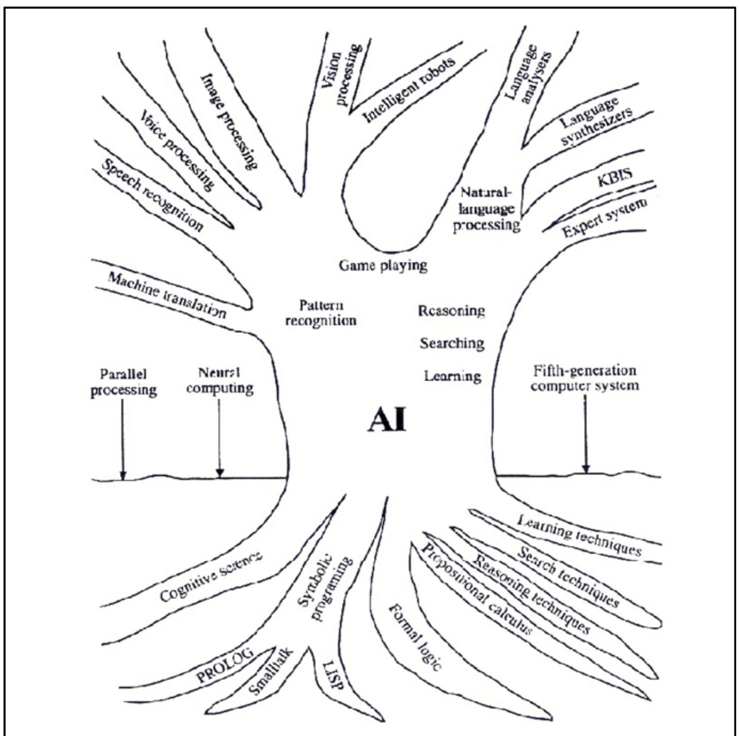


Figure 2-8 Artificial Intelligence (AI) Research Overview [88]

One of the most famous AI machine is HAL 9000, a fictional character in Arthur C. Clarke's movie *2001: A Space Odyssey,* which 'is capable of speech recognition, natural language understanding, lip reading, and thinking well enough to beat humans at chess.' [90] HAL 9000 inspires a lot of subsequent AI machines developments. One example is from Adam Cheyer. He dreams of building an actual HAL, and he serves as chief architect in Pentagon's CALO project, aiming at building cognitive assistants. After that, he 'works at Apple as director of engineering for the iPhone. Apple "acquired" Cheyer when it bought the company he co-founded, Siri Inc. The only difference is that HAL will live in iPhone.' [91]

Another example is from automobile industry.

> '…Audi recently introduced a HAL 9000 of sorts for all of its new car models. Called AviCoS, for Avatar-based Virtual Co-driver System, Audi's HAL was developed by researchers at Technical University Munich and Audi engineers. It functions as an in-vehicle expert about all the car's features and systems. The AviCoS system uses virtual reality and a video avatar to interact with the driver via spoken language. The system monitors what's happening with the car, but it avoids distracting the driver at inopportune moments -- during acceleration, for example. …' [91]

In addition to industry product development, academic researchers employs the cutting-edge AI techniques to develop design toolsets. One of the latest developments is from Varadraj Gurupur and Urcun J Tanik. [92] They propose an Artificial Intelligence Design Framework (AIDF) for developing software based on database, knowledge-based and inference engine. In the proposed framework, the database and knowledge-base store initial design information and domain knowledge. At the beginning, AIDF designs the software and verifies the correctness of the design according to its rule-base and risk-mitigation algorithms; Then if it finds that the design is fault free, it requests the user to verify the design. Once the design has been verified the code generator will generate the required code.

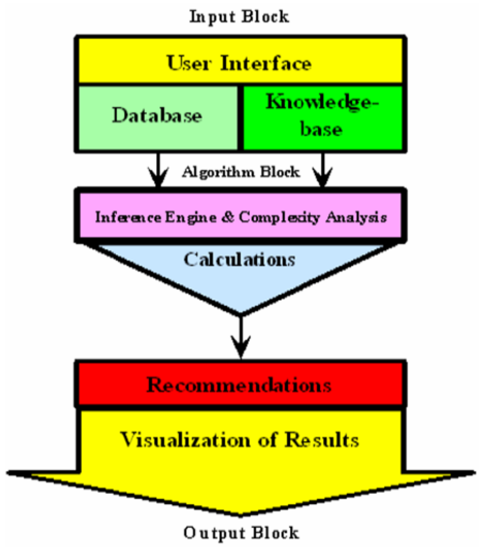


Figure 2-9 AIDF Methodology (92)

As an improvement, AVD Laboratory not only proposes a AI design methodology, but also builds the functional system and implements it into practices.

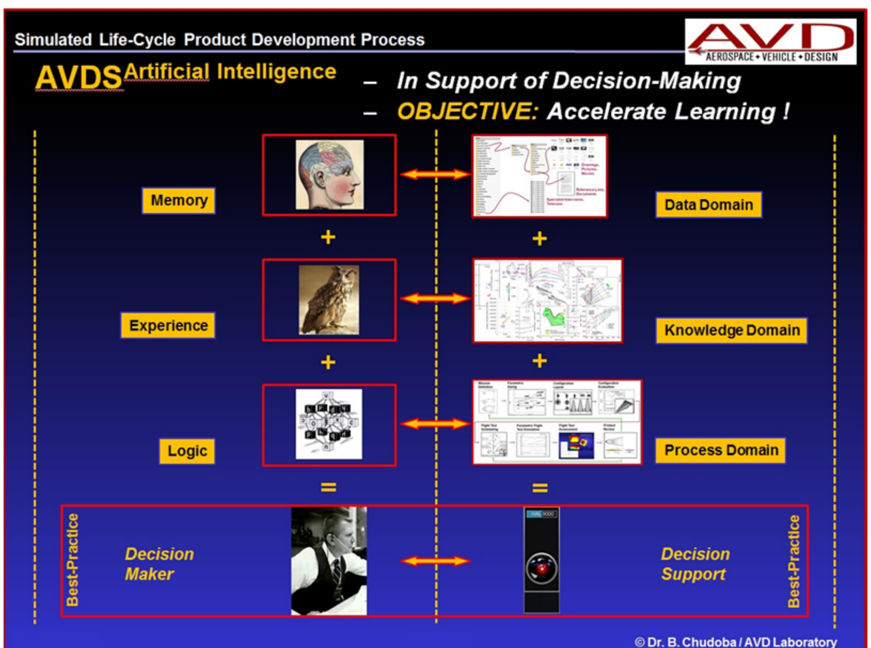


Figure 2-10 AVD AI Design Environment (93)

The AVD AI design environment [93] consists of the data domain, AVD^{DBS}, which resembles the human memories, the knowledge domain, AVD^{KBS}, which resembles the human experiences, and the process domain, AVD^{PP}, which resembles the human logic. Those three systems work together to finish AVD design tasks, resembling the process of human solving design problems. These AVD design tools will be further explained in Chapter 4.

Knowledge-Based Systems (KBSs), as an important research area in AI, mainly employ the following techniques: representing, searching, and reasoning.

Representing: information representing is an essential ingredient in any artificial intelligence application. For KBSs, it is mainly about the knowledge representation issues. It specifies the knowledge representation methods, including the knowledge representation structure, format and tools. It solves the problems regarding how the knowledge is stored and how it is retrieved from the knowledge base.

Searching: In KBSs, searching mainly refers to the searching process within the knowledge base, which leads the user to the required knowledge. The knowledge base is a deterministic, observable and completely known environment. As a result, KBS searching is an uninformed search, and both breadth-first and depth-first searches are usually employed.

Reasoning: In KBSs, reasoning mainly helps the user choose the right piece of knowledge. There are usually several pieces of knowledge in the field, but the question is which one to choose. The most common KBS reasoning technique is *Rule-Based Reasoning*. It makes the selection based on the input information.

As a result, the representing, searching and reasoning characteristics of the human brain, AI and KBS can be summarized in the following table:

Table 2-2 Comparison of Representing, Searching and Reasoning Functions in Human Brain, AI and KBS

Item	Human Brain	AI	KBS
Representing	Neuron based information storage and processing methods, while its mechanisms is still largely unknown Information is outputted in the format of natural language	Information stored in the format of syntactic and inferential representation Various programming languages are employed, like PROLOG and LISP	Knowledge stored in the knowledge base, which is built in programming languages, or software tools, like Excel and Access Inferential mechanism provided by the inference engine, which is developed by programming languages
Searching	"Attention" from certain neurons provides the searching capabilities [94] Searching can only be done in single task mode, while specific mechanism remains unknown	Searching is categorized into classical search and the beyond classical search Searching techniques, like breadth-first search, uninform-cost search and hill-climbing search, local beam search, are invented for both categories.	Searching is mostly done in a deterministic environment, which is within the knowledge base. The breadth-first search and depth-first search are the most common techniques for knowledge base
Reasoning	Generally classified into rational and instinct reasoning [95] Rational reasoning is mainly based on education, while instinct reasoning can be from both nature and education	Sorted by reasoning environments: deterministic and uncertain First-order reasoning and Bayesian network are broadly applied techniques in the according category.	Rule-based Reasoning is the most common technique Aim at figuring out the proper piece of knowledge for the problem

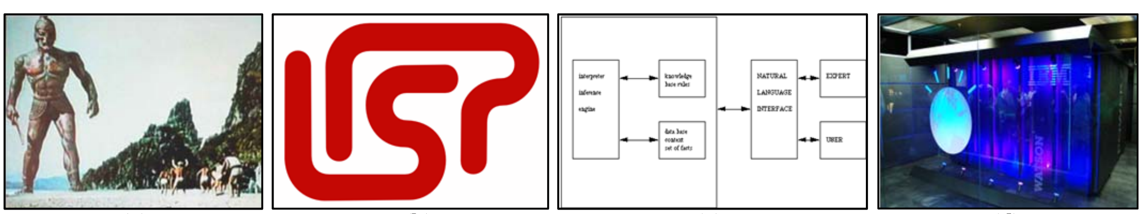
After reviewing the AI techniques, an introduction to the KBS will be given.

2.3 Knowledge-Based System

A KBS is an efficient knowledge management software that stores knowledge from human experts and is able to offer advice to help people solve problems, which normally require expertise.

2.3.1 Development History

The development of KBSs had not started until the birth of the first programmable computer, the Colossus Computer, during World War II [96]. It provided the hardware tool to



(a) (b) (c) (d)

Figure 2-11 (a) Robot of Hephaestus, (b) LISP, (c) Dendral and (d) Watson [96] develop KBSs. In addition to the hardware, the software tool, a high-level programming language, became available when the LISP language was born in 1958. After that, researchers developed the *General Problem Solver* [97]. It was the first program to separate the knowledge and the strategy of how to solve problems.

In the 1970s, the ancestor of KBSs, *Dendral*, was born. Its purpose was to use the KBS to discover chemical molecules, and identifying unknown organic molecules was chosen as its first application. Later, KBSs also had applications in industry. *R1* from Digital Equipment Corporation was the first successful commercial KBS. It helped manufacturing companies determine how to arrange manufacturing equipment according to customers' orders.

Starting in the late twentieth century, KBSs have extended their applications into more fields, such as equipment fault diagnosis and spam email filtering. Some of the most famous systems have even become stars that attract attention from all across the world, such as Watson, which can answer questions in natural languages and beat human players easily in the quiz show Jeopardy [98].

2.3.2 Knowledge-based System Components

In general, the components of KBSs can be illustrated by the following figure [99]

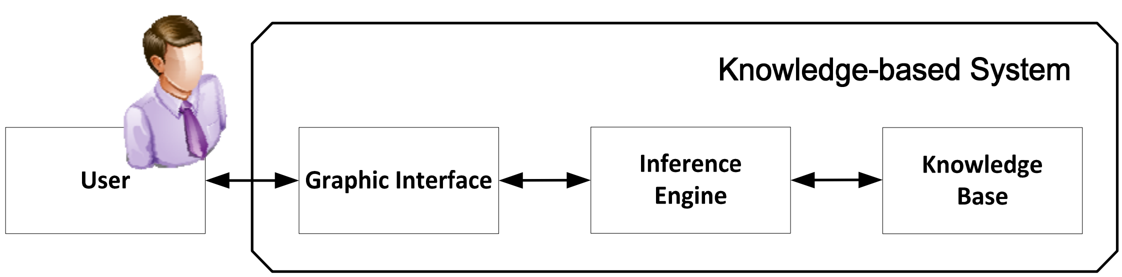


Figure 2-12 KBS Components

The user interface provides the user with access to the KBS, and it transfers the user's commands to the inference engine. The inference engine performs all of the KBS's functions. It uses the searching and reasoning techniques from AI. For the searching techniques, it locates knowledge candidates in the knowledge base. For the reasoning techniques, it uses logical judgments to make the selection from the knowledge candidates based on the input information. The knowledge base is a pool of knowledge, and it stores the knowledge content and the inference marks. It uses representation techniques from AI.

2.3.3 Knowledge-Based System Applications

Since the birth of KBSs, there has been broad applications in industry. Table 2-3 summarizes the application fields and their respective functions. [100]

Table 2-3 KBS Applications [100]

Application Fields	**Function**
Diagnosis	To identify a problem given a set of symptoms or malfunctions
Interpretation	To provide an understanding of a situation from available information
Prediction	To predict a future state from a set of data or observations
Planning	To make plan for both short term & long term in areas l
Monitoring	To check performance and flag exceptions
Control	To collect and evaluate evidence and form opinions on that evidence
Instruction	To train students and correct their performance
Debugging	To identify and prescribe remedies for malfunctions

In those applications, compared to human experts, KBSs offer the following advantages. [100]

- Knowledge storage is permanent. KBSs can master and apply knowledge like an expert, and this expert will never retire. Human experts, however, all eventually leave, retire and die.
- Knowledge transfer is easy. Knowledge kept in KBSs can be easily transferred and work at other places. However, human expertise cannot be easily transferred between persons, and it takes a long time for fresh people to gain knowledge from experts.
- Knowledge content is consistent. The knowledge stored in KBSs is always interpreted in the same way, which can prevent any mistake. Human experts, however, may make mistakes because of carelessness or bad mood.

– Knowledge maintenance cost is low. The cost of storing knowledge in KBSs is low and mainly consists of the cost of computer hardware. Human experts, however, cost much more money because of their wages.

2.3.4 Research Conclusion

Both KBS and traditional knowledge management methods can accomplish basic knowledge management functions, including *knowledge record*, *knowledge share* and *knowledge apply*.

– *Knowledge storage* functions refer to the knowledge management activities that happen between humans and the knowledge documentation medium, including knowledge edit and store.

– *Knowledge education* functions refer to the knowledge management activities that happen between humans, including knowledge transfer and educate.

– *Knowledge application* functions refer to the knowledge management activities that happen between humans and work, including knowledge utilization.

For those basic knowledge management functions, the KBS offers an efficiency increase. For example, a KBS can make changes to the knowledge content within seconds. However, if changes need to be made to the knowledge documented in books, it needs to go through a process of erasing, writing, book binding and so on. Those efficiency characteristics will be measured in terms of *processing speed, manipulation cost, storage density* and *storage cost*.

For the *knowledge education* functions, a KBS can transfer the knowledge to any place around the world within seconds. However, if the knowledge documented in books needs to be transferred, it takes at least several days to arrive in another continent. Those efficiency characteristics will be measured in terms of *manipulating speed* and *manipulating cost*.

For the *knowledge application* functions, because the knowledge is stored in electronic media, a KBS can directly apply it to the numerical analysis process conducted by computer. However, if the knowledge documented in books needs to be utilized, manual writing and calculating must be performed, which will take a much longer time. Those efficiency characteristics will be measured in terms of *analyzing speed* and *analyzing accuracy*.

In addition to those, the KBS approach also offers advanced knowledge management functions, like reasoning. A KBS can aid an analysis task by independently selecting the required piece of knowledge during analysis processes.

Those efficiency characterization parameters will be defined and explained in detail in Chapter 4.

Table 2-4 Comparisons between KBS and Traditional Knowledge Management Methods

Item	**Stone** -Cave, Wall	**Paper** -Book, Journal	**Computer** -Hard disk, Tape	**KBS**
Storage (Human – Media)		**Efficiency Increase** →		
Edit	✓	✓	✓	✓
Store	✓	✓	✓	✓
Education (Human – Human)		**Efficiency Increase** →		
Transfer	✓	✓	✓	✓
Educate	✓	✓	✓	✓
Application (Human – Work)		**Efficiency Increase** →		
Utilize	✓	✓	✓	✓
Intelligent Feature				
Reasoning	✗	✗	✗	✓

2.4 Research Contribution Summary

The original research contributions from Chapter 2 are as follows:

1. For the first time, propose a knowledge evaluation criterion, which takes characteristics of both the knowledge and user into consideration and uses quantification parameters with physical meanings to quantitatively substantiate the

evaluation. This development represents a significant progress compared to tradition qualitative knowledge evaluation criteria.

2. Innovatively assess the advantages of KBS over traditional knowledge management methods in terms of knowledge storage, education, application and reasoning. Those advantages demonstrate that the KBS is an ideal solution for knowledge management and stands for a substantial improvement.

Chapter 3

Knowledge-Based System Literature Review and Research Objective

An introduction of KBS, including its originality, components and applications, has been made in Chapter 2. In this chapter, a history review of KBS research development will be presented and classified. Although *Dendral*, the ancestor of KBSs, was developed in the 1970s [96], the KBS research community had not begun to extensively explore the field until the 1980s. Throughout the primary KBS literature search, 92 representative publications, consisting of journal and conference papers, were reviewed, ranging from 1984 to present. Those publications discuss the KBS research work performed in 26 disciplines, ranging from computer science and engineering to business fields. 248 authors from 137 research organizations contributed to those publications. Based on those literature sources, four KBS development stages are proposed: *early preparation, independent system, integrated system* and *new frontier*. Within the following sections, characteristics of each development stage will be explained in detail. A complete list of literature review publications can be found in Appendix A.

3.1 Literature Review

3.1.1 Early Preparation

In the early 1980s, computer science technologies developed rapidly in both hardware, such as the fifth generation computer system, and software, such as the programming language LISP. Researchers began to make technical preparations for the KBS development. The research progress in this era was mainly proposals for KBSs, and no functional KBS was developed. As a result, the period is named *early preparation*, and it has the following characteristics.

Researchers were mainly stemming from the computer science field. KBS is a branch in computer science. Researchers from computer science had the earliest chance to get in touch with the latest computer technology developments, and they proposed KBS concepts and development requirements. John F Gilmore et al [101] proposed the KBS system construction requirements. The proposed KBS should include application knowledge, domain models, temporal correspondence and processing history, and it should be able to communicate with the control strategy to retrieve the required knowledge.

In this period, KBS research focused on investigating the prerequisites of KBS development instead of building the functional systems. This early period thus represented a technology preparation stage before the actual KBS implementation. Some researchers proposed the KBS framework, such as Q. Wu [102], who proposed the framework of an automatic chromosome classification KBS. It was designed to contain the image processing and pattern recognition knowledge, and the expert chromosome classification knowledge. The automatic chromosome classification task was proposed to be finished through a process of image segmentation, feature extraction, type classification and verification. Some researchers made technical preparations for KBS development, such as knowledge representation methods, including Yutaka Ogawa et al [103], who invented a knowledge representation method called KRINE and discussed objectives and mechanisms in knowledge representation.

3.1.2 Independent System

Starting around 1990, researchers began to develop functional KBSs. KBSs developed in this era were mainly equipped with basic knowledge management functions, such as knowledge searching and retrieval, and they worked as independent systems without cooperating with other toolsets. Their applications included aiding current work and educating fresh engineers. Their characteristics can be summarized as follows.

KBSs were built with basic knowledge management functions. Those systems were able to aid work by offering professional advice and guidelines, and they could also educate fresh engineers by retrieving past experiences and lessons learned from the knowledge base. For example, M.A. El-Kady et al [104] built a power cable design KBS that could aid designers during design work and educate novice engineers. It had two function modules: PARENT Frame and CHILD Frame. The PARENT Frame helped the user determine the cable type and general design features; the CHILD Frame aided the user to decide the specifications and graphics of the cable and installation cross-sections. Stipe Fustar et al [105] built a work scheduling KBS for weekly power system operation. It made weekly working plans for the power system operations based on load predictions, inflow predictions and generator maintenance requirements. It consisted of working memory, knowledge base and inference engine. The working memory included the problem descriptions and according solutions; the knowledge base stored production rules; the inference engine repeatedly checked the problems from working memory and generated working plans by employing production rules from the knowledge base.

KBSs were applied in more and more fields. In the *early preparation* stage, the researchers were mainly from computer science. In the *independent system* stage, however, the KBSs were developed in many engineering fields, including mechanical engineering, electrical engineering, industrial engineering, and civil engineering. In geotechnical engineering, Teresa M. Adamas et al [106] developed a structural design KBS, documenting diagnostic knowledge for inferring structure failure mechanisms, design knowledge for identifying rehabilitation strategies and evaluation knowledge for analyzing design adequacy and estimating costs. In civil engineering, Abdulrezak Mohamed et al [107] developed a KBS for construction scheduling and cost estimating. Its functions included on-line schematic drawing, material selection, crew selection and productivity analysis.

According to the literature search results listed in Appendix A. In the *early preparation* stage, there are 17 publications in total and 10 of them are from researchers in computer science field, which is 59%, and 7 of them are from researchers in engineering fields, which is 41%; while in the *independent system* stage, there are 35 publications in total and 5 of them are from researchers in computer science field, which is 14%, and 30 of them are from researchers in engineering fields, which is 86%. As a result, the application of KBS sees a big expansion in engineering fields.

3.1.3 Integrated System

After 2000, as computer technologies were broadly applied in science and engineering research, researchers developed many other computer toolsets to aid their work, such as databases and numerical processing tools. Accordingly, researchers began to explore how to make KBSs and those systems work together so that they were capable of finishing much more complex tasks.

One such effort was to develop KBSs that could work with database systems. The combined systems could use the data from databases as past experiences and the knowledge from KBSs as skills to solve more complicated tasks. Ali Malkawi et al [108] integrated a structural design KBS with a local building database to provide a decision support service for the selection of building features. During the process, the user selected the window visual transmission, energy requirements and color from the database, and those would be checked by rules from the knowledge base to find out whether they matched the design requirements.

Another kind of effort was to combine KBSs with numerical processing tools. The numerical processing tool could control the entire analysis process, and the KBS could provide suggestions and make selections at key points during the process. When they worked together, they were capable of accomplishing analysis tasks automatically. Shaobin Chen et al [109] built an image identification KBS to work with a remote sensing module, which could accomplish target recognition tasks. The knowledge base received the low-level data and object characteristics generated by the element description and feature abstraction functions of the remote sensing module. After that, it used stored knowledge to identify the target.

3.1.4 New Frontiers

As computer technologies are applied in almost every corner of the world, KBSs have also gained applications in fields other than science and engineering, such as business and agriculture. KBSs are also equipped with newest technologies, such as cloud-based online services.

In business management, W. Wen et al [(110)] present a mobile business management KBS to automatically provide users with decision-making and management solutions. It consists of a user interface, assignment agent, knowledge reasoning agent, search agent, knowledge base, database, and model base. The knowledge reasoning agent and search agent select proper knowledge from the knowledge base to aid the solution searching process. While the database and model base provide the facts and past cases for references. In addition to expanding their application areas, KBSs are also equipped with the latest technologies. S. Wood et al [(111)] build an on-line help support KBS to work as an automatic customer service representative answering users' questions. The KBS is connected to the web-based user interface through the internet. It receives the key-phrase search inquiries from the user and outputs the search results. The KBS is maintained by local knowledge engineers.

After about 30 years of evolving, the KBSs in non-Aerospace Engineering fields have been become quite mature. They have been incorporated into existing toolsets to provide professional advice aiding practices. One of the latest developments is from researchers at Carnegie Mellon University. They build the Never-Ending Language Learning system (NELL) based on KBS technologies [(112)]. It can identify the fundamental semantic relationships of the given elements and make new connections using its current knowledge. In this way, it mimics the way humans learn new knowledge. By October 2010, NELL had learned 440,000 facts with an accuracy of 87%.

In addition, KBSs also get broadly applied in industries. Vehicle diagnosis system is a kind of broadly used KBSs [(113)]. It reads the test data from a vehicle; after that, it uses the fault tree table and fault rule table from the knowledge base to automatically finish the diagnosis process and give the problem solution.

In the following section, a literature survey of KBS development in Aerospace Engineering will be given.

3.1.5 Knowledge-based System in Aerospace Engineering

The research of KBSs in Aerospace Engineering can be traced back to the 1980s, when J.R. Zumsteg and D.L. Flaggs began to investigate the integration problems of linking a possible KBS with an existing analysis code [(114)]. The research topics included the input and output format and the function requirements of the interfaces. It could be considered as the preparation for developing real functional KBSs in Aerospace Engineering.

After that, most researchers continued to analyze the architectures of KBSs instead of getting into the functional KBS development. Only a few functional KBSs have been developed, and their applications focus on simple tasks during the detail design phase. Gianfranco La Rocca and M.J.L. van Tooren [(115)] built a pre-meshing support KBS (DEE) to implement an automatic meshing process. It gathered surface segmentation rules from FE specialists and documented them in a knowledge base. The KBS aided the process of dividing the given geometry and delivering a set of surfaces which were suitable for the following meshing steps. Jin-Woo Choi, Don Kelly and John Raju [(116)] developed a KBS(KBES) for estimating the weight and manufacturing cost of composite structures. The knowledge related with manufacturing cost, such as density, price, fastener weight and flange width, was collected from experts, books and design specifications. The cost estimation process happened after the FEA and before the manufacturing process. It determined whether the designed structure satisfied the requirements. If not, the whole process would be repeated.

In addition, the giant companies and research institutions in Aerospace Engineering may have developed their own KBSs, although few journal and conference publications can be found. However, other online resources also bring us an overview of their KBS developments.

3.1.5.1 National Aeronautics and Space Administration (NASA).

As a huge research organization, NASA conducts research in fields of aeronautics, aerospace and earth science (117). Accordingly, it develops several KBSs to document their research findings, such as NASA Modeling Guru Knowledge Base (118), NASA HECC Knowledge Base (119), NASA Astrophysics Research Knowledgebase (ARK) (120). The ARK is selected as an example to introduce the latest NASA KBS development.

Introduction

ARK aims at providing astrophysics knowledge search, edit and update services (120). It is developed by NASA's High Energy Astrophysics Science Archive Research Center (HEASARC).

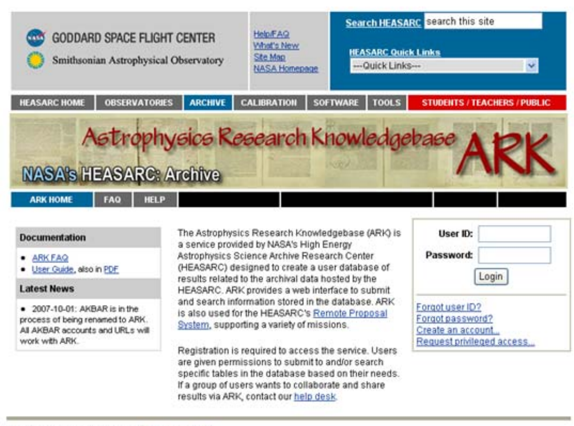


Figure 3-1 ARK Online Access (120)

ARK provides online services, which are implemented though the web page. The service can be accessed through http://heasarc.gsfc.nasa.gov/ark/. However, users are categorized and a registration procedure is required before utilizing the service, during which the users' rights are determined. As a result, not all of users have the right to edit and update new knowledge into ARK.

Functions

ARK offers knowledge search, edit and update functions. The knowledge search can be done in two ways: basic search and advanced search. The basic search starts by selecting: Tag ID, Analyst Initials and Archive Date; while besides those three criteria, the advanced search can choose: Tag Note, Tag Root and Review Date.

In the knowledge update functions, ARK provides four sections to input knowledge: Archive Date & Tag, Stripchart, Errors and Summary. After an input is finished, a verify process is required to double check the input knowledge before updating it into the system.

The knowledge edit function can be used only by the knowledge author, but others can update similar items into the system with different IDs. The process is similar to that of knowledge update functions.

Evaluation

ARK provides knowledge storage and education functions, so it is only a passive knowledge documentation tool, such as books and hard drives. Moreover, it is an independent system. As a result, it cannot cooperate with other toolsets thus actively involve itself during the knowledge application processes.

3.1.5.2 Airbus

Introduction

Airbus World In-Service Experience (WISE) is a KBS developed to share the operation and maintenance knowledge with customers [121]. It provides users with an online access to the knowledge base and offers suggestions on aircraft reliability improvement and cost reductions. By March 2011, 1500 aircrafts operated by 28 airlines benefit from the project.

Function

The WISE knowledge search function is implemented through online search. Its working mode is similar to the search engines, like Google and Bing. The user types the search

Figure 3-2 WISE Search Example [121]

keywords, and the WISE inference engine will retrieve related materials from the knowledge base and display them through the webpage.

The knowledge update process takes four steps in general:

a) Airlines report raw data on problems to Airbus.

b) Airbus processes raw data and identifies the causes.

c) Airbus works with suppliers to work out solution plans.

d) Airbus updates the cause-effect relationship as a piece of new knowledge into WISE and reports it to Airlines.

Evaluation

WISE works as a communication platform between Airbus and its customers, and a user guide for improving aircraft reliability and reducing cost. As a result, it only provides the knowledge storage and education functions. Moreover, the knowledge update process is a time consuming process and can last months.

WISE is still an independent KBS and mainly works as a knowledge storage medium. It can't cooperate with other systems to aid current work.

3.1.5.3 Raytheon

Raytheon is a world leading defense technology developer. Its products include missile systems, space & airborne systems, integrated defense systems, network centric systems and intelligence & information systems [122].

<u>Introduction</u>

The KBS at Raytheon(KM) aims at collecting and transferring knowledge within the company, so that it can "*provide the right knowledge to the right person at the right time in order to enable more informed decisions and to ensure customer success*." [122] It is designed to involve all of the 1316 experts and 14435 specialists in the company to participate in the knowledge collection, share and reuse process.

<u>Function</u>

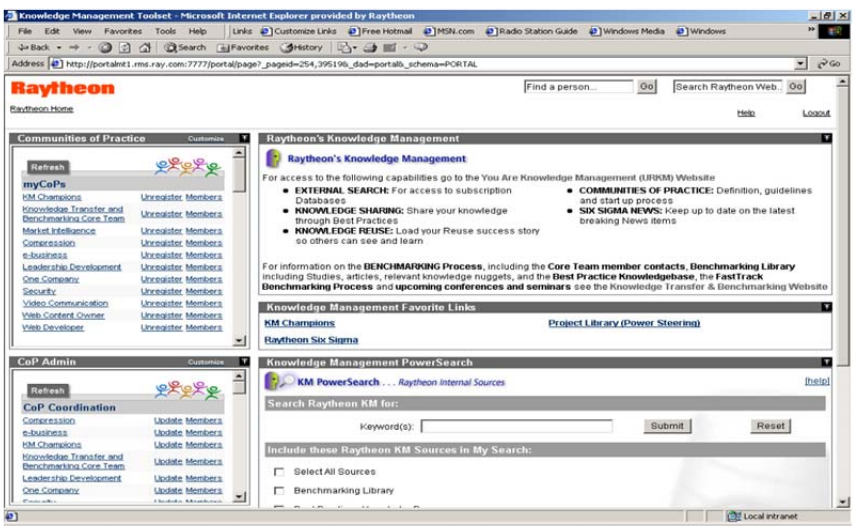


Figure 3-3 Raytheon KM Access GUI [122]

The knowledge collection and update process is done through KM people meeting with experts and specialists. Meetings happen either at lunch-hour or after hours, and the people who contribute to the knowledge collection will be rewarded in the forms of shirts or small gifts. After that, KM people will update it into the knowledge base and make it a company asset.

The knowledge search function can accessed online at http://portalmt1.rms.ray.com:7777/. It is a one-stop shop for the company knowledge, and the knowledge can be searched by keywords. In addition, the user can confine the search scope by selecting searching areas, such as Benchmarking Library and All Sources.

Evaluation

KM works as a platform for the knowledge collection, retention and share within Raytheon Company. It provides the knowledge storage and education functions. The knowledge collection and update processes are both finished manually. In addition, it provides an online search access.

However, KM is an independent KBS and works as a knowledge documentation media. It can't cooperate with existing Raytheon analysis algorithms and directly apply stored knowledge into research work.

Other significant companies and institutions also developed various KBSs for different purposes, such as ESDS for documenting materials technology knowledge from Boeing [123]. More KBSs are still under development, such as the High-Performance Knowledge Base(HPKB) from Darpa [124], which is designed to find out new ways of acquiring, organizing, sharing and reasoning with stored knowledge, and AeroText from Lockheed Martin Corporation [125], which is capable of automatically browsing and searching documents.

As a result, the KBSs in Aerospace Engineering are either still under development or equipped with basic knowledge management functions, such as knowledge storage and education. All of the existing KBSs are still in the independent system stage, and cannot cooperate with existing toolsets. Moreover, until now, no KBS has been developed to aid the multidisciplinary conceptual design stage in Aerospace Engineering, especially for the most important parametric sizing analysis process.

3.2 Research Conclusion

From the above literature review, the development of KBSs has passed through the *early preparation, independent system, integrated system* and *new frontier* four stages. It starts from proposing KBS frameworks, to building independently working KBSs and forming integrated KBSs.

However, no existing KBS takes the knowledge as the key concern and develops a systematic approach to form a closed loop for knowledge management, including *knowledge storage, education, application* and *innovation* functions.

1. <u>Knowledge storage</u>: the most basic knowledge management function, which provides the base for the following knowledge manipulations. It organizes the knowledge content in a predefined format.
2. <u>Knowledge education</u>: an important knowledge management function, which teaches the young generation. It employs various education technologies to illustrate the knowledge content.
3. <u>Knowledge application</u>: the most valuable knowledge management function, which applies the accumulated knowledge into practices. It demonstrates the value of knowledge.
4. <u>Knowledge innovation</u>: an important knowledge management function, which generates new knowledge during the knowledge application processes.

The above four knowledge management functions form a closed loop in knowledge management. It starts from knowledge storage as a base; then it uses knowledge to teach fresh engineers or apply it into work; at last, it generates new knowledge during application processes and updates it back to KBS. As a result, the above four knowledge functions have to be the foundation for a modern KBS development activity. However, existing Aerospace Engineering KBSs are only equipped with one or a few of those functions. For example, the WISE and KM used at Airbus and Raytheon only have knowledge storage and education functions. While the HPKB proposed by DARPA is designed to employ all of those functions, it, however, is still under development and no progress has been reported for the past 15 years. In the next chapter, we are going to propose the AVD^{KBS} methodology based on the systematic knowledge management concept.

Table 3-1 Overview of Selected Aerospace Engineering KBSs

KBS	**KBES** [116]	**DEE** [115]	**ARK** [120]	**WISE** [121]	**KM** [122]	**HPKB** [124]
Year	2007	2009	———	———	———	2000
Institution	University of New South Wales	Delft University of Technology	NASA HEASARC	Airbus	Raytheon	DARPA
Area	Research	Research	Research	Industry	Military	Military
Status	In service	In service	In service	In service	In service	In development
Contribution	Estimate the cost and weight of composite aerospace structures	Automate the surface segmentation process during the premeshing stage in FEA	Online knowledge search and update services	Online help, and share maintenance knowledge with customers	Online help, document and share expert knowledge	Develop new ways of acquiring, organizing, sharing, and reasoning with knowledge
Working Mode	Integrated system, post processing, work after FEA	Integrated system, prior processing, work before FEA	Independent system, providing knowledge retrieval and update services	Independent system, providing knowledge retrieval service	Independent system, provide knowledge retrieval service	Integrated system, working with a lot of systems, database, online sources, etc.
Function	Knowledge storage, Knowledge education	Knowledge storage, Knowledge education	Knowledge storage, Knowledge education	Knowledge storage, Knowledge education	Knowledge storage, Knowledge education	Knowledge, storage, Knowledge education, Knowledge, application, Knowledge innovation

3.3 Research Objective and Approach

From the above discussion, a clear research opportunity exists for us to advance the KBS research for the Aerospace Engineering community: propose and develop a KBS that provides systematical knowledge management functions. It will bring the following benefits:

(i) offer a convenient method to store past knowledge;

(ii) efficiently teach fresh engineers by illustrating the knowledge in multiple ways;

(iii) apply the current knowledge into practice by integrating with existing toolsets;

(iv) innovate new knowledge based on past project data.

3.3.1 Research Objective

To advance the state-of-the-art KBS research in Aerospace Engineering, the following research objectives have been proposed:

1. Development of a dedicated KBS that provides systematic knowledge management functions. Through the literature review, we know that no existing KBS has been build to systematically manage knowledge efficiently whilst taking knowledge as the key consideration. Existing KBSs only use available technologies to develop some knowledge management functions. They fail to solve the knowledge management problems from a very top level of view and specify the necessary knowledge management functions in terms of knowledge storage, education, application and innovation.
2. Demonstrate efficiency advantages of KBS through case studies. To prove the success of the KBS development, case studies are necessary to show how the KBS works in different scenarios and aids researchers to accomplish research tasks more efficiently.
3. Integrate with existing toolsets to aid the truly multi-disciplinary parametric sizing analysis during the aerospace engineering conceptual design stage.

3.3.2 Research Approach

To meet the research objective, the following research approach has been selected:

1. Propose a knowledge categorization criterion. Knowledge is the sole research object in KBS research. However, until now, no effort has been made to analyze the characteristics of knowledge itself. This also explains why existing KBSs fail to form a systematic knowledge management approach because they lack sufficient understanding of the inherent characteristics of knowledge, described via measurable parameters with physical plausible unit. As a result, the best way to start building a KBS is to analyze the characteristics of knowledge and categorize them based on their intrinsic properties.
2. Propose and build knowledge management functions based on the above knowledge categories. After the knowledge categories are defined, the knowledge management functions can be logically proposed. Then, those functions are developed to form AVD^{KBS}.
3. Propose an efficiency evaluation criterion. To demonstrate the efficiency advantages of AVD^{KBS} over traditional knowledge management methods, such as book, journals and hard drives, the development of an efficiency evaluation criterion is necessary. It will use quantitative parameters to consistently measure the efficiency differences among different knowledge management methods. As a result, it will be straight-forward to demonstrate the efficiency advantages of the AVD^{KBS} implementation.
4. Apply AVD^{KBS} to selected case studies. Throughout the case studies, knowledge application examples are conducted: educate young generations accelerated via stored knowledge, apply knowledge efficiently to research and design work, innovate new knowledge and directly update the dynamic AVD^{KBS} system. The efficiency advantages of AVD^{KBS} are demonstrated through those examples.

3.4 Research Contribution Summary

The original research contributions from Chapter 3 are as follows:

1. For the first time, KBS developments are categorized into four stages: *early preparation, independent system, integrated system* and *new frontier*, based on their system functions and application areas. This chapter concludes the KBS developing trends and it gives guidance on the necessary knowledge management functions which should be incorporated into KBS.
2. For the first time, a KBS methodology concept has been proposed, which forms a closed loop for knowledge management, including knowledge storage, application, education and innovation functions. The proposed methodology concept represents a considerable improvement compared to existing aerospace engineering KBSs which can only provide partial knowledge management functions instead of being a complete knowledge management solution.

Chapter 4

AVD^{KBS} Methodology

Having determined the research objectives, the next step is to propose the AVD^{KBS} methodology, which specifies the knowledge management logic of AVD^{KBS}. The proposed AVD^{KBS} not only will work as a standalone knowledge storage and education tool but also will work with the existing AVD design systems to deduce new knowledge whilst directly supporting the parametric sizing analysis tasks. As a result, it is necessary to first introduce the knowledge accumulations at the AVD Laboratory and the existing AVD design forecasting systems.

After that, the AVD knowledge categorization criterion is proposed to classify knowledge according to its formats and representations, followed by a proposal for an efficiency evaluation criterion for knowledge management methods. Those activities serve to develop the foundation for the unique AVD^{KBS} knowledge management functions. For each knowledge management function, the function method logic and the involved AVD design systems are introduced.

4.1 AVD Design Environment Introduction

The AVD Design Environment consists of three systems: the database system, AVD^{DBS}, the knowledge-based system, AVD^{KBS}, and the parametric sizing tool, AVD^{PP}. Before introducing those systems, the AVD knowledge accumulation, which is used to build the knowledge base in AVD^{KBS}, will be introduced first.

4.1.1 AVD Knowledge Accumulation

As discussed in Chapter 2, data, information and knowledge have close relationships.

> "Data by itself has little relevance or purpose due to its characteristics of being a set of discrete, objective facts about events. Data represents raw material without implying nay judgement or interpretation, thus it says nothing about its own importance or irrelevance.
>
> Information can be thought of as data that makes a diference due to its impact on judgement and behavior. Information must inform, thus it has a meaning and it is organized to some purpose.

> Knowledge represents a mixture of experience, values, contextual information, and expert insight that provides a setting for evaluating and incorporating new experiences and information." (126)

The AVD knowledge accumulations can be categorized into three categories:

– Member Industry Accumulations: knowledge is accumulated through AVD members' individual industry work experiences.

– Contract Accumulations: knowledge is accumulated through the projects during which the AVD Laboratory provide professional services to customers.

– Inheritance Accumulations: knowledge is accumulated through outside researchers, companies or research institutions, who donate their knowledge accumulations to AVD Laboratory.

4.1.1.1 Member Industry Accumulations

One significant knowledge accumulation has been produced by Dr. Bernd Chudoba, whilst working for Airbus Industries with access to Airbus partner aircraft design archives in Europe. Based on those comprehensive sources, Dr. Chudoba established a unique knowledge based covering conventional to unconventional flight vehicles from subsonic to hypersonic speeds. The resulting aircraft conceptual design knowledge base served as the foundation for the development ofa generic stability and control design methodology. (126)

A key step in developing this generic stability and control design methodology has been to collect stability and control design lessons-learned of the variety of flight vehicles. The knowledge collection process for this dedicated conceptual design knowledge base can be summarized by the following five steps (126):

1. Survey the complete range of engineering practices, including design, construction & production, and operation. During the process, the knowledge sources are formulated from: '(a) public domain literature, (b) institution and company internal sources, and (c) expert advice.'

2. Conduct the first filtering process by classifying the collected design knowledge on aircraft design motivations and constraints into three categories: '(1) infrastructure (political contents, work share, financing, development risk awareness, conservatism, …); (2) operation (mission specification, aircraft category, performance, safety, critical light conditions, …); (3) technology (state-of-the-art technology, design philosophy, aircraft configuration, …).' The purpose of the step is to enable a multidisciplinary understanding of the early aircraft conceptual design stage.

3. Conduct the second filtering process by selecting design knowledge in 'disciplinary topics interfering with flight mechanics at conceptual design level', including '(a) geometry and mass properties, (b) aerodynamics, and (c) flight evaluation experience.'

4. Conduct the third filtering process by identifying knowledge on key elements within each selected discipline, targeting the critical constituents influencing the aircraft stability and control characteristics. Those key elements are '(a) aircraft configurations and concepts [geometry and mass properties], (b) configuration aerodynamics [aerodynamics], and (c) design constraining flight conditions (DCFC) [flight evaluation experience].'

5. Conduct the last filtering process by selecting knowledge about 'global design parameters,' which is the key constituent in the knowledge collections.

For the knowledge collection, each piece of knowledge is categorized by two sections:

"(a) Longitudinal Motion and (b) Lateral/Directional Motion.

Each motion is subdivided into:

- Flight Character (Design constraining flight conditions: trim, control, stability)
- Aerodynamic Character (Stability and control derivatives: u, u/t, w(a), …)
- Flow Character (Flow phenomena: tuck, pitch-up, non-linearity, …)
- Additional Grounds (Landing gear location, geometry limitations, …)"

In this manner, a uniquely comprehensive set of knowledge entries on aircraft stability and control during the early conceptual design stage have been accumulated. An example of the collected knowledge is C_{m_α} , which is a key parameter in determining the aircraft pitch stiffness. [127] A portion of the knowledge collections on C_{m_α} is given with Figure 4-1.

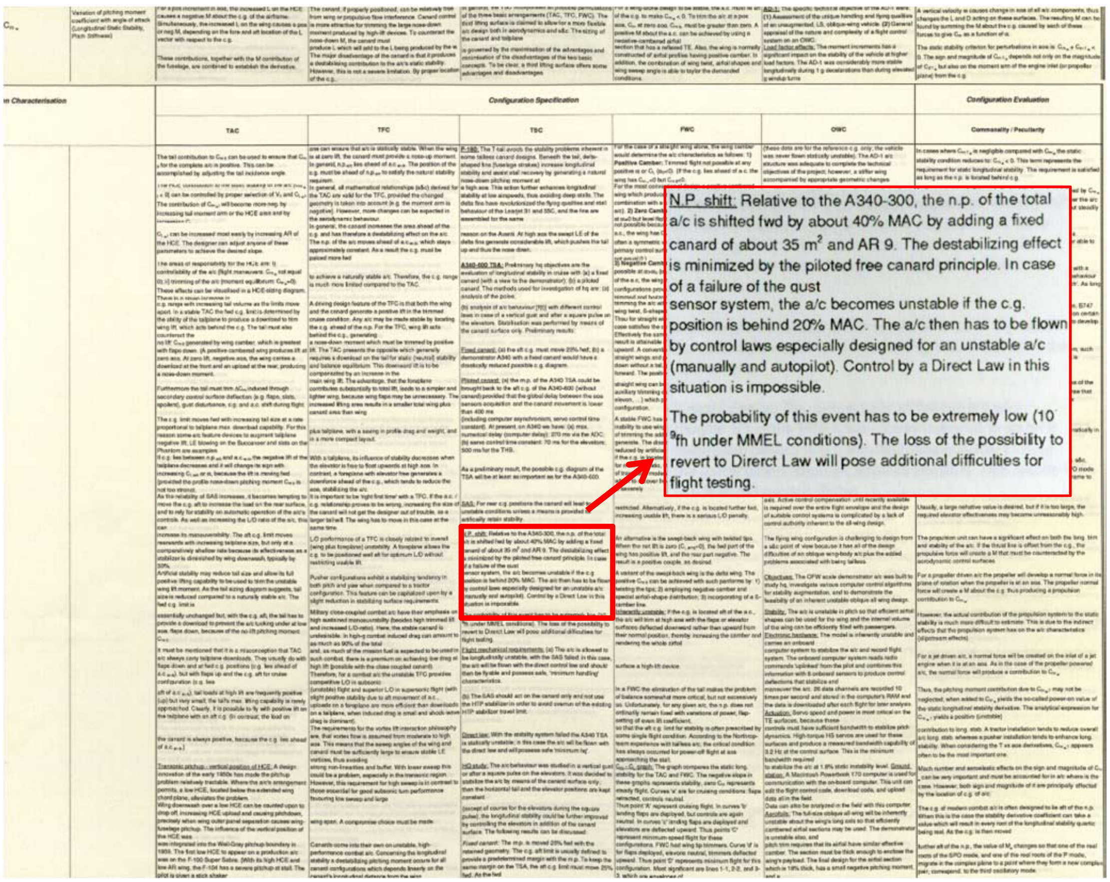


Figure 4-1 A portion of C_{m_α} Knowledge Collections [128]

For the C_{m_α} parameter, 205 knowledge entries have been collected relating to 39 aircrafts of different configuration arrangement and design speed regime. [128] The consistent comparison of the pitch stability behavior across the flight vehicle configuration spectrum and speed regime enabled the researcher to formulate a generic set of stability and control algorithms.

Based on such extensive design knowledge survey and collections, the aircraft stability and control design parameter interactions can be identified resulting in knowledge-based design guide parametrics. This process enabled the first ever generic aircraft conceptual design stability and control methodology. Figure 4-2 is an example of the center of gravity design interaction and design guide parametrics.

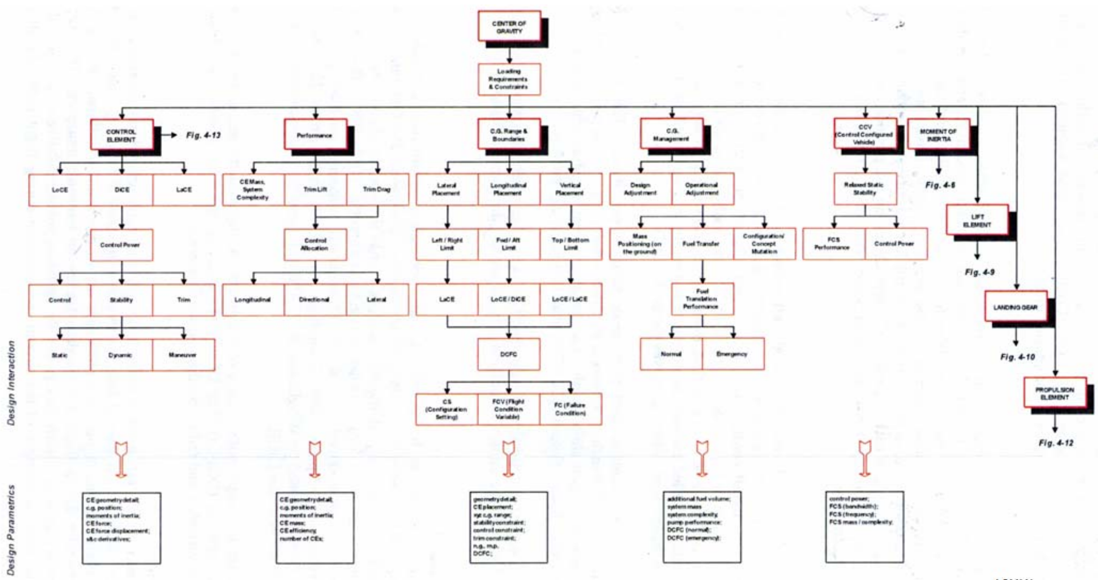


Figure 4-2 Center of Gravity Design Interaction and Design Guide Parametrics (126)

4.1.1.2 Contract Accumulations

For the past three decades, the AVD Laboratory setting headed by Dr. Chudoba has participated in several vehicle design projects, including subsonic, supersonic, hypersonic and space vehicles, serving a wide variety of customers.

Table 4-1 AVD Past Projects

Year	Customer	Project
1989	Dornier/Gyroflug-FFT	FAA 2000 Trainer
1992-1993	Airbus Industrie	UHCA/A3XX/A380
1994	British Aerospace	HSCT
1995-1999	DASA, Bae, AI, AS	HSCT
1999-2002	Fairchild Dornier	328,728,928 Regional Transport
2004-2005	Rocketplane	Rocketplane XP Space Tourism
2004-2005	NASA LaRC, NIA	Commercial Transport
2005-2006	SpiritWing	SpiritLear SSBJ
2006	NASA LaRC	Reusable Space Access Vehicle
2008-2009	NASA	N+3 Transonic Transport
2009	ESA	Hypersonic Transport
2009	NASA Chief Scientist	Truss-Braced Wing Aircraft
2010	NASA LaRC	Hypersonic X-Plane
2010-2011	NASA/DARPA	Manned Satellite Servicing
2011-2012	Lindbergh FDN	Electric Aircraft
2011-2012	NASA	Hypersonic Vehicle Database
2013	NASA	Transport Aircraft Mission Research
2014	Airbus Helicopter	New Helicopter Configuration Assessment
2015	Airbus Helicopter	New UAV Product Evaluation

The AVD Laboratory has accumulated a large amount of aerospace engineering conceptual design data and knowledge. For example, AVD researchers have implemented over 70 sizing relevant disciplinary methods into the parametric sizing code, along with 194 individual subroutines that have been developed for transonic and supersonic transports, hypersonic cruisers, launch vehicles, reentry vehicles and orbital transfer vehicles [(129)].

Another example is the Hypersonic Vehicle Database project [(130)]. During the development, a Hypersonic Vehicle Database was established for NASA Langley Research Center. Over 1700 references have been screened, and over 300 of them were utilized to extract relevant information. In the database, 92 hypersonic vehicles were recorded, and detailed information has been collected on both development and technical details.

All of those works provide valuable data and knowledge accumulations for aerospace vehicle design.

4.1.1.3 Inheritance Accumulations

The AVD laboratory has been collaborating over decades and subsequently inherited aerospace engineering design knowledge from other researchers and institutions. The most important collaboration and inheritance stem from Paul A. Czysz. Mr. Czysz was a professor emeritus at the Department of Aerospace and Mechanical Engineering, Parks College of Engineering and Aviation, Saint Louis University. Professor Czysz dedicated his entire industry career at McDonnel Douglas Aerospace to hypersonic vehicle design research and development, contributing since the beginning of the hypersonic era. He has participated in many industry-led supersonic and hypersonic vehicle projects, such as National Aero-Space Plane (NASP) and Advanced Supersonic Transport (AST).

One of the most significant contribution from Professor Czysz has been the development of unique design continuum maps [131]. A design continuum is based on the fact that projects with similar design missions show similar properties. In this way, researchers are able to determine the correct trends for problem-solving by skillfully deducing design trend from the available data, information and design knowledge of similar past projects. Subsequently, the vast amount of flight vehicles developed throughout history represent yet untapped resources of data and knowledge for current and future design work.

Clearly, such knowledge-based insights cannot be obtained from literature surveys, such as conference publications, journals and books. Such holistic or synthesis convergence research and development.

Throughout his industry career, Professor Czysz successfully accumulated over decades system-convergence relevant data, information and knowledge entries enabling the formalization of unique 'continuum trend graphs'. He led research groups to conduct vehicle convergence research studies during the conceptual design stage, covering a wide speed range, from subsonic, transonic to supersonic and hypersonic.

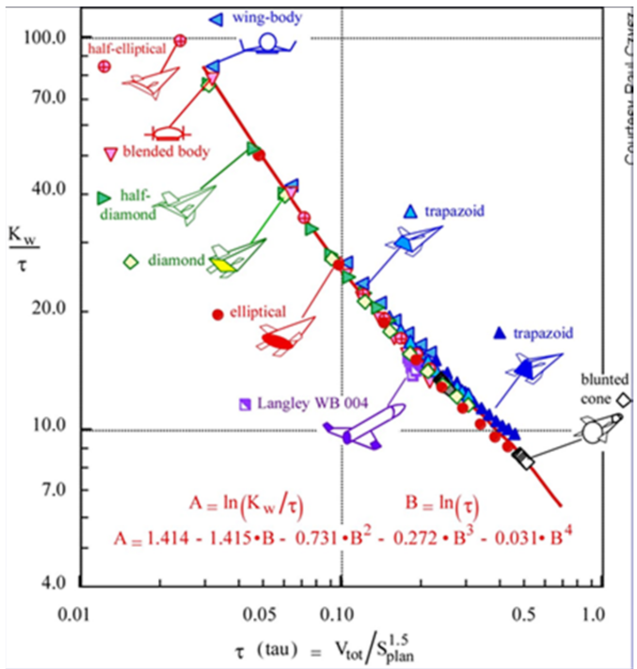


Figure 4-3 Design Trend between $\frac{K_w}{\tau}$ and τ from Paul A. Czysz(8)

Figure 4-3 presents an example survey of potential supersonic and hypersonic vehicle configurations conducted by Paul A. Czysz (8). Without detailing its extensive underlying derivation, the resulting trend-regression as shown is presenting a geometry-generic guide directly supporting the parametric sizing analysis. The logarithms of *Kuchemann's tau* τ and *geometry sizing parameter* $\frac{K_w}{\tau}$ form a linear relationship, which means the geometry parameter K_w can be determined by τ . As a result, a first order estimation of the vehicle size and weight can be made based on the value of τ .

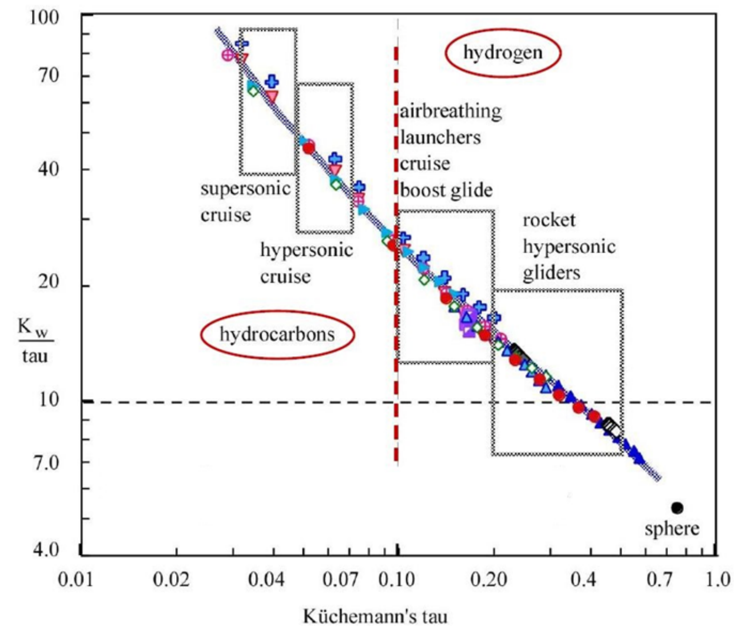


Figure 4-4 Deductions of Design Trend Knowledge from Paul A Czysz[8]

In order to determine the value of τ, Professor Czysz correlates the mission requirements and propellant information of those vehicles in a single figure, see Figure 4-4. As a result, the mission and propellant information are categorized into two sectors: hydrocarbon sector and hydrogen sector.

> "Within the hydrocarbon sector, there are the room temperature liquid hydrocarbons for supersonic aircraft, and the cryogenic hydrocarbons for hypersonic aircraft (generally Mach 6 or less); while within the hydrogen sector, there are the airbreathing cruise, boost-glide, and first stages of two stage to orbit vehicles that have low values of oxidizer to fuel ratio and lower net propellant densities, and the rocket launchers, rocket boost glide vehicles and the upper stage of two stage to orbit vehicles that have high values of the oxidizer to fuel ratio". [132]

Since the vehicle mission and propellant selection are always specified in the design mission requirements, then τ can be estimated based on Figure 4-4. After that, using the equation from Figure 4-3, the geometry parameter K_w can be determined. Thus this curve in Figure 4-3, summarized by Paul, can provide a first order estimate as to where a converged solution may lie based on the design mission requirements.

In summary, Professor Czysz has accumulated unique insights into the design of flight and space access vehicles. He transitioned this unique generic vehicle design knowledge into practical design guidelines. Such knowledge-derived design guidelines are not found elsewhere in the world. With the passing of Professor Czysz, the AVD Laboratory inherited all of his research documentations and library.

The following two sections will introduce the other two AVD design systems: AVD^{DBS} and AVD^{PP}.

4.1.2 AVD^{DBS}

This dedicated next-generation aerospace database, AVD^{DBS}, uses a unified format to encompass the data of past, present, and proposed projects and programs [133]. In this way, it guarantees data consistency and quality. Besides project data, it also includes the technology evolution history to track and comprehend cause and effect relations behind the project developments. AVD^{DBS} provides customizable depictions of data and information to aid the decision-making process, and it is also capable of dynamically updating the content. AVDDBS development is concurrently carried on by another AVD researcher Eric Haney, and the progress has been published in the Aeronautical Journal.

The database building process consists of:

1. Data Collection: the data collected is from the public domain, proprietary domain, expert domain and data domain.
2. Data Tabulation: the data tabulation is the process of inputting the collected data into a structured data repository.
3. Data Categorization: the data categorization classifies the data according to their similarities to help the users gain some level of insight.

4. Data Comparison: the data comparison provides the broadest view of a data-set, and it unveils the hidden merits by comparing the data subsets for professional users.

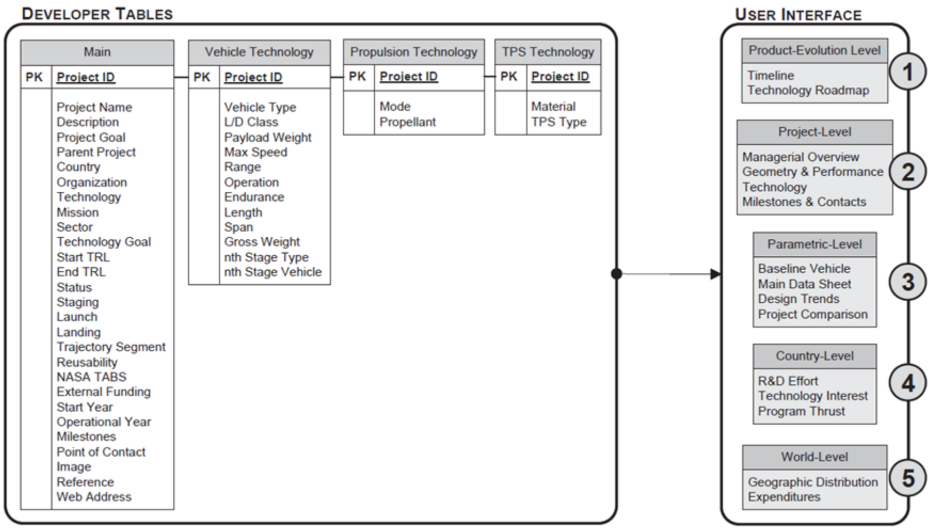


Figure 4-5 AVD^{DBS} Architecture [133]

AVD^{DBS} can aid various levels of users to accomplish their particular tasks, including the *product evolution level, project level, parametric level, country level* and *worldwide level*.

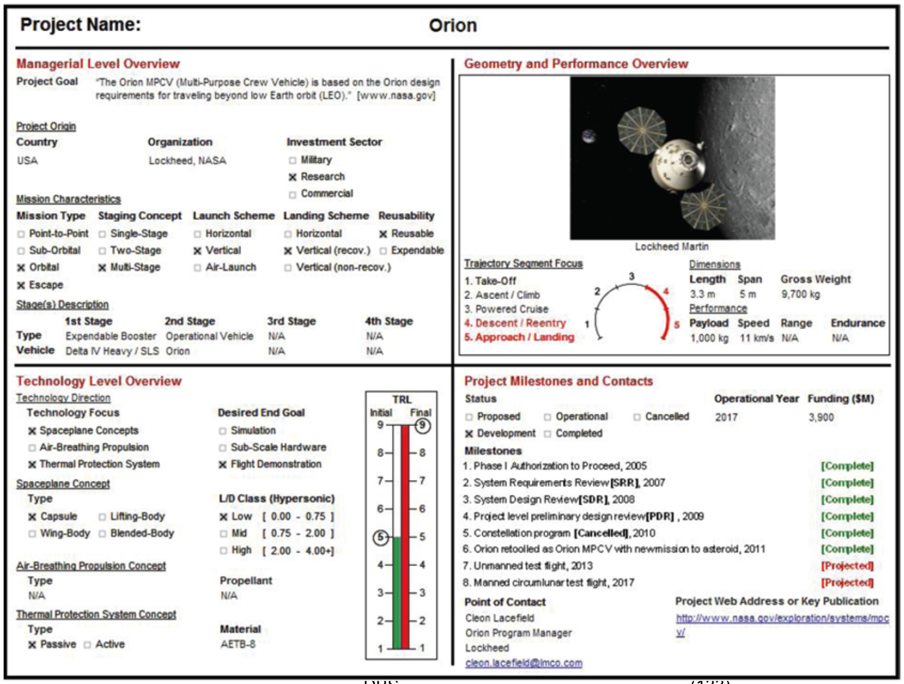


Figure 4-6 AVD^{DBS} - Project Level example [133]

At the *product evolution level*, it provides a top-level program understanding and oversight with little or no technical information. At the *project level (Figure 4-6)*, it delivers project-level specific information relevant to the main user in a graphically formatted dashboard. At the *parametric level*, it provides detailed technical specifics about a project compared to similar past and current projects. At the *country level (Figure 4-7)*, it aims at helping the strategist, policy-maker and integrator augment program planning purposes. At the *worldwide level (Figure 4-8)*, it is used to determine what countries and regions are actively engaged in which technology research areas.

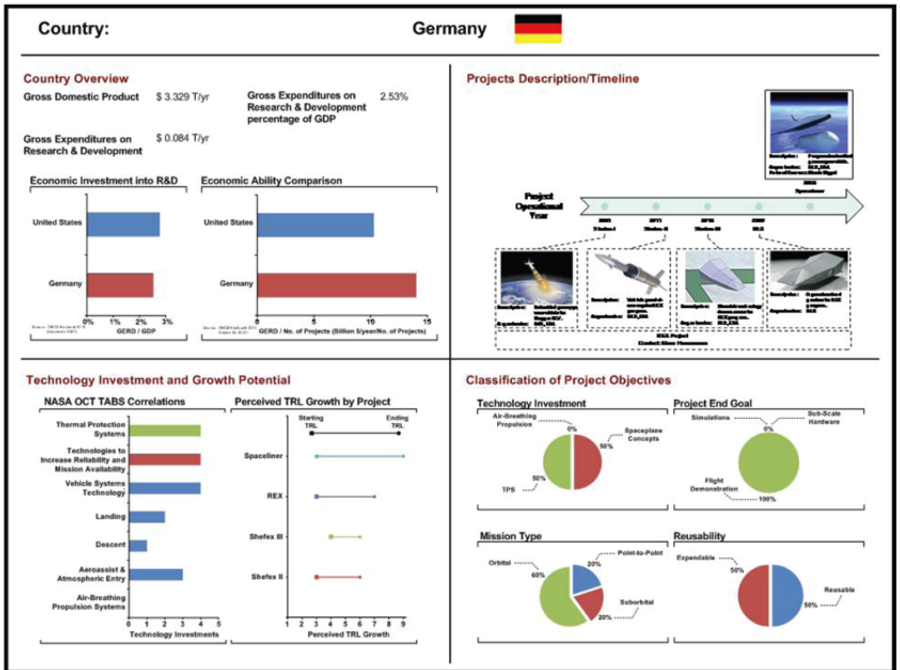


Figure 4-7 AVD[DBS] - Country Level example [133]

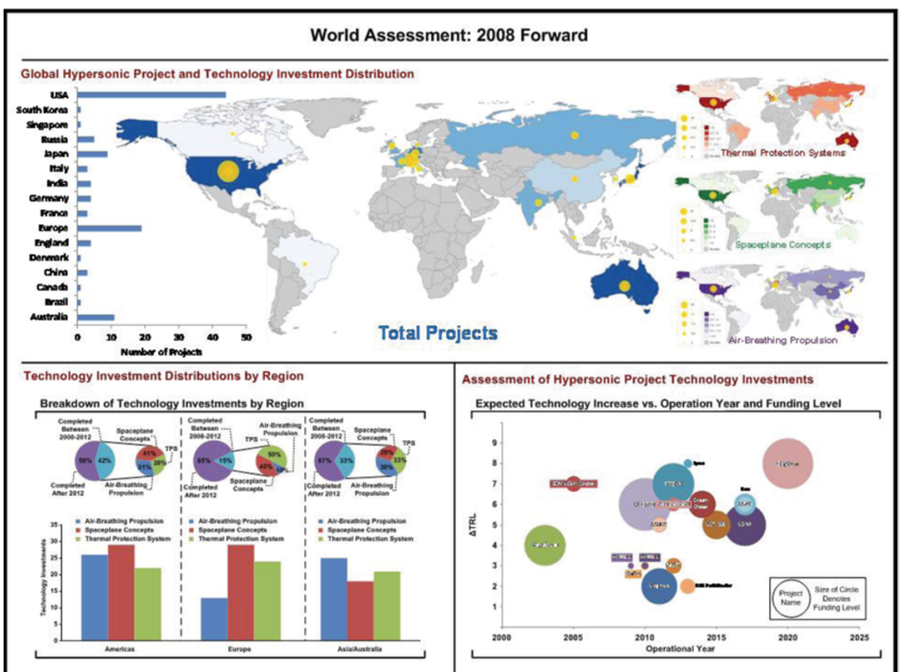


Figure 4-8 AVD[DBS] - World Level example [133]

4.1.3 AVD^{PP}

Conceptual design is the most important stage during aerospace engineering design process. It determines around 80% of the vehicle configuration. The synthesis system is a design environment used to determine the solution space of the product based on its mission requirements, and it estimates the vehicle size and determines its configuration concept. Synthesis systems have evolved through five stages: *early dawn, manual design sequence, computer automation, multidisciplinary integration* and *generic design capability* [(126)]. AVD^{PP} represents a cutting-edge parametric sizing methodology developed for generic design capability synthesis systems [(134)]. In the multidisciplinary design context, it comprehends the influencing design variables with strong interdisciplinary effect, forms a simple and robust modular analysis methodology and identifies the design mission's solution space.

The merit of AVD^{PP} is that it converges both weight and planform area simultaneously for a given set of design variables, while the other existing parametric sizing tools only converge weight. The process begins with the weight and volume budgets. From the weight and volume budgets, the trajectory and constraint analysis are conducted. These analyses provide the fuel fraction and thrust/weight ratio to perform the mission. All of the above analyses are connected through the geometry module of the vehicle. The geometry module acts as the 'gearbox' of the system, where the geometry is specified through algebraic equations and constant values that adapt the configuration for each new planform area. Formulated in this manner, the process is applicable to any fixed wing aircraft or launcher with changes in the disciplinary methods and geometry module when appropriate. Figure 4-3 summarizes the entire parametric sizing analysis methodology and logic.

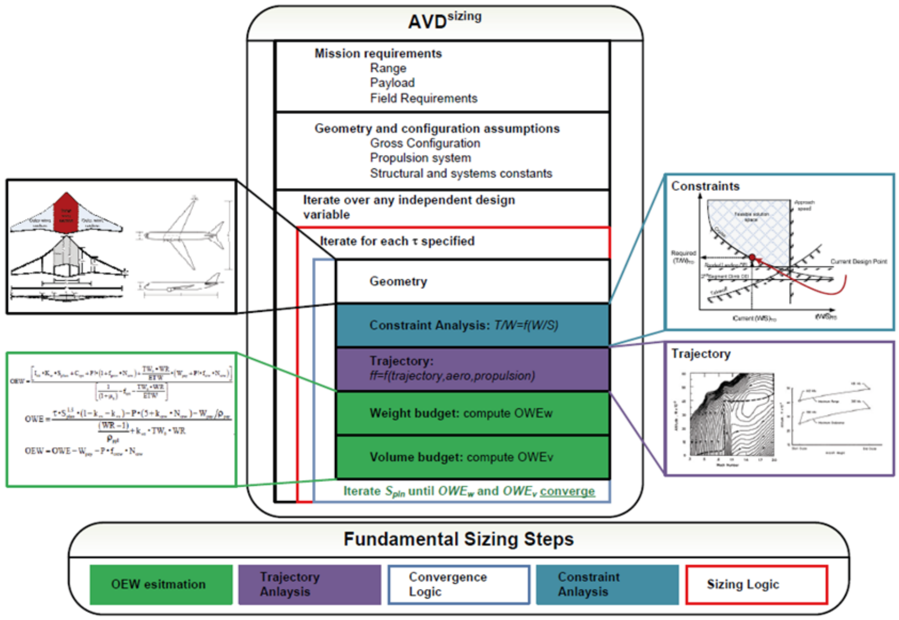


Figure 4-9 AVD^{PP} Parametric Sizing Analysis Methodology [134]

AVD^{KBS} will cooperate with both AVD^{DBS} and AVD^{PP} so that it is able to aid the deduction of new knowledge based on past project data and accomplish the parametric sizing analysis.

4.2 Knowledge Categorization

Traditionally, knowledge is classified according to its respective disciplines, such as art, aerospace engineering, or computer science, just to mention a few [66].

However, from the point of view of knowledge management, knowledge should be categorized according to its formats and representations because those categorizations indicate the types of knowledge applications, for designing the knowledge management functions.

In the following section, for the first time, three knowledge categories are proposed according to their formats and representations: *literal knowledge, qualitative knowledge* and *quantitative knowledge*. An overview of this knowledge categorization can be found with the following table.

Table 4-2 Knowledge Category Overview

	Literal Knowledge	Qualitative Knowledge	Quantitative Knowledge
Content	Conception illustration, background introduction, structure overview	Developing trend, constituent information, property evaluation, quality assessment	Numerical analysis, analytical formula
Representation	Sentences, figures	Figures, sentences	Analytical equation, figures, sentences
Format	Word description	Word and numerical value description	Numerical value description
Transferability	Nontransferable	Can be transferred into literal knowledge	Can be transferred into literal knowledge and qualitative knowledge

4.2.1 Literal Knowledge

Literal knowledge only includes words in its content. It is expressed in the form of sentences or figures, and it usually gives an introduction or summary of the object, such as concept illustration, background introduction, structure overview, and method description.

However, literal knowledge cannot be transformed into other types of knowledge because of its inherent lack of numerical values associated with its content.

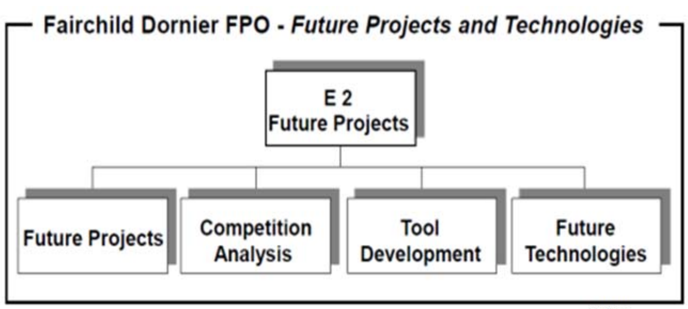


Figure 4-10 Fairchild Dornier FPO Structure [132]

Figure 4-10 shows an example of literal knowledge. It introduces the structure of the Future Project Office (FPO) at Fairchild Dornier [132]. The piece of knowledge shows that the Fairchild Dornier FPO has four sections: the overall Future Projects management, the Competition Analysis development office, the Tool Development office and the Future Technologies development office. It teaches us how the FPO at Fairchild Dornier is organized and how it divides the conceptual design analysis tasks within itself. However, the knowledge does not contain numerical values, so it cannot be described in analytical equations or bar graphs, and it cannot be directly transformed into qualitative or quantitative knowledge.

4.2.2 Qualitative Knowledge

Qualitative knowledge includes both words and numerical values in its content. It can be expressed in the form of figures or sentences, and it is used to describe a developing trend, property evaluation, quality assessment, and constituent information. All of these can also be expressed solely in words, so qualitative knowledge can be transformed to literal knowledge. However, these cannot be expressed by pure numerical values, so qualitative knowledge cannot be described in the form of analytical equations, thus it cannot be transformed into quantitative knowledge.

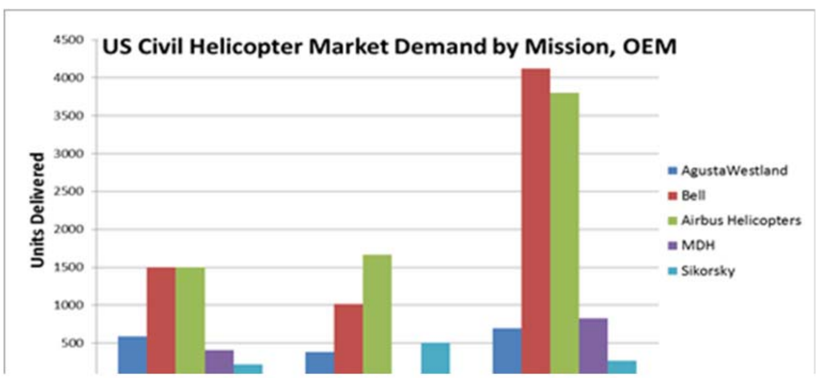


Figure 4-11 US Civil Helicopter Market Demand by Mission

Figure 4-11 shows an example of qualitative knowledge. It attempts to explain the U.S. civil helicopter market demand. It describes the delivered units from the major helicopter companies in the U.S. market in terms of mission type. It introduces characteristics of the U.S. helicopter market, such as how large the market is, which company is leading in each market segment, and which segment is the largest with regard to market demand.

This knowledge can be easily expressed using words. For example, parapublic civil helicopters have the highest market demand, and Bell Helicopter and Airbus Helicopters are the leading companies in terms of market share, while service and transport helicopters have a much lower market demand. As a result, it can be transformed into literal knowledge. However, it cannot be expressed in analytical equations because its content cannot be expressed by pure numerical values, so it cannot be transformed into quantitative knowledge.

4.2.3 Quantitative Knowledge

Quantitative knowledge content can be expressed via pure numerical values. As a result, it can be expressed in the form of analytical equations, and it typically describes numerical analysis, technical details, and analytical formulas. All of these can also be expressed in pure words, so they can be transformed into literal knowledge and qualitative knowledge.

$$I_p = 106.2 * \exp(-0.1877 * M) \tag{4.1}$$

I_p: propulsion index, M: Mach number

Equation (4.1) [132] is an example of quantitative knowledge. It describes the relationship between the propulsion index and Mach number using an analytical formula.

This knowledge form can be easily transformed into a figure. Figure 4-12 is a figure expression of the knowledge. It depicts the trend between propulsion index and Mach number. In pure words, it can be expressed as "*The propulsion index is an exponential function of the Mach number, and it has a decreasing trend as the Mach number increases*." As a result, it can be transformed into both qualitative and literal knowledge.

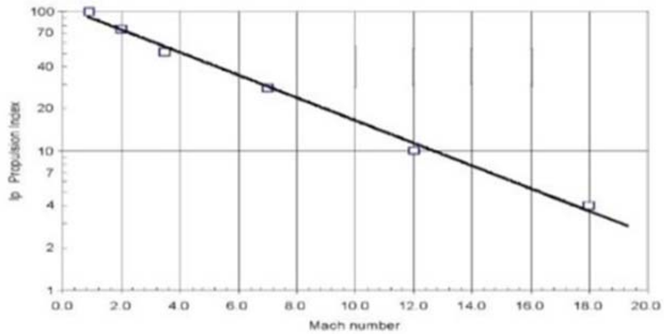


Figure 4-12 Relationship between Propulsion Index and Mach Number (132)

4.3 Efficiency Evaluation

Having knowledge categories classified, an efficiency evaluation criterion for knowledge management methods will be established. This unique efficiency evaluation criterion is designed to be an objective measurement criterion and used to compare the efficiencies of different knowledge management methods.

The concept of the AVD efficiency evaluation criterion is a further development of the Montserrat Prats Lopez's work (79) introduced in Chapter 2. In Montserrat's work, he innovatively includes the evaluator's background and knowledge application fields into the knowledge evaluation criterion. The AVD efficiency evaluation criterion takes the characteristics of both the knowledge and the user, who is an agent actively utilizing knowledge and conducting knowledge application processes, into account. As an improvement, the AVD evaluation criterion evaluates the knowledge and the user characteristics more specifically by using quantification parameters, such as processing speed, manipulation cost, and analyzing accuracy. Moreover, this efficiency index is proposed to measure the overall efficiency of the knowledge application process. The details of the AVD knowledge application efficiency evaluation criterion will be introduced with the following sections.

An overview of knowledge and user efficiency evaluation characteristics can be found in Table 4-3.

Table 4-3 Overview of Knowledge and User Efficiency Evaluation Characteristics

Evaluation aspect	Category	Parameter	Unit	Symbol
Knowledge characteristics				
Acquisition	Source	Accuracy	%	K_{Mva}
	Evolving period	Developing period	Years	K_{Mnc}
Storage	Medium	Storage density	GB/m3	K_{Asd}
		Storage cost	$/GB	K_{Asc}
Application	Education	Completeness	%	K_{Pec}
	Work	Relevance	1/0	K_{Par}
		Correctness	%	K_{Pac}
User characteristics				
Manipulation	Speed	Manipulating speed	GB/s	S_{Mps}
	Cost	Manipulating cost	$/GB	S_{Mmc}
Application	Education	Teaching efficiency	%	S_{Asc}
	Utilization	Analyzing speed	flops	S_{Aps}
		Analyzing accuracy	%	S_{Aac}

4.3.1 Efficiency Characteristics of Knowledge

Knowledge efficiency characteristics are analyzed based on the discussions in Chapter 2. In Chapter 2.1.4, knowledge is evaluated utilizing three aspects: *acquisition, storage and application*.

4.3.1.1 Acquisition

Acquisition aspect evaluates the quality of knowledge based on its sources. In Chapter 2, knowledge sources are categorized into six sources: language, sense perception, emotion, reasoning, intuition and memory (77). These sources can be classified into two types: *observational sources* and *correlational sources*. (135)

Table 4-4 Knowledge Source Types

Type of knowledge sources	Knowledge Sources
Correlational Source	Reasoning
Observational Source	Language, Sense perception, Emotion, Intuition and memory

The correlational source includes only reasoning, which is mainly related to scientific and engineering research activities. These are all peer reviewed and have been demonstrated by experiments and projects. Observational sources include language, sense perception, emotion, intuition and memory. These sources mainly generate knowledge related with daily life and societies, such as cultural knowledge. All of the aerospace engineering knowledge originates from correlational sources, so there is no need to develop efficiency evaluation parameters to evaluate observational sources.

However, for the correlational source, some of knowledge has been tested through a great number of experiments and projects, while other knowledge has not been tested at all. This situation indicates a significant difference in the knowledge quality. In order to differentiate such discrepancy, *accuracy* (%) is proposed. It describes the knowledge robustness based on its number of confirmations in past project applications. The value should be high if the knowledge entry has been validated and demonstrated to be correct repeatedly. For example, the analysis of fuel fraction is used to aid the determination of vehicle's range. It has been utilized and demonstrated through a lot of projects, such as the F-4, F-15 and F-22 (136), which results in a higher accuracy value. However, the Monte Carlo simulation for vehicle design developed by J.M. Hanson (137) was just proposed in 2010, and it has not been demonstrated in any project. As a result, the accuracy value is much lower.

Knowledge can also be evaluated through its *evolving period*. Some knowledge entries have evolved over more than one hundred years and have been demonstrated and confirmed thousands of times, while others have just been born and still lack validation. In order to differentiate their qualities, a parameter *accumulation* (Years) is proposed. It describes the incubation period of the knowledge entry. If the knowledge development period is extensive, it tends to be more mature and its quality tends to be better, so its value should be higher. Human wisdom is directly related to this parameter.

4.3.1.2 Storage

The storage aspect evaluates the quality of knowledge based on its documentation methods. From the knowledge documentation methods review in Chapter 1, there have been many kinds of knowledge documentation media used throughout human history, from stones, cave walls, bamboo, to books and hard drives. Some of them are easier to transport, like books and hard drives; whereas the others are more difficult or even impossible to move, such as stones or walls of caves. Their efficiency differences in storage can be differentiated in terms of *volume* and *cost*. With these in mind, two parameters are proposed to evaluate their performances: *storage density* (GB/m^3) and *storage cost* ($/GB).

The storage density uses GB to measure the amount of knowledge contained and uses m^3 to measure the according space occupation. For a more efficient documentation medium, the storage density value should be higher. This means that, for the same amount of knowledge, the more efficient documentation medium should occupy less space. Alternately, for the same amount of storage volume, the more efficient documentation medium contains more knowledge. For example, the Code of Hammurabi is a Babylonian law code documented on a block of basalt with a volume of 0.64 m^3 (138)and its content is 0.02 GB, so its storage density is 0.03 GB/ m^3 ($\frac{0.02\ GB}{0.64\ m3}$); while for an electronic version of The Code of Hammurabi (stored in flash drive), its volume is 0.00001155 m^3 (139), so its storage density is 1731.6 GB/m^3 ($\frac{0.02\ GB}{0.00001155\ m3}$). As can be seen, the electronic storage medium is much more efficient than the stone storage medium.

Figure 4-13 The Code of Hammurabi (138)

The storage cost uses $ to measure the cost of the knowledge documentation medium, and it uses GB to measure the amount of knowledge. For a more efficient documentation medium, the value should be lower. This means that, for the same amount of knowledge, the more efficient documentation medium costs less money. Alternately, for the same amount of expenditure, the more efficient documentation medium stores more knowledge. For example, the price of a natural basalt column same to the one shown in Figure 4-13 is $150 per piece [140], while the price of the flash drive is $6 [139]. As a result, the storage cost of the Code of Hammurabi documented in basalt is 7500 $/GB ($\frac{150\ \$}{0.02\ GB}$), and the storage cost of the Code of Hammurabi documented in flash drive is 300 $/GB ($\frac{6\ \$}{0.02\ GB}$). The comparison also demonstrates the flash drive storage medium is much more efficient than the stone storage medium.

4.3.1.3 Application

The application aspect evaluates the quality of knowledge based on its fields of applications. The application of knowledge is usually categorized according to disciplines, such as engineering, natural sciences and human sciences. However, the application of AVD^{KBS} focuses on knowledge management for aerospace engineering during the conceptual design stage. As a result, the knowledge application fields are divided according to their application objects. There are two categories of knowledge application objects: human and work. The former means knowledge is applied to humans, referring to education; the latter means knowledge is applied to all of the other knowledge application objects except humans. As a result, the knowledge application can be classified into two categories: *education* and *work*.

There are two major differences between the two categories. (i) The parties involved in the knowledge application processes are different. For the education category, the knowledge application process is between humans; while, for the work category, the knowledge application process is between humans and work practices. (ii) There is generation of new knowledge during the knowledge application processes. For the education category, there is no new knowledge generation during the application process; while, for the work category, there are usually new knowledge findings. When people apply knowledge into new tasks, new findings are usually generated.

Knowledge applications for the education category are processes referring to the education of fresh engineers. *Completeness* (%) is used to evaluate the knowledge education efficiency based on its comprehensiveness. The more comprehensive the knowledge is, the higher completeness value it receives. This means more knowledge is available for the education process. For example, the aerodynamic methods collections from Nicolai include fuselage, engines, propulsion, empennage and landing gear methods; while the collections from Torenbeek only has empennage methods [132]. As a result, the knowledge from Nicolai is more complete and results in a higher knowledge education efficiency.

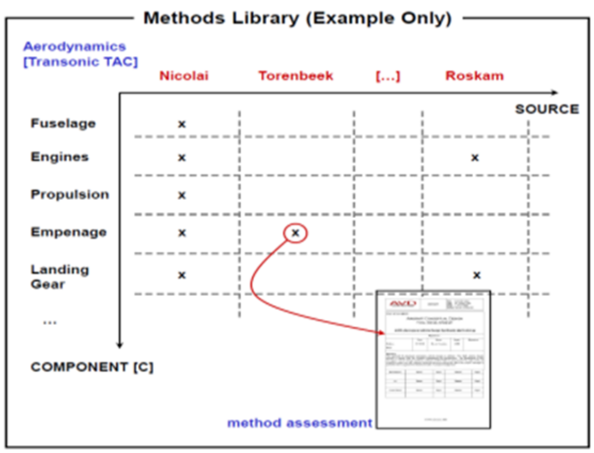


Figure 4-14 Aerodynamics Methods Library [132]

The work category includes all of the other knowledge applications. It uses the *relevance* (1/0) and *correctness* (%) to describe the efficiency of knowledge. There are only two possible values for the relevance variable: 1and 0. 1 means that the chosen knowledge is used in the right field and the knowledge application process will be efficient, while 0 means that the chosen knowledge is used in the wrong field and the knowledge application process will be futile. Correctness measures how well the knowledge fits the application purpose. If a piece of knowledge fits the application better, the knowledge application process will be more efficient, therefore the value should be higher.

4.3.2 Efficiency Characteristics of User

From the literature review in Chapter 2, Montserrat includes the evaluator's background into the knowledge evaluation criteria. He argues the evaluator's

> "… prior knowledge can be seen as a moderator or necessary condition for knowledge evaluation. Furthermore, the adoption of new knowledge will be easiest when prior and new knowledge are related and that, therefore, the broader the prior knowledge base the highest the likelihood of recognizing the value of new knowledge. …" (79).

However, he does not further substantiate the criterion with detailed specifications and evaluation parameters. Moreover, no other reference makes contributions in this regard. As an improvement, the AVD evaluation criterion substantiates the users' characteristics in terms of *manipulation* and *application*, and it proposes parameters with physical meanings to quantitatively measure the users' efficiency differences during the knowledge application processes. The users are humans and KBSs. Humans are the users of the knowledge documented in stones, papers and electronic media, while individual KBSs are the users of the knowledge documented using electronic media.

4.3.2.1 Manipulation

The manipulation aspect analyzes the user's efficiency characteristics based on their performance when manipulating knowledge. It refers to the activities of knowledge searching, retrieving or editing. The feature of those activities is that the value of knowledge is not manifested during those processes, like for example, locating knowledge and moving knowledge from one place to another.

For the manipulation aspect, *manipulating speed* (GB/s) and *manipulating cost* ($/GB) are used to measure the user efficiencies in manipulating knowledge. The manipulating speed uses

GB to measure the amount of knowledge manipulated, and it uses seconds to measure the time length of the manipulating process. A more efficient knowledge manipulating user receives a higher value. This means that, for a given amount of knowledge, the manipulating time is less. Alternatively, for a given amount of time, more knowledge can be manipulated. For example, in order to locate a specific sentence in the Constitution of the United States [141], it takes a human about 3 minutes (180 seconds) (although it may vary among people with different reading capabilities), while it only takes a KBS about 0.1 second. As a result, the manipulating speed of humans is 3.33E-5 GB/s ($\frac{0.006\ GB}{180\ s}$), and the KBS p manipulating speed is 0.06 GB/s ($\frac{0.006\ GB}{0.1\ s}$).

For the manipulating cost, it measures the expenditure during the knowledge manipulation processes. It uses GB to measure the amount of knowledge manipulated, and it uses $ to measure the manipulation cost. For a more efficient system, the value should be lower. It means that, for a given amount of knowledge, the manipulation cost is lower. Alternatively, for a given amount of expenditure, more knowledge can be manipulated.

4.3.2.2 Application

The application aspect analyzes the user efficiency characteristics during the knowledge application processes. The knowledge application processes refers to the activities of user applying knowledge into practices, and it divides the knowledge applications processes into two categories: *education* and *utilization*. The difference between the two categories is similar to that between the knowledge application categories introduced in Chapter 4 early sections.

The education category refers to the process of a user teaching learners. *Teaching efficiency* (%) is used to measure the user's efficiencies. A high teaching efficiency means that the teacher can educate the students efficiently, and the students can get a good understanding of the knowledge. For example, a human teacher can interact with students, and actively change the teaching strategy based on the students' feedback; in contrast, the KBS cannot interact with students. As a result, a human teacher will help students understand the knowledge better; consequently, the teaching efficiency will be higher.

The utilization category refers to the process of a user applying knowledge to work practices. *Analyzing speed* (flops) and *analysis accuracy* (%) are used to quantify the user's efficiencies during the knowledge utilization process. An efficient user receives a high analyzing speed value. It means that the user can finish tasks fast. The analysis accuracy variable evaluates the accuracy of a user during the knowledge utilization processes. An efficient user receives a high analysis accuracy value. It means that a user is efficient if it can finish tasks with few mistakes.

4.3.3 Efficiency Index

After defining the efficiency characteristics of both the knowledge and user followed by the proposing of the quantification parameters, an efficiency evaluation parameter, *efficiency index* I_e, is proposed to systematically organize those parameters into a single index. The purpose of this index is to rate and compare the overall efficiency of individual knowledge management methods.

4.3.3.1 Efficiency Index Formula

According to the literature search results, no previous research has tried to propose a parameter which can quantitatively indicate the overall efficiency of knowledge management method. The efficiency index I_e is the first parameter of this kind.

The basic logic in calculating the efficiency index can be expressed as follows:

I_e = *Knowledge generic attributes * (Knowledge application attributes*User attributes)*

- The knowledge generic attributes refer to the innate attributes of knowledge, including the storage and acquisition aspects. No matter what type of application it is, the knowledge generic attributes always play a role in the efficiency evaluation process.

– The knowledge application attributes refer to the attributes that are related to the application processes, such as work and educate categories. Different types of knowledge applications use different application attribute parameters accordingly.

– The user action attributes refer to the attributes that are related with the user characteristics, such as manipulation and application aspects. These attributes differ from one user to another.

A summary of the attributes categories and their related efficiency quantification parameters is listed in Table 4-5:

Table 4-5 Summary of Attributes Categories and Their Related Parameters

Attributes Categories	**Parameters**
Knowledge generic attributes	K_{Mva}, K_{Mnc}, K_{Asd}, K_{Asc}
Knowledge application attributes	K_{Pec}, K_{Par}, K_{Pac}
User action attributes	S_{Mps}, S_{Mmc}, S_{Asc}, S_{Aps}, S_{Aac}

Based on the above discussions, the *efficiency index* can be formulated as:

For education knowledge applications:

$$I_e = \frac{K_{Asd}}{K_{Asc}} * K_{Mva} * K_{Mnc} * ((K_{Pec}) * (\frac{S_{Mps}}{S_{Mmc}} * S_{Asc})) \tag{4.2}$$

For the other knowledge applications:

$$I_e = \frac{K_{Asd}}{K_{Asc}} * K_{Mva} * K_{Mnc} * ((K_{Par} * K_{Pac}) * (\frac{S_{Mps}}{S_{Mmc}} * S_{Aps} * S_{Aac})) \tag{4.3}$$

4.3.3.2 Efficiency Index Unit

Based on the efficiency index formula, the deduction of the efficiency index unit is introduced. It demonstrates physical meaning of the efficiency index. The units of the efficiency quantification parameters are first listed with the following table.

Table 4-6 Units of Knowledge and User Efficiency Quantification Parameters

Parameter	**Unit**
Knowledge characteristic parameters	
K_{Asd}	$\frac{GB}{m^3}$
K_{Mnc}	$Years$
K_{Asc}	$\frac{\$}{GB}$
K_{Pac}	%
K_{Mva}	%
K_{Par}	1/0
User characteristic parameters	
S_{Mps}	$\frac{GB}{s}$
S_{Aac}	%
S_{Mmc}	$\frac{\$}{GB}$
S_{Asc}	%
S_{Aps}	flops

From Equation 6.2, the unit of I_e for educate knowledge application is:

$$= \frac{\frac{GB}{m^3}}{\frac{\$}{GB}} * \% * Years * ((\%) * (\frac{\frac{GB}{s}}{\frac{\$}{GB}} * \%))$$

$$= \frac{\frac{GB}{m^3}}{\frac{\$}{GB}} * 10^{-2} * 3.07584 * 10^{7} s * ((10^{-2}) * (\frac{\frac{GB}{s}}{\frac{\$}{GB}} * 10^{-2}))$$

$$= 30.7584 \frac{GB^4}{s \cdot m^3 \cdot \$^2}$$

From Equation 6.3, the unit of I_e for utilization knowledge application is:

$$= \frac{\frac{GB}{m^3}}{\frac{\$}{GB}} * \% * Years * ((1 * \%) * (\frac{\frac{GB}{s}}{\frac{\$}{GB}} * flops * \%))$$

$$= \frac{\frac{GB}{m^3}}{\frac{\$}{GB}} * 10^{-2} * 3.07584 * 10^{7} s * ((10^{-2}) * (\frac{\frac{GB}{s}}{\frac{\$}{GB}} * flops * 10^{-2}))$$

$$= 30.7584 \frac{GB^4 \cdot flops}{s \cdot m^3 \cdot \$^2}$$

From the deduction process, it is seen that the unit of the efficiency index is $30.7584 \frac{GB^4}{S \cdot m^3 \cdot \$^2}$ or $30.7584 \frac{GB^4 \cdot flops}{S \cdot m^3 \cdot \$^2}$. As a result, a higher efficiency index I_e means more knowledge application can be achieved in a way with less cost, time and space, which is exactly the key characteristic of a higher efficiency knowledge management method. In this way, the efficiency index offers a promising efficiency evaluation criterion for knowledge management methods.

4.4 AVD^{KBS} Methodology

This section introduces the methodology of AVD^{KBS}. It first describes the AVD^{KBS} components; after that, it introduces the proposed AVD^{KBS} knowledge management functions; last, it explains the working principles of those functions.

4.4.1 AVD^{KBS} Components

AVD^{KBS} consists of three components: *the GUI, the inference engine* and *the knowledge base.* An overview of AVD^{KBS} components can be found in Figure 4-15.

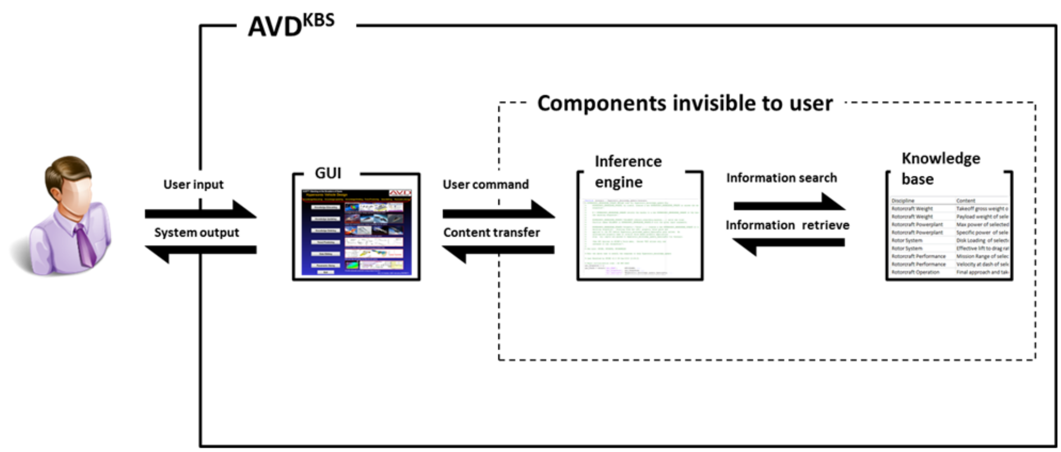


Figure 4-15 AVD^{KBS} Components.

4.4.1.1 GUI

An overview of the GUI methodology is introduced with Figure 4-16:

The GUI provides users with graphical access to AVD^{KBS}. It allows users to use AVD^{KBS} like they use any other piece of software in the Microsoft Windows environment. For example, the

GUI uses text boxes for the user to input design requirements, and uses check boxes to help the user make design stage selections.

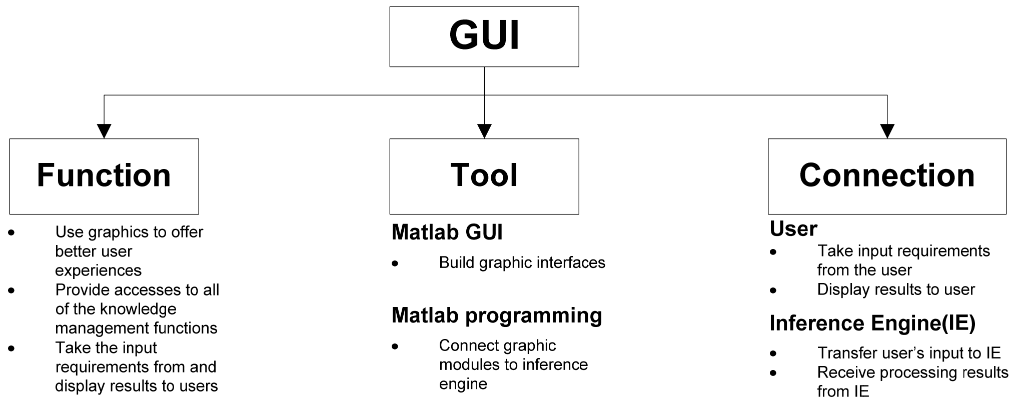


Figure 4-16 AVD^{KBS} GUI Methodology.

Researchers usually select the programming language which is most compatible with the inference engine to build the GUIs. As a result, a variety of programming languages have been used, such as C, LISP and Python. For example, Jin-Woo Choi et al [116] uses the CATIA V5 environment to build the GUIs for the composite aerospace structure cost estimation KBS because their knowledge base is built in the CATIA V5 knowledge environment and connected to CATIA CAD system.

Accordingly, the AVD^{KBS} GUI is programmed using Matlab's GUI-creation functionality. The setup of a GUI is determined according to the requirements of its related knowledge management function, and details of each GUI setup will be introduced with the following sections. The GUI takes inputs from the user, such as design mission requirements or knowledge search requests, and passes them to the inference engine. The inference engine and the knowledge base will work together to finish processes, such as knowledge searching. After the process is finished, the inference engine will feed the output back to the GUI. The GUI finally displays it to the user. In this way, the user can take fully advantages of the AVD^{KBS} knowledge management functions through simple mouse and keyboard interactions.

4.4.1.2 Inference Engine

An overview of the inference engine methodology is introduced with Figure 4-17:

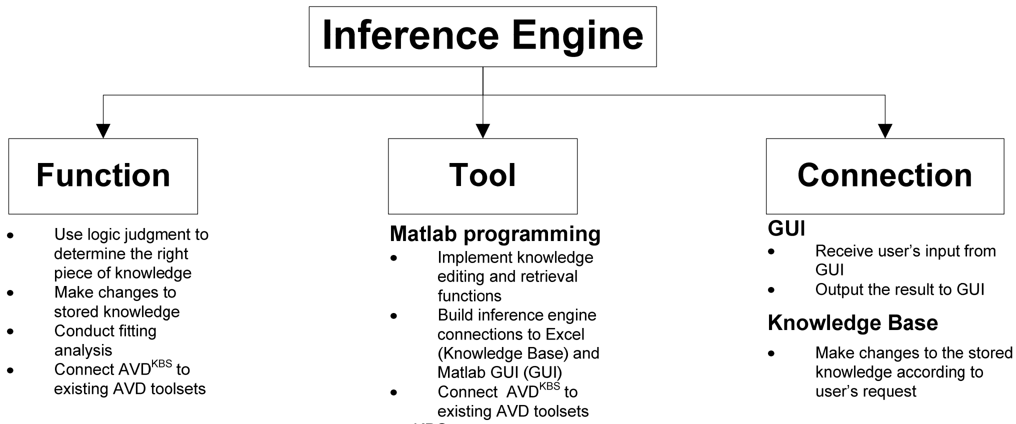


Figure. 4-17 AVD^{KBS} Inference Engine Methodology

The inference engine is the "brain" of AVD^{KBS}. It receives the command from the user through the GUI and finishes all of the knowledge searching, editing, innovating and applying tasks. It has four functions:

– The first function is *logic judgment*. According to the user's search request, the inference engine needs to determine which piece of knowledge matches the user's demand. The logic judgment is implemented through "If-Then" rule-based reasoning, which is broadly applied in KBS applications.

– The second function is *knowledge editing*. The inference engine will receive the new knowledge from the user and update it into AVD^{KBS} or make changes to the current knowledge according to the user's input.

– The third function is *fitting analysis*. When the user tries to predict an unknown design trend, the inference engine will retrieve the available data and use the built-in fitting methods to make design trend predictions.

– The fourth function is *connecting* AVD^{KBS} with all of the other AVD toolsets. The AVD^{KBS} not only can work alone but it is also able to cooperate with existing AVD toolsets, such as AVD^{DBS} and AVD^{PP}. The inference engine is the bridge connecting all of them. For example, the inference engine can retrieve the stored knowledge from AVD^{KBS} and apply it into the parametric sizing analysis process, which is conducted by AVD^{PP}, to solve unknown variables.

The inference engine is developed using the Matlab programming language. However, many other programming languages have been applied in KBS developments, such as LISP, C, Python, and so on. The reason for choosing Matlab as the primary programming language for AVD^{KBS} is that it can perfectly communicate with AVD^{PP}, which is also developed using Matlab. Moreover, Matlab programming language can also work with the knowledge base and AVD^{DBS}, which are built using Microsoft Excel and Access, respectively. As a result, the inference engine is able to communicate with all of the AVD toolsets whilst implementing the proposed knowledge management functions.

4.4.1.3 Knowledge Base

An overview of the knowledge base methodology is introduced with Figure 4-18:

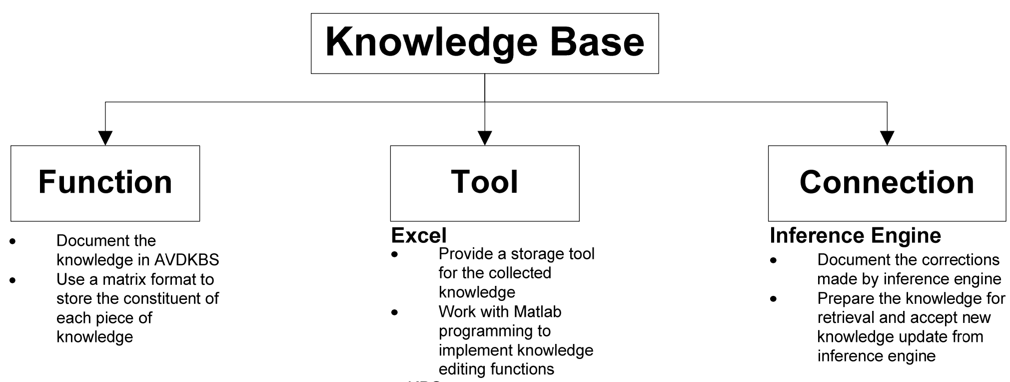


Figure 4-18 AVD^{KBS} Knowledge Base Methodology

The knowledge base is the intelligence tank of AVD^{KBS} and stores the knowledge contained in AVD^{KBS}. It uses a predefined format to store the knowledge and make it ready for use, and it also accepts newly updated knowledge and allocates space to it.

The knowledge base is developed using Microsoft Excel. It uses a matrix structure to store knowledge. The columns of the matrix store all of the constituents of each piece of knowledge, including the author, the application discipline, the reference, the input and output; each row of the matrix stores a piece of knowledge. When the inference engine needs to update new knowledge into or retrieve current knowledge from the knowledge base, it uses the command ‘xlswrite’ or ‘xlsread’, respectively, to implement the operations.

4.4.2 AVD^{KBS} Functions

In the early Chapter 4 sections, three categories of knowledge have been defined. In this section, three groups of knowledge management functions are proposed to manage the respective knowledge categories. An overview of the AVD^{KBS} knowledge management functions is presented with Table 4-7:

Table 4-7 Overview of AVD^{KBS} Knowledge Management Functions

Involved AVD systems	**Knowledge management function categories**	**Advantages**
AVD^{KBS}	Literal knowledge management functions	Fast manipulating: help the user quickly search, retrieve and edit knowledge
AVD^{KBS}+AVD^{DBS}	Qualitative knowledge management functions	Design trend analysis: help the user predict design trend knowledge based on past project data Fast manipulating
AVD^{KBS}+AVD^{DBS}+AVD^{PP}	Quantitative knowledge management functions	Parametric sizing analysis: help the user finish the parametric sizing analysis. Fast manipulating Design trend analysis

For literal knowledge, literal knowledge management functions are proposed, and those functions are implemented via AVD^{KBS} working independently. The management functions of literal knowledge are: knowledge educating, knowledge updating, and knowledge deleting. The purpose of those knowledge management functions is to provide an efficient education tool, which is mainly implemented by the knowledge educating function. The knowledge updating and knowledge deleting functions are support functions, which are designed to keep AVD^{KBS} up-to-date and for removing unnecessary content from it.

The key advantage of the literal knowledge management functions is *fast manipulation*. It aims to help users search, retrieve and edit knowledge in a fast, convenient and low cost manner.

For qualitative knowledge, the qualitative knowledge management functions are proposed and implemented through AVD^{KBS} working with AVD^{DBS} together. The management functions of qualitative knowledge are: trend predicting, data updating, and data deleting. The purpose of these qualitative knowledge management functions is to provide an efficient knowledge innovation tool, which is mainly implemented by the trend predicting function. The data updating and data deleting functions are support functions, which keep the data up-to-date in AVD^{DBS} and remove outdated data from it.

The key advantage of the qualitative knowledge management functions is *design trend analysis*. It aims to help users predict the design trend based on the past project data.

Qualitative knowledge can be transferred into literal knowledge, so the qualitative knowledge management functions also include all of the literal knowledge management functions. This means that *fast manipulation* is also an advantage of qualitative knowledge management functions.

For quantitative knowledge, quantitative knowledge management functions are proposed. They are implemented through AVD^{KBS} working with both AVD^{DBS} and AVD^{PP}. The main application of quantitative knowledge is parametric sizing analysis. Its purpose is to apply the stored knowledge from AVD^{KBS} into the parametric sizing analysis controlled by AVD^{PP}, while AVD^{DBS} provides the starting point vehicle data for said analysis.

The key advantage of the quantitative knowledge management functions is *parametric sizing analysis*. It aims to help users finish the parametric sizing analysis. It is able to receive the mission requirements from the user, finish the parametric sizing analysis independently and feed the analysis result back to the user.

Quantitative knowledge can be transferred into qualitative knowledge, so the quantitative knowledge functions also include all of the qualitative knowledge management functions. This means the *design trend analysis and fast manipulation* are also advantages of quantitative knowledge management functions.

In the following sections, the implementations of these knowledge management functions are introduced.

4.4.2.1 Literal Knowledge Management Function

The parties involved in the literal knowledge management functions are the user and AVD^{KBS}. Literal knowledge management functions consist of:

1. Knowledge Educating: help the user learn knowledge from AVD^{KBS}, such as lessons learned, design guidelines and past project experiences;
2. Knowledge Updating: help the user update new knowledge into AVD^{KBS};
3. Knowledge Deleting: help the user remove outdated or unnecessary knowledge from AVD^{KBS}.

When the knowledge deleting function and knowledge updating function work together, they offer a knowledge editing function. Its process is as follows: the user can use the knowledge deleting function to remove the piece of knowledge that is going to be edited and then use the knowledge updating function to update the edited knowledge into AVD^{KBS} as a new piece of knowledge. In this way, the user can edit the current knowledge in AVD^{KBS}.

<u>Knowledge Educating</u>

The working principle of the knowledge educating function is:

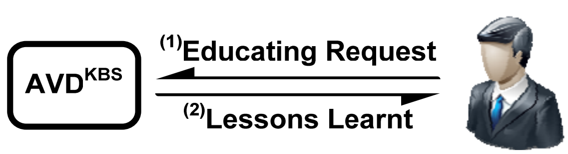


Figure 4-19 Working Principle of Knowledge Educating

1. Educating Request
   - The user inputs the knowledge education request through the GUI.
   - The GUI transfers the user's request to the inference engine.
   - The inference engine starts the search process within the knowledge base.
2. Lessons Learned

- The inference engine finds the location of the requested knowledge
- It retrieves the knowledge and feeds it back to the GUI.
- The GUI displays the knowledge to the user and aids in the knowledge learning process.

Knowledge Updating

The working principle of the knowledge updating function is:

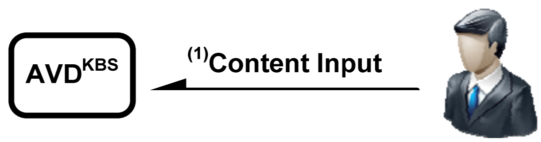


Figure 4-20 Working Principle of Knowledge Updating

1. Content Input
    - The user inputs the content of the new knowledge into the GUI.
    - The GUI transfers it to the inference engine.
    - The inference engine searches within the knowledge base and identifies the next available place to put the new knowledge.

Knowledge Deleting

The working principle of the knowledge deleting function is:

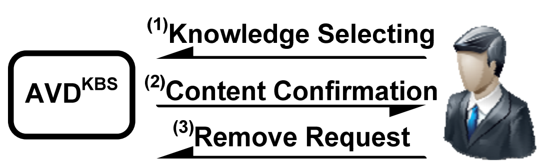


Figure 4-21 Working Principle of Knowledge Deleting

1. Knowledge Selecting
    - The user makes selections through the GUI to find the knowledge that is going to be removed.
    - The GUI transfers the user's request to the inference engine.
    - The inference engine starts the search process within the knowledge base.

2. Content Confirmation

   - After the inference engine finds the knowledge, it retrieves the knowledge and feeds it back to the GUI.
   - The GUI displays the knowledge content to the user, waiting for the user's confirmation.

3. Remove Request

   - The user confirms it is the knowledge to be removed and hits the "Delete" button.
   - The GUI transfers the command to the inference engine.
   - The inference engine removes the knowledge from AVD^{KBS}.

An overview of the literal knowledge management functions is represented with Fig. 4-22.

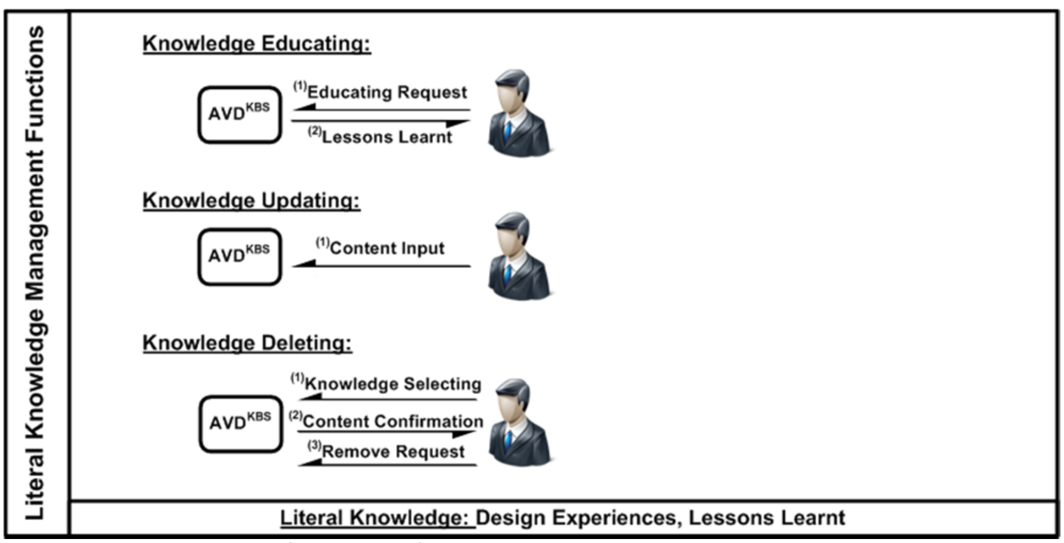


Figure 4-22 Overview of Literal Knowledge Management Functions

4.4.2.2 Qualitative Knowledge Management Functions

The parties involved in the qualitative knowledge management functions are the user, AVD^{KBS} and AVD^{DBS}. Qualitative knowledge management functions consist of:

1. Trend predicting: help the user utilize AVD^{KBS} to deduce the unknown design trend based on past project data from AVD^{DBS}.

2. Data Updating: help the user update the project data into AVD^{DBS}.
3. Data Deleting: help the user remove outdated or unnecessary project data from AVD^{DBS}, avoiding using inaccurate data during the design trend prediction process.

Similar to the knowledge editing function, when the data deleting function and data updating function work together, they can offer a data editing function. The user can first remove the data that is going to be edited using the data deleting function; after that, the user can update the edited data into the database using the data updating function. In this way, the user can edit the current data in AVD^{DBS}.

<u>Trend Predicting</u>

The working principle of the trend predicting function is:

Figure 4-23 Working Principle of Trend Predicting

1. Parameter Selection
    - The user selects the parameters of interest through the GUI.
    - The GUI transfers the selections to the inference engine.
2. Parameter Searching
    - The inference engine searches the input parameters within the AVD^{DBS} and locates them.
3. Data Retrieving
    - The inference engine retrieves all of the parameters' past project data from AVD^{DBS}.
4. Fitting Deduction
    - The inference engine uses the built-in fitting method to make design trend predictions

- Then it sends the result to the GUI.
- The GUI displays the design trend to the user.

<u>Data Updating</u>

The working principle of the data updating function is:

Figure 4-24 Working Principle of Data Updating

1. Data Input
   - The user inputs the new project data through the GUI
   - The GUI transfers it to the inference engine.
2. Data Update
   - The inference engine searches for and locates the proper place within AVD^{DBS} and updates the data.

<u>Data Deleting</u>

The working principle of the data deleting function is:

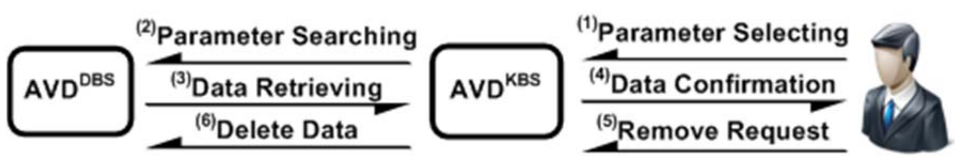


Figure. 4-25 Working Principle of Data Deleting

1. Parameter Selecting
   - The user selects the outdated or unnecessary project data through the GUI.
   - The GUI passes the selections to the inference engine.
2. Parameter Searching
   - The inference engine searches for and identifies the project data within AVD^{DBS}.

3. Data Retrieving
    - The inference engine retrieves the project data from the database and sends it back to the GUI.
4. Data Confirmation
    - The GUI displays the project data to the user, waiting for the user to confirm that it is the data to be deleted.
5. Remove Request
    - The user confirms the search result and issues the delete command through the GUI.
6. Delete Data
    - The GUI transfers the user's command to the inference engine.
    - The inference engine implements the command and removes the data.

Qualitative knowledge can be transferred to literal knowledge, so the literal knowledge management functions can also be applied to qualitative knowledge. This means the knowledge educating, knowledge updating and knowledge deleting can be used on qualitative knowledge. As a result, an overview of the qualitative knowledge management functions is given with Figure 4-26.

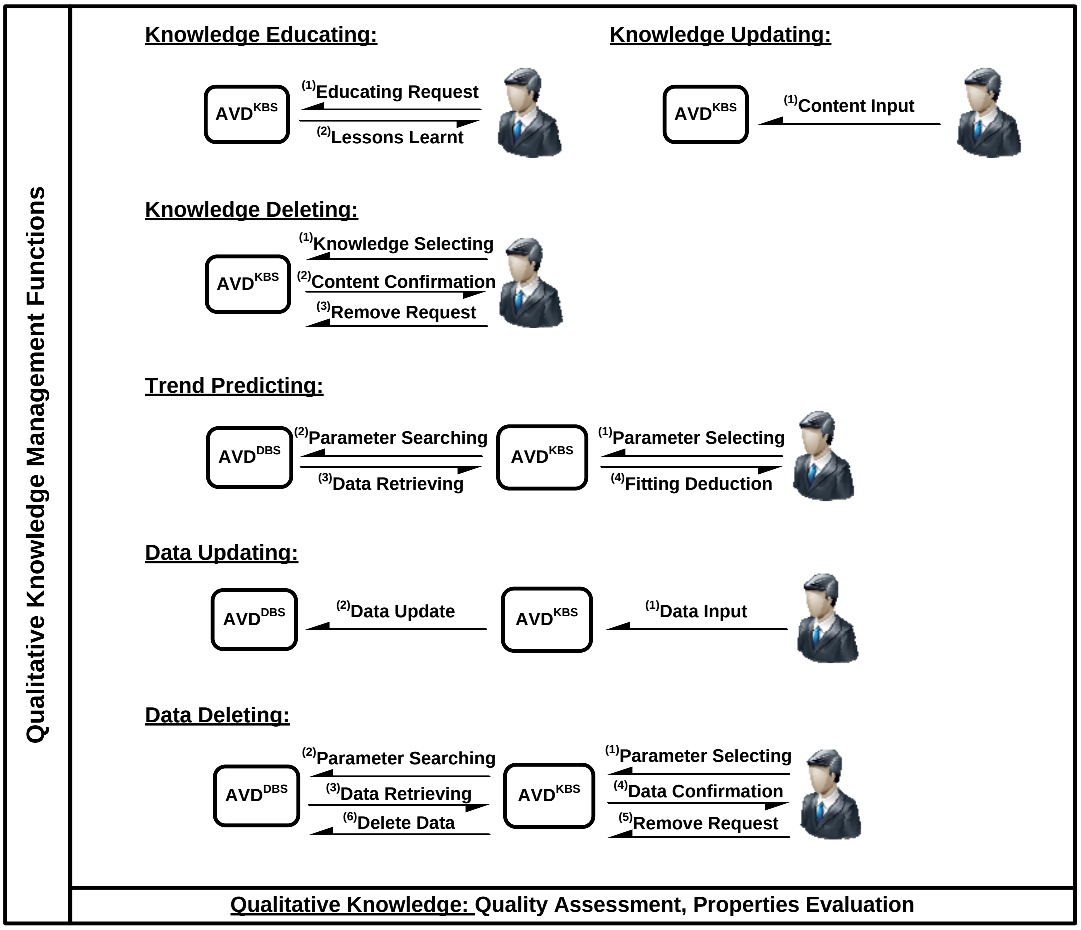


Figure 4-26 Overview of Qualitative Knowledge Management Functions

4.4.2.3 Quantitative Knowledge Management Functions

The parties involved in the quantitative knowledge management functions are the user, AVD^{KBS}, AVD^{DBS} and AVD^{PP}. Quantitative knowledge management functions consist of:

Parametric sizing analysis: help the user utilize the knowledge and methods from AVD^{KBS}, the past project data from AVD^{DBS} and the parametric sizing analysis methods from AVD^{PP} to finish the parametric sizing analysis.

Parametric sizing analysis

The working principle of the parametric sizing analysis function is:

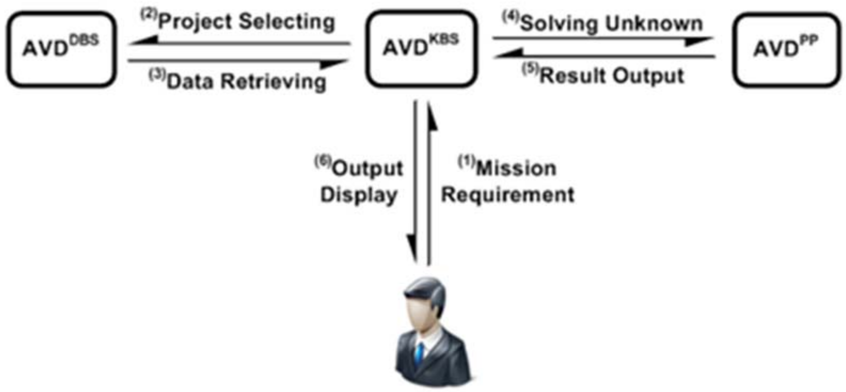


Figure 4-27 Working Principle of Parametric Sizing Analysis

1. Mission Requirement
   - The user inputs the mission requirements through the GUI.
   - The GUI transfers them to the inference engine.
2. Project Selecting
   - The inference engine searches within AVD^{DBS} and finds the most similar past project as the starting point.
3. Data Retrieving
   - The inference engine retrieves all of the available data from the selected project and sends them back to AVD^{KBS}.
4. Solving Unknown
   - The inference engine compares the input requirements of the parametric sizing analysis code from AVD^{PP} and the project data from AVD^{DBS}. As a result, it identifies the unavailable data.
   - Then, it uses the methods from AVD^{KBS} to solve for the unknown data.
   - After that, the inference engine inputs all of the project data into the parametric sizing analysis code and starts the analysis process.
5. Result Output

- After the parametric sizing analysis is finished, the inference engine fetches the analysis result.

6. Output Display
    - The inference engine passes the analysis result to the GUI
    - The GUI displays it to the user.

Quantitative knowledge can be transferred to qualitative knowledge, so the qualitative knowledge management functions can also be applied to quantitative knowledge. This means the trend predicting, data updating, data deleting, knowledge educating, knowledge updating and knowledge deleting functions can be applied to quantitative knowledge. As a result, Figure 4-28 overviews the quantitative knowledge management functions.

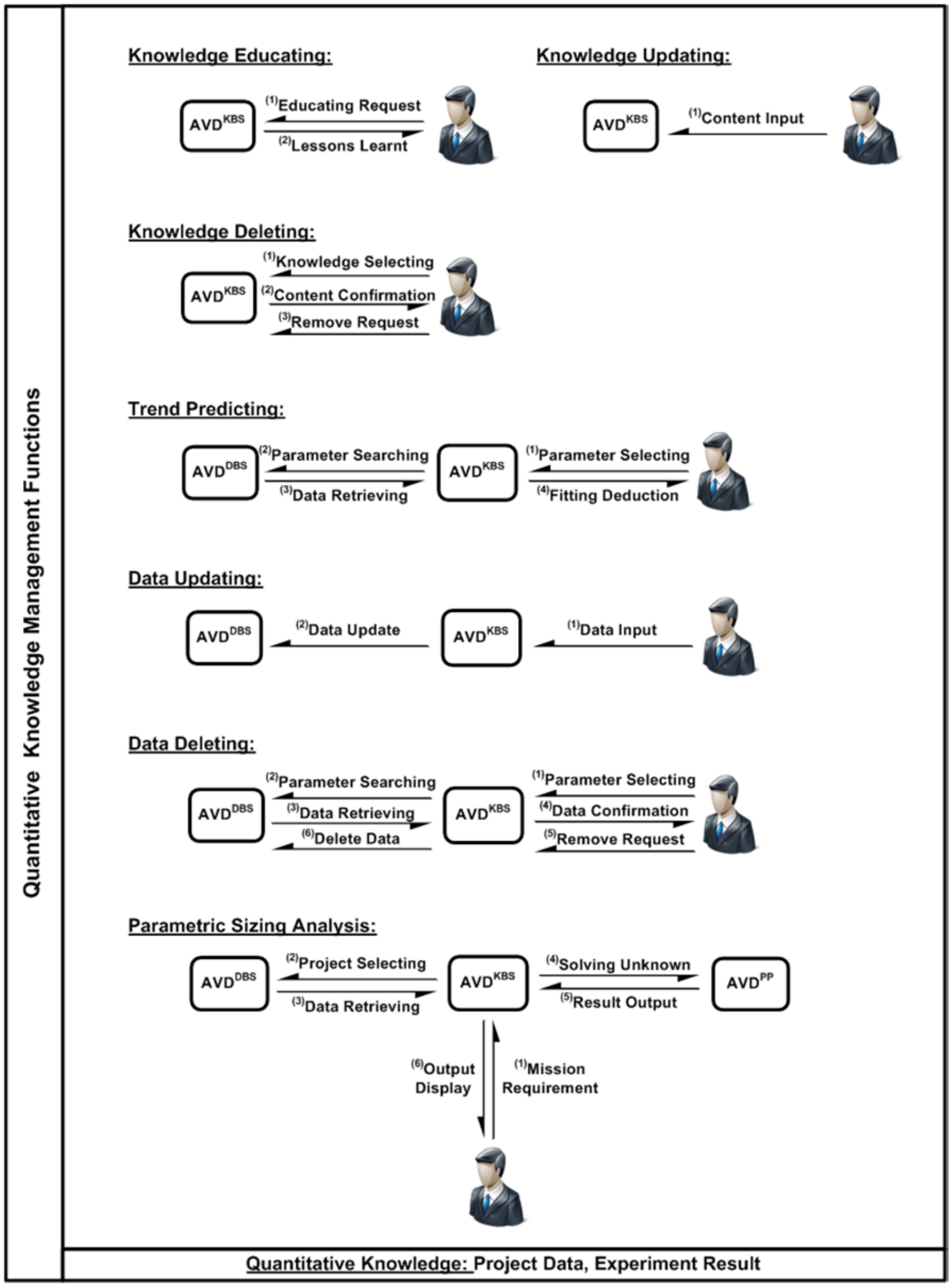


Figure 4-28 Overview of Quantitative Knowledge Management Functions

The following table is summarizing the AVD^{KBS} knowledge management functions, their related knowledge categories and the involved AVD toolsets. In this way, the proposed knowledge management functions form a systematic knowledge management approach, and they make

AVD^{KBS} not only work along as a knowledge storage and education tool, but also work with AVD^{DBS} and AVD^{PP} to accomplish knowledge innovation and parametric sizing analysis tasks.

Table 4-8 Knowledge Categories and Their Management Functions

Knowledge Categories	Knowledge Management Functions	Involved AVD Toolsets
Literal Knowledge	Literal knowledge management functions: Knowledge Educating Knowledge Updating Knowledge Deleting	AVD^{KBS}
Qualitative Knowledge	Qualitative knowledge management functions: Trend Predicting Data Updating Data Deleting Literal knowledge management functions	AVD^{KBS} + AVD^{DBS}
Quantitative Knowledge	Quantitative knowledge management functions Parametric Sizing Analysis Qualitative knowledge management functions	AVD^{KBS} + AVD^{DBS} + AVD^{PP}

4.5 Research Contribution Summary

The original research contributions from Chapter 4 are as follows:

1. Uniquely classify the knowledge into three categories according to their formats and representations: literal knowledge, qualitative knowledge and quantitative knowledge, which is different from traditional academic discipline classification methods. It is the key to the success of KBS developments.
2. Analyze efficiency characteristics of both the knowledge and user, and propose quantification parameters to quantitatively evaluate their characteristics. It provides a solid foundation for the following development of knowledge management efficiency evaluation criterion, because the development of knowledge management efficiency evaluation criterion will not be successful if it is not built on profound understandings of efficiency characteristics of both the knowledge and the user, which are the two parties involved in the knowledge management processes.
3. Uniquely propose and develop an AVD efficiency evaluation criterion for knowledge management methods, which serves an objective measurement scale to demonstrate the AVD^{KBS} efficiency advantages over traditional knowledge

management methods. It is the first ever criterion which can quantitatively determine the efficiency of a knowledge management method.

4. Propose the methodology of AVD^{KBS}, consisting of three groups of knowledge management functions and forming a closed loop in knowledge management. In this way, it not only provides knowledge management functions for each knowledge category, but also builds a bridge for the evolutions from data, information to knowledge and transformations among the three knowledge categories.

Chapter 5

AVD^{KBS} Development

After establishing the AVD^{KBS} methodology in Chapter 4, this chapter introduces the AVD^{KBS} software development process. To help users of AVD^{KBS} start using the knowledge management functions, a classification of users is required first. It teaches users which knowledge management functions the user can start using immediately and how to use those functions to enrich their current knowledge accumulations.

After that, the knowledge management function development processes are explained in terms of the function method logic and the GUI buildup. The function method logic describes how the knowledge management functions are implemented. The GUI buildup illustrates the setup of each GUI and the function of each control module in the GUI.

5.1 User Groups

Throughout the literature search, existing KBSs can be categorized into *commercial KBSs* and *academic KBSs*. Commercial KBSs have been applied into practices and served a great number of customers, while academic KBSs are developed by research institutions, and their purposes are to demonstrate new KBS concepts or technologies, and most of them have not been put into broad applications, so they often don't have a great number of users.

Commercial KBSs usually classify users into two groups according to their knowledge management rights. For example, the NASA ARK KBS classifies its users into *administrators* and *normal users* [(121)]. Normal users can only use knowledge management functions, like knowledge search, retrieval and update. While administrators can not only modify normal users' input, but also can change their statuses. For example, administrators can ban a normal user from using the KBS.

The academic KBSs usually focus on a small group of users. For instance, A.M. Buis *et al* [(142)] developed a KBS aiding the parceling design processes, and its users are only the local packaging designers. Their users are well defined, so no user classification has been done for academic KBSs developments.

However, as an improvement, AVD^{KBS} proposes a user classification according to the AVD knowledge categorization criterion. Users are classified into three groups: *literature specialist* (literal knowledge), *data specialist* (qualitative knowledge) and *numerical analysis specialist* (quantitative knowledge). Details of this classification are going to be introduced with the following sections.

5.1.1 Literature Specialist

The literature specialist is an expert whose knowledge accumulations are collections of literal knowledge. A large quantity of projects have been developed in the course of history, which left a large number of documents behind in the form of reports or publications. These materials include background knowledge, introductions and conclusions of the past and current projects. For example, the Final Report of the Commission on the Future of the United States Aerospace Industry [(143)] tries to raise the alarm for the U.S. aerospace industry through summarizing its current faltering development background. These materials are valuable and require management. They preserve knowledge gained during the project development processes, which can be used as references for future work. As a result, a set of knowledge management functions needs to be developed to help literature specialists manage these legacies.

Literal knowledge management functions provide the following advantages to the literal specialist:

1. Literature specialists can input all of their knowledge accumulations into AVD^{KBS} and form a knowledge base, using the knowledge updating function. AVD^{KBS} uses an electronic storage medium to store the knowledge, so it requires much less space and money than traditional storage methods, such as books.

2. Literature specialists can find the required knowledge much faster using the knowledge educating function. No matter how much knowledge is stored in AVD^{KBS}, literature specialists can always locate and retrieve the required knowledge within seconds.

3. Literature specialists can easily remove outdated or unnecessary knowledge from AVD^{KBS} using the knowledge deleting function. The knowledge removal process can be finished within seconds. The traditional knowledge management method, however, requires much more time and money. For example, if literature specialists want to remove the knowledge documented in a book, they need to go through a process of locating the knowledge, removing the page, and rebinding, or even reprinting the book.

Literature specialists can add other documents into their collections, such as experimental data or processing tools. After that, they can use quantitative knowledge management functions to apply the current knowledge into the analysis process and generate new knowledge, or they can use the qualitative knowledge management functions to deduce new design trends and update AVD^{KBS}.

5.1.2 Data Specialist

The data specialist is an expert whose knowledge accumulations consist of past project data. Such data represents technical descriptions of past projects and quantitatively summarize the overall project developments. For example, the Mercury Spacecraft NO. 15A Configuration Specification [(144)] report documented the technical data of design, construction and equipment requirements for the Mercury spacecraft, and contains a large amount of experiment data during the project development process. The FAA Aerospace Forecast Fiscal Years 2014-2034 [(145)] contains the demand trend data of the U.S. and global economy and commercial transportation. All of this data represents valuable references and should be well kept. As a result, a set of knowledge management functions needs to be developed to help data specialists manage these legacies.

Qualitative knowledge management functions provide the following advantages to data specialists:

1. Data specialists can deduce design trends using the trend predicting function. The trend predicting function can aid the data specialists to quickly accomplish the design trend deduction and offer interpretations of the result.
2. Data specialists can easily update new project data using the data updating function. There are always ongoing projects, generating new data. To keep their knowledge accumulations up-to-date, data specialists can use the data updating function to update new data into AVD^{KBS}.
3. Data specialists can remove outdated data using the data deleting function. If some data are found to be inaccurate or unnecessary, data specialists can use the data deleting function to delete them.

After deducing the design trend, data specialists can upload it into AVD^{KBS} as a new piece of knowledge using the knowledge updating function. They can also edit the knowledge using the knowledge deleting function and educate fresh engineers using the knowledge educating functions. Provided with analysis toolsets, they can use the quantitative knowledge management functions to link their knowledge accumulations with the analysis process.

5.1.3 Numerical Analysis Specialist

The numerical analysis specialist is an expert whose accumulations consist of numerical analysis tools. These numerical processing tools are generated based on the theories and principles that are concluded from a huge amount of experiments, tests and theoretical models. For example, the USAF stability and control characteristic analysis tool Digital Datcom [146] is developed from past USAF projects and provides a compendium of systematic methods for estimating aircraft stability and control characteristics. As a result, a set of knowledge management functions need to be developed to help numerical analysis specialists manage those analysis tools.

Quantitative knowledge management functions provide the following advantages to numerical analysis specialists:

Numerical analysis specialists can finish the parametric sizing analysis using the parametric sizing analysis function. The parametric sizing analysis function connects the numerical processing tools with the particular data and knowledge. Numerical analysis specialists have to input their design mission requirements, and AVD^{KBS} will execute the parametric sizing analysis by using past projects from AVD^{DBS} as the analysis starting point and using the knowledge from knowledge base to solve the unknown data during the analysis process.

In addition to the parametric sizing analysis function, numerical analysis specialists can also utilize the qualitative and literal knowledge management functions. After the parametric sizing analysis, they can update the analysis result into AVD^{DBS} using the data updating function. Then, one is able to deduce the new design trend using the trend predicting function, and upload it into AVD^{KBS} as a new piece of knowledge using the knowledge updating function.

5.2 AVD^{KBS} functions development

The development process of AVD^{KBS} knowledge management functions is going to be introduced in this section. The proposed AVD^{KBS} knowledge management functions are:

- Literal knowledge management functions: *knowledge learning, knowledge updating and knowledge deleting;*
- Qualitative knowledge management functions: *trend predicting, data updating, data deleting and literal knowledge management functions;*
- Quantitative knowledge management functions: *parametric sizing analysis and qualitative knowledge management functions.*

An overview table follows below:

Table 5-1 An Overview of AVD^{KBS} Knowledge Management Functions

Knowledge Management Function Categories	**Knowledge Management Functions within Each Categories**
Literal knowledge management functions	Knowledge learning Knowledge updating Knowledge deleting
Qualitative knowledge management functions	Trend predicting Data updating Data deleting Literal knowledge management functions
Quantitative knowledge management functions	Parametric sizing analysis Qualitative knowledge management functions

The development process of each knowledge management function includes:

1. Method logic implementation: use MATLAB coding to implement the proposed method logic of knowledge management functions. The implementation processes are explained as follows.
2. GUI development: use MATLAB's GUI-creation functionality to build graphic user interfaces allowing the user to input requirements and receive the AVD^{KBS} analysis output. The setup of the GUI and functions of each control module are explained as follows.

5.2.1 Literal Knowledge Management Functions

There are three knowledge management functions in the literal knowledge management function group: knowledge educating, knowledge updating and knowledge deleting, which mainly serve literal specialists. The AVD toolset involved with these functions is AVD^{KBS}.

5.2.1.1 Knowledge Educating

The knowledge educating function is developed to help the user study the current knowledge in AVD^{KBS}. It is used for engineer education and research work references.

The method logic implementation process is:

1. Knowledge Selection. Users select the piece of knowledge in which they are interested. The AVD^{KBS} component working in this section is the GUI, and it receives the input from the user and transfers it to the inference engine. The following are the knowledge selection steps:

- o The user chooses the discipline to which the knowledge belongs.
- o The user selects the required knowledge from the selected discipline.

After the knowledge is chosen, the GUI transfers the selection to the inference engine.

2. Knowledge Search. The inference engine locates the selected knowledge within AVD^{KBS}. The AVD^{KBS} components working in this section are the inference engine and knowledge base. The inference engine identifies the required knowledge within the knowledge base and retrieves it. The search method is a breadth-first search, and the search steps are:

- o The inference engine searches through the list of knowledge disciplines in the knowledge base and finds the one matching the user's input discipline. The process is that the inference engine selects the first item from the knowledge discipline list in the knowledge base and compares it with the user's input. If they match, the search stops there. Otherwise, the inference engine searches the next item until it finds the matching discipline.
- o After finding the matching discipline, the inference engine switch to search the knowledge. The search process of knowledge is similar to that of discipline.

After having located the knowledge, the process continues to the knowledge retrieve step.

3. Knowledge Retrieve. The inference engine retrieves the located knowledge and feeds it back to the GUI, which displays the knowledge content to the user. The AVD^{KBS}

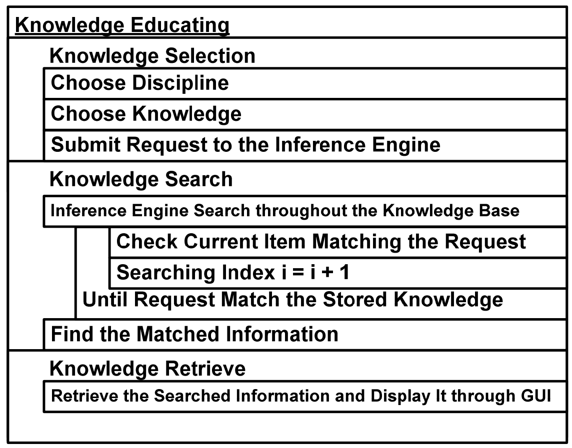


Figure 5-1 Method Logic Implementation Process of Knowledge Educating

components working in this section are the inference engine and the GUI. The knowledge retrieval steps are as follows:

- o The inference engine retrieves all of the knowledge content and passes it to the GUI.
- o The GUI displays the knowledge content to the user for education or reference purposes.

The setup of the knowledge educating GUI is introduced in the following paragraphs.

The knowledge educating GUI can be divided into two sections: knowledge selection and knowledge display.

In the knowledge selection section, there is a pull-down menu on the left labeled 'Discipline'. It is utilized by the user to select the interested knowledge discipline. The other pull-down menu labeled 'Knowledge' is in the middle. It is used by the user to select the required piece of knowledge. The push-button on the right labeled 'Educate' is clicked by the user to start the search process. After the user hits the 'Educate' button, the inference engine will start the search process.

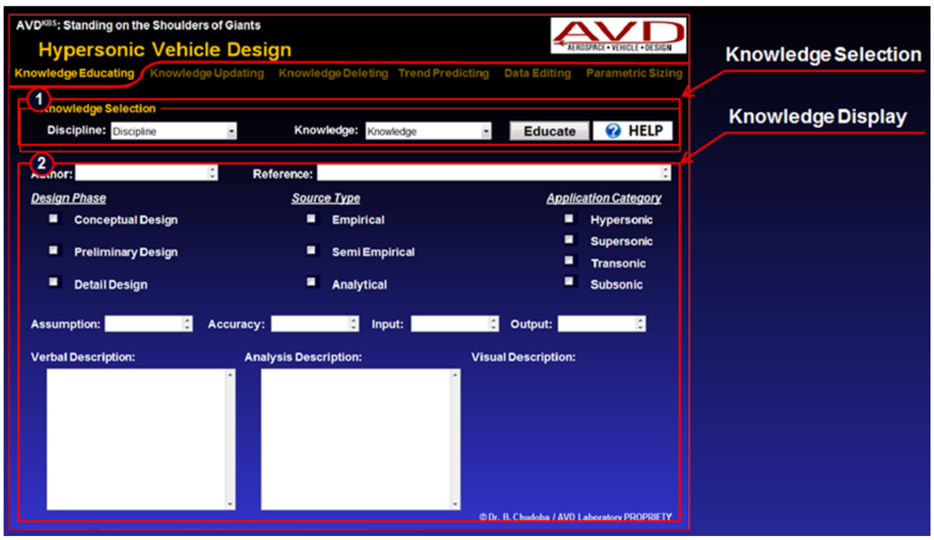


Figure 5-2 GUI Setup of Knowledge Educating

The knowledge display section is where the knowledge content is displayed after the search process.

In the top line, the textbox on the left labeled 'Author' displays the authors of the selected knowledge. The textbox on the right labeled 'Reference' introduces the source of the knowledge.

In the center area, there are ten checkboxes in total. They specify the Design Phase, Source Type and Application Category. The Design Phase section uses Conceptual Design, Preliminary Design and Detail Design to illustrate in which design stage the knowledge should be used. The Source Type section uses Empirical, Semi Empirical and Analytical to specify the knowledge type. The Application Category section uses Hypersonic, Supersonic, Transonic and Subsonic to indicate the speed range in which the knowledge should be used.

In the lower center section, there are four textboxes: Assumption, Accuracy, Input and Output. Assumption clarifies the prerequisites that need to be satisfied to use the knowledge. Accuracy specifies the exactness of the output. Input is the user's specifications to the knowledge application process. Output is the result of the knowledge application process.

In the bottom section, there are three textboxes. The textboxes use three forms to express the knowledge content: Verbal Description, Analysis Description and Visual Description. Words, analytical equations and figures are used to describe the knowledge content, respectively. They are intended for different application purposes. For example, the verbal description is mainly used for background introduction, while the analysis description is mainly used for numerical analysis applications.

5.2.1.2 Knowledge Updating

The knowledge updating function is developed to help the user update new knowledge into AVD^{KBS} to keep it up-to-date. It is used for knowledge editing purposes.

The method logic implementation process is:

1. Knowledge Collect. The user inputs the new knowledge content into the GUI. The AVD^{KBS} component working in this section is the GUI, and it receives the input from the user and transfers it to the inference engine. The following are the knowledge collect steps:
    - The user inputs all of the knowledge content into the GUI.
    - After the user finishes the input, the GUI transfers it to the inference engine.
2. Location Search. The inference engine searches the available empty space for each piece of content of the new knowledge. The AVD^{KBS} components working in this section are the inference engine and the knowledge base. There is only one step in the location search process:

o The inference engine searches through the knowledge base and identifies the next available space for the new knowledge.

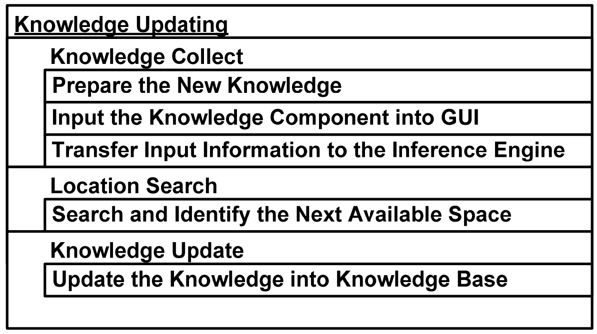


Figure 5-3 Method Logic Implementation Process of Knowledge Educating

3. Knowledge Update. The inference engine updates the new knowledge into the knowledge base. The AVD^{KBS} components working in this section are the inference engine and the knowledge base. The following step completes the knowledge update process:

o The inference engine put the new knowledge content in the appropriate locations, found in the previous step.

The setup of the knowledge updating GUI is introduced in the following paragraphs:

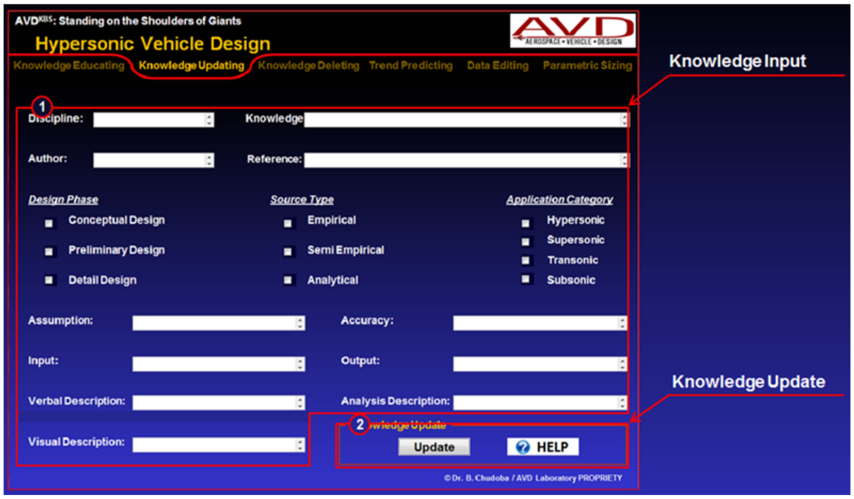


Figure 5-4 GUI Setup of Knowledge Updating

The knowledge updating GUI can be divided into two sections: knowledge input and knowledge update.

In the knowledge input section, eleven textboxes are used by users to input the content of the new knowledge. They include: Project, Discipline, Author, Reference, Assumption, Accuracy, Input, Output, Verbal Description, Analysis Description, and Visual Description. The meaning of each item has been explained in the previous section. Ten check boxes are used by the user to specify the Design Phase, Source Type and Application Category of the new knowledge. Users can fill in the items on which they have the available information, and it is not required to finish all of them.

In the knowledge update section, the 'Update' button is used by users to issue the update command. After the user is finishing inputting all of the knowledge content, they need to hit the 'Update' button, and the inference engine will then update the new knowledge into AVD^{KBS}.

5.2.1.3 Knowledge Deleting

The knowledge deleting function is developed to help the user remove outdated or unnecessary knowledge from AVD^{KBS}. It is used for knowledge editing purposes.

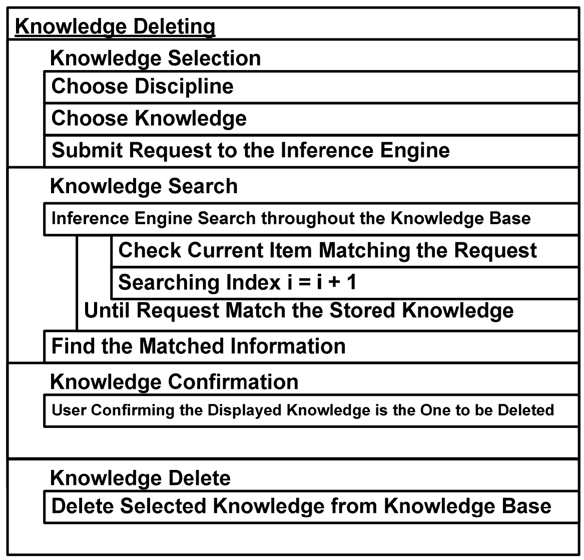


Figure 5-5 Method Logic Implementation Process of Knowledge Deleting

The method logic implementation process is:

1. Knowledge Selection. Users select the knowledge that is going to be removed. The AVD^{KBS} component working in this section is the GUI, which receives the selection from users and transfers it to the inference engine. The following are the knowledge selection steps:

   - The user chooses the discipline to which the knowledge belongs
   - The user chooses the knowledge that is going to be removed within the selected discipline.

After the selection is determined, the GUI transfers the selected knowledge to the inference engine.

2. Knowledge Search. The inference engine searches for the selected knowledge within the knowledge base. The AVD^{KBS} components working in this section are the inference engine and the knowledge base.

The search process is exactly the same as the one used in the knowledge educating function.

3. Knowledge Confirmation. The inference engine retrieves the knowledge from knowledge base and feeds it back to the GUI. Then the GUI displays the knowledge content to the user. The AVD^{KBS} components working in this section are the inference engine and the GUI.

- The user confirms that the retrieved knowledge is the one to be deleted and issues the ‘Delete’ command.

4. Knowledge Delete. The GUI transfers the “Delete” command to the inference engine, and the inference engine deletes the knowledge. The AVD^{KBS} components working in this section are the inference engine, the knowledge base and the GUI. The following are the knowledge deletion steps:

- The GUI transfers the command to the inference engine.
- The inference engine removes the knowledge from the knowledge base.

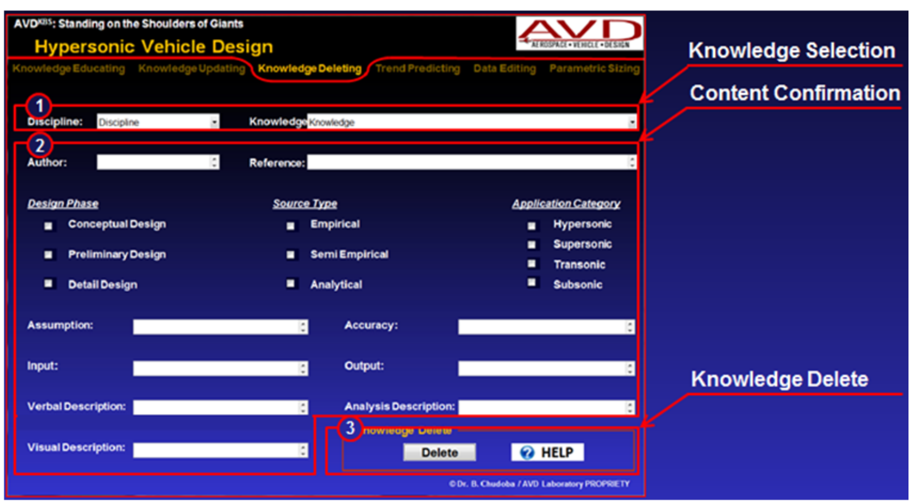


Figure 5-6 GUI Setup of Knowledge Deleting

The setup of the knowledge deleting GUI is introduced in the following paragraphs:

The knowledge deleting GUI can be divided into three sections: Knowledge Selection, Content Confirmation and Knowledge Delete.

In the knowledge selection section, there is a pull-down menu on the left labeled 'Discipline'. It is used by the user to select the appropriate knowledge discipline. The pull-down menu on the right labeled 'Knowledge' is for the user to select the knowledge that is going to be removed. After the knowledge is selected, all of the selected knowledge content will be displayed in the content confirmation section.

In the content confirmation section, eleven textboxes are used to display the knowledge content. They include: Project, Discipline, Author, Reference, Design Phase, Source Type, Application Category, Assumption, Accuracy, Input, Output, Verbal Description, Analysis Description and Visual Description.

In the knowledge delete section, the push button on the left labeled "Delete" is used to receive the user's delete command.

5.2.2 Qualitative Knowledge Management Functions

There are three new knowledge management functions in the qualitative knowledge management function group: trend predicting, data updating and data deleting, which mainly serve data specialists. The AVD systems involved in those functions are AVD^{KBS} and AVD^{DBS}.

5.2.2.1 Trend Predicting

The trend predicting function is developed to help the user predict design trends based on past project data and knowledge. It is used for knowledge innovation purposes, such as deducing a relationship between the interested parameters, which has not been researched.

The method logic implementation process is:

1. Parameter Selection. Users select the parameters of interest between which they think a possible design trend may exist. The AVD^{KBS} component working in this section is

the GUI, and it receives the input from the user and transfers it to the inference engine. The following are the parameter selection steps:

- The user determines the knowledge type: qualitative knowledge or quantitative knowledge. If it is qualitative knowledge, the user only needs to choose one parameter, or the user needs to choose two parameters.
- The user selects the knowledge discipline.
- The user chooses the required parameter within the discipline.

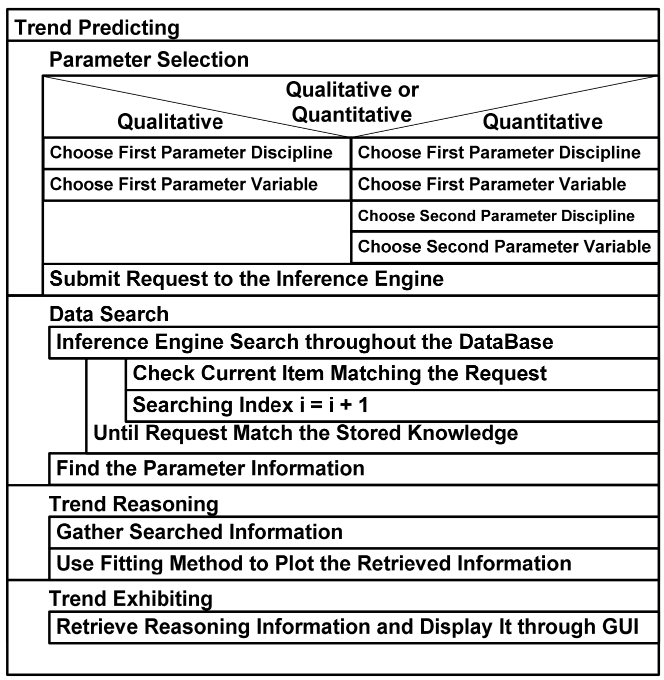


Figure 5-7 Method Logic Implementation Process of Trend Predicting

However, if the interested knowledge type is quantitative knowledge, the user needs to choose two parameters. The selection process is same to that of the qualitative knowledge parameter, with the only difference being that the user needs to repeat the selection process for a second parameter. After that, the user needs to determine the interpolation method for the trend. After all of the selections are made, the GUI transfers them to the inference engine.

2. Data Search. The inference engine searches for the selected parameter within AVD^{DBS}. The AVD^{KBS} components and other AVD toolsets working in this section are the inference engine and the AVD^{DBS}.

The search method is exactly the same as the one used in the knowledge educating function.

3. Trend Reasoning. The inference engine retrieves all of the matching data for the selected parameters and finishes the design trend deduction process. The AVD^{KBS} components and other AVD toolsets working in this section are the inference engine and AVD^{DBS}. The following are the trend reasoning steps:

- o The inference engine retrieves all of the matching parameters' data from AVD^{DBS}.
- o The inference engine uses the selected fitting method to finish the trend prediction analysis.
- o The inference engine generates figures to express the fitting results. For qualitative knowledge, it will generate literal explanations for the result; for quantitative knowledge, it will generate a fitting equation for the result and an R^2 value to indicate the quality of the fit.

4. Trend Exhibition. The inference engine sends the design trend prediction result back to the GUI, and the GUI displays it to the user. The AVD^{KBS} components working in this section are the inference engine and the GUI. The following are the trend exhibition steps:

- o The inference engine gathers all of the fitting results and sends them back to the GUI.
- o The GUI displays them to the user.

After that, the user can analyze the result and determine whether the predicted design trend is useful.

The setup of the trend prediction GUI is introduced in the following paragraphs:

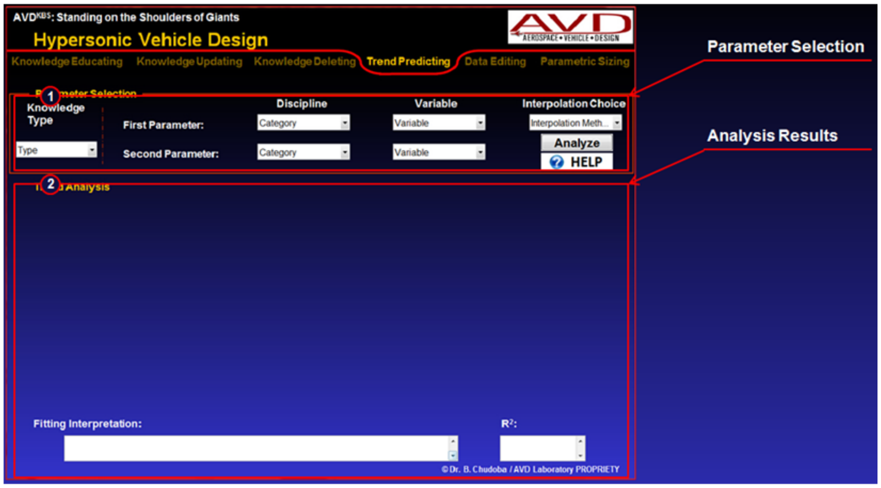


Figure 5-8 GUI Setup of Trend Predicting

The trend prediction GUI can be divided into two sections: Parameter Selection and Analysis Results.

In the parameter selection section, there is one pull-down menu on the left labeled 'Knowledge Type'. It is used by the user to select the type of knowledge: qualitative or quantitative. Four pull-down menus in the middle, labeled 'First Parameter', 'Second Parameter', 'Discipline' and 'Variable', are used by the user to select the required parameters. The pull down menu on the right, labeled 'Interpolation Method', is used by the user to select the fitting method. There is a push button on the right labeled 'Analyze', which is used by the user to start the trend predicting process.

In the analysis result section, the box in the top labeled 'Trend Analysis' displays the trend prediction result. The box at the bottom left labeled 'Fitting Expressions' shows the literal descriptions for the qualitative knowledge design trend prediction result and the design trend equation for the quantitative knowledge design trend prediction result. The box on the bottom right labeled 'R^2' displays the coefficient of determination.

5.2.2.2 Data Updating

The data updating function is developed to help the user update new data into AVD^{DBS}. It helps the user keep the system up-to-date and improves the design trend prediction accuracy.

The method logic implementation process is:

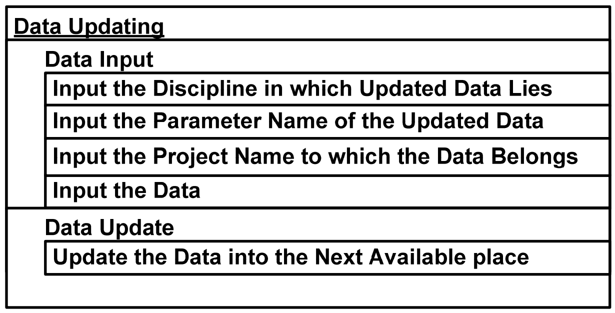


Figure 5-9 Method Logic Implementation Process of Data Updating

1. Data Input. In this section, the user inputs the new project data. The AVD^{KBS} component working in this section is the GUI, and it receives the input from the user and transfers it to the inference engine. The following are the data input steps:

   - The user fills in the discipline of the data.
   - The user fills in the parameter name of the data.
   - The user fills in the name of the project where the data belongs.
   - The user fills in the value of the data.

After the user finishes inputting all of the information, the GUI transfers it to the inference engine.

2. Data Update. In this section, the inference engine updates the data into AVD^{DBS}. The AVD^{KBS} components and other AVD toolsets working in this section are the GUI, the inference engine and AVD^{DBS}. The following are the data update steps:

   - The inference engine searches within AVD^{DBS} and finds the next available location.
   - The inference engine puts the data into said location.

The setup of the data updating GUI is introduced in the following paragraphs:

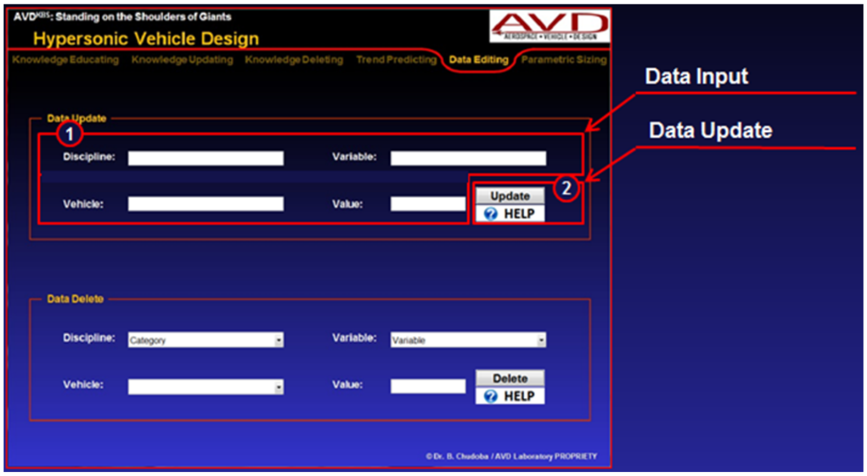


Figure 5-10 GUI Setup of Data Updating

The data updating GUI can be divided into two sections: Data Input and Data Update.

In the data input section, there are four textboxes for the user to input the data information. The upper left textbox labeled 'Discipline' indicates the discipline to which the data belongs. The upper right textbox labeled 'Variable' indicates the parameter name of the data. The lower left textbox labeled 'Vehicle' indicates to which project the data belongs. The lower right textbox labeled 'Value' indicates the numerical value of the input data.

In the data update section, there is one push button labeled 'Update'. After the user finishes inputting all of the data information and hits the 'Update' button, the data will be updated into AVD^{DBS}.

5.2.2.3 Data Deleting

The data deleting function is developed to help the user remove outdated or unnecessary data from AVD^{DBS}. It helps researchers avoid storing obsolete data.

The method logic implementation process is:

1. Data Selection. In this section, the user selects the data that is going to be removed. The AVD^{KBS} component working in this section is the GUI, and it receives the selection

from the user and transfers it to the inference engine. The following is the data selection steps:

- o The user selects the discipline to which the data belongs.
- o The user selects the parameter name of the data.
- o The user selects the project to which the data belongs.

After the user finishes all of the selections, the GUI transfers them to the inference engine.

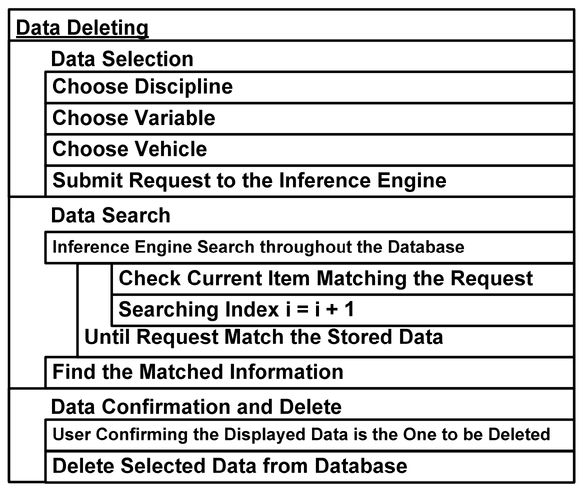


Figure 5-11 Method Logic Implementation Process of Data Deleting

2. Data Search. In this section, the inference engine searches for and locates the selected data within AVD^{DBS}. The AVD^{KBS} components and other AVD toolsets working in this section are the inference engine and AVD^{DBS}. The search method is exactly the same as the one used in the knowledge educating function.

3. Data Confirmation and Delete. In this section, the user confirms the search result and issues the command to remove the data. The AVD^{KBS} components and other AVD toolsets working in this section are the GUI, the inference engine and AVD^{DBS}. The following are the data confirmation and deletion steps:

- o The GUI displays the data to the user.
- o The user checks the data and confirms it is the one to be deleted.
- o The user issues the deletion command by pressing the ‘Delete’ button.

- The GUI passes the command to the inference engine.
- The inference engine removes the data from AVD^{DBS}.

The setup of the data deleting GUI is introduced in the following paragraphs:

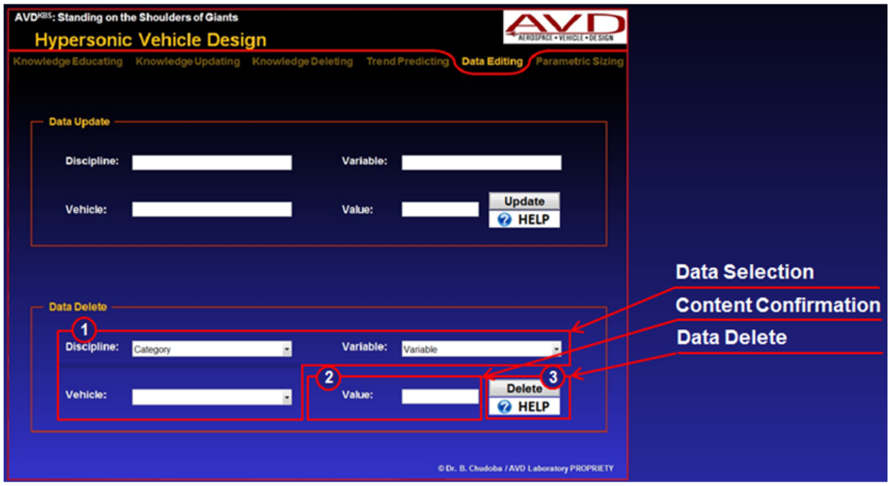


Figure 5-12 GUI Setup of Data Deleting

The data deleting GUI can be divided into three sections: Data Selection, Content Confirmation and Data Deletion.

In the data selection section, there are three pull-down menus. They are used by the user to specify the data that is going to be removed. The upper left pull-down menu labeled 'Discipline' indicates the discipline to which the data belongs. The upper right pull-down menu labeled 'Variable' indicates the parameter name of the input data. The lower left pull-down menu labeled 'Vehicle' indicates the project to which the data belongs.

In the content confirmation section, there is one textbox labeled 'Value'. It displays the numerical value of the data after the inference engine finishes the search process and feeds the search result back to the GUI.

In the data delete section, there is one push button labeled 'Delete'. It receives the delete command from the user and transfers it to the inference engine.

Literal knowledge management functions can also be applied to qualitative knowledge because the qualitative knowledge can be transformed to literal knowledge. As a result, the complete set of qualitative knowledge management functions include: trend predicting, data updating, data deleting, knowledge educating, knowledge updating and knowledge deleting.

5.2.3 Quantitative Knowledge Management Functions

There is only one new knowledge management function in the quantitative knowledge management function group: parametric sizing analysis, which mainly serves numerical analysis specialists. The AVD toolsets involved in those functions are AVD^{KBS}, AVD^{DBS} and AVD^{PP}.

5.2.3.1 Parametric Sizing Analysis

The parametric sizing analysis function is developed to help the user finish the parametric sizing analysis.

The method logic implementation process is:

1. Mission Requirement Input. The user inputs the design mission requirements for the parametric sizing analysis. The AVD^{KBS} component working in this section is the GUI, which receives the mission requirements from the user and transfers them to the inference engine. The following are the mission requirement input steps:
    - o The user inputs the design mission requirements into the GUI. There are seven design mission requirements: Design Payload, Range, Velocity, Initial Cruise Altitude, Take-off Field Length, Landing Field Length and Reserve Mission.
    - o The GUI transfers the mission requirements to the inference engine.
2. Starting Point Search. The inference engine selects the starting point vehicle and solves for any of the unknown parameters. The AVD^{KBS} components and AVD toolsets working in this section are the GUI, inference engine, AVD^{DBS} and AVD^{PP}. The following steps form the starting point search:
    - o The inference engine compares the design mission requirements with those from other projects in AVD^{DBS}. A grading process is conducted on the past projects to select the most similar project as the starting point based on the current

design mission requirements. This grading mechanism is a comparison of each of mission requirement input by the user with the according mission requirement of a past project. If they match within a specified tolerance, the past project receives one point for this mission requirement; if they do not match, the past project receives zero point. The same process is conducted for all seven of the design mission requirements. The sum of these points is the given grade for the past project. The grading process is conducted for all of the past projects. After the grading process is finished, the inference engine chooses the vehicle with the highest grade as the starting point vehicle.

- The inference engine retrieves all of the starting point vehicle's technical data.
- The inference engine compares the vehicle data with the parametric sizing analysis input requirements for AVD^{PP}. If all of the input requirements can be found within the vehicle data, they will be directly transferred to the parametric sizing analysis process. However, if some of the input requirements cannot be found in the vehicle data, the inference engine uses the knowledge from AVD^{KBS} to solve for the unknown data. After it figures out all of the unknown data, the inference engine will put them into the analysis process.

3. Parametric Sizing Analysis. The inference engine initiates and finishes the parametric sizing analysis. The AVD^{KBS} components and other AVD toolsets working in this section are the GUI, inference engine and AVD^{PP}. The following are the parametric sizing analysis steps:

- The inference engine starts the parametric sizing analysis.
- After the analysis is finished, the inference engine retrieves the analysis results and transfers them back to the GUI.
- The GUI displays the results to the user for review.

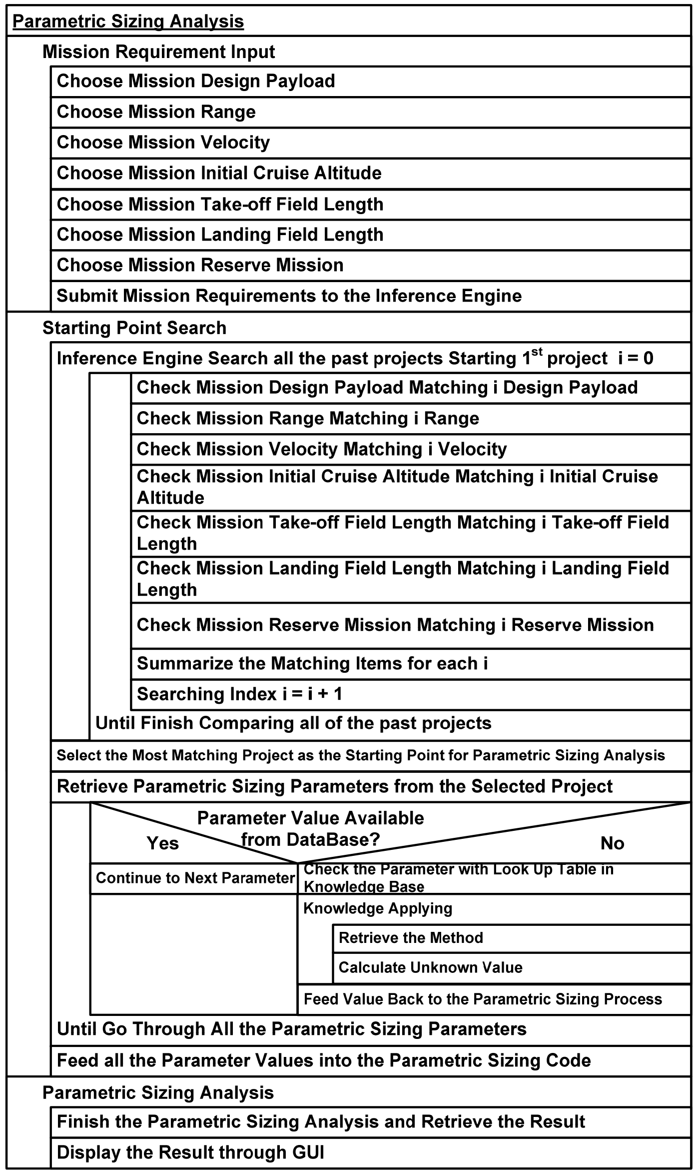


Figure 5-13 Method Logic Implementation Process of Parametric Sizing Analysis

The setup of the parametric sizing analysis GUI is introduced via the following paragraphs:

The parametric sizing GUI can be divided into three sections: Mission Input, Analysis Control and Analysis Output.

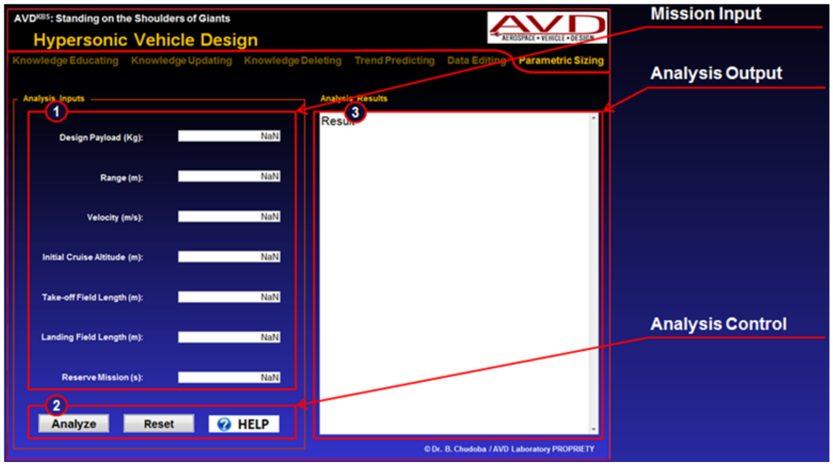


Figure 5-14 GUI Setup of Parametric Sizing Analysis

In the mission input section, there are seven textboxes for the user to input the design mission requirements: Design Payload, Range, Velocity, Initial Cruise Altitude, Take-Off Field Length, Landing Field Length and Reserve Mission.

In the analysis control section, the push button on the left labeled 'Analyze' is used by the user to start the parametric sizing analysis process. The push button in the middle labeled 'Reset' is used to set the current values of the design mission requirements to the default values. It is usually used when the user thinks there might be something wrong with the input and wants to restart the input process.

In the analysis output section, there is a large textbox. It records and displays the parametric sizing analysis results. The output has three sections. The first section shows which vehicle is selected as the starting point vehicle; this information shows up after the inference engine finishes the grading process. The second section shows which knowledge from AVD^{KBS} is used to solve for the unknown data; they show up after the inference engine solves for all of the unknown vehicle data. The third section shows the parametric sizing analysis results, and they show up at the end of the parametric sizing analysis process.

Moreover, qualitative knowledge management functions can also be applied to quantitative knowledge because quantitative knowledge can be transformed to qualitative knowledge. As a result, the complete set of quantitative knowledge management functions are: parametric sizing analysis, trend predicting, data updating, data deleting, knowledge educating, knowledge updating and knowledge deleting.

5.3 Research Conclusion

In this chapter, for the first time, the KBS users are categorized into three groups: literature specialists, data specialists and numerical analysis specialists. The definitions and current status quo of each user group are described. For each user group, current suitable AVD^{KBS} knowledge management functions are introduced, along with suggestions for their future explorations in AVD^{KBS} knowledge management function utilizations.

In the later sections, the development process of each knowledge management function is described in detail. In this way, it introduces how those functions are implemented through the interactions among AVD^{KBS}, AVD^{DBS} and AVD^{PP} and how those functions are presented to users through the GUI.

Table 5-2 Overview of AVD^{KBS} user groups and knowledge management functions

User group	Current Access		Future Development	
	Specific Knowledge Management Functions	**Involved AVD Systems**	**Specific Knowledge Management Functions**	**Involved AVD Systems**
Literature Specialist	Knowledge Educating Knowledge Updating Knowledge Deleting	AVD^{KBS}	Trend Predicting Data Updating Data Deleting Parametric Sizing Analysis	AVD^{KBS}, AVD^{DBS}, AVD^{PP}
Data Specialist	Trend Predicting Data Updating Data Deleting	AVD^{KBS}, AVD^{DBS},	Parametric Sizing Analysis Knowledge Educating Knowledge Updating Knowledge Deleting	AVD^{KBS}, AVD^{DBS}, AVD^{PP}
Numerical Analysis Specialist	Parametric Sizing Analysis	AVD^{KBS}, AVD^{DBS}, AVD^{PP}	Trend Predicting Data Updating Data Deleting Knowledge Educating Knowledge Updating Knowledge Deleting	AVD^{KBS}, AVD^{DBS}, AVD^{PP}

5.4 Research Contribution Summary

The original research contributions from Chapter 5 are as follows:

1. For the first time, KBS users are classified into three distinct groups. Such understandings does provide a better connection between the users and the KBS. This compares to the traditional way of not distinguishing between naturally differing user requirements.
2. Implement the proposed methodology and build a functional knowledge management software prototype - AVD^{KBS} . For the first time, a systematic knowledge management approach for aerospace engineering community focusing on the early conceptual design stage.

Chapter 6

AVD^{KBS} Case Studies

Two case studies will be conducted: Launch Vehicle design and Rotorcraft Vehicle Design. A case study roadmap will be given to illustrate the strategies the case studies use to demonstrate the efficiency advantages of AVD^{KBS}. After that, each case study will be introduced in four sections: *research motivation, research background, research steps* and *research contributions*.

6.1 Case Study Roadmap

Based on the efficiency characteristic analysis of both the knowledge and the user in Chapter 4, the efficiencies of the knowledge management methods, including manual and AVD^{KBS} approaches, are going to be compared in three aspects: *knowledge manipulation, knowledge trends* and *knowledge analysis*. For both approaches, the knowledge content is the same but documented in different media and formats.

- Knowledge manipulation: evaluate the efficiencies of knowledge management methods during the process of manipulating knowledge, such as searching knowledge and retrieving knowledge.
- Knowledge trends: evaluate the efficiencies of knowledge management methods during the process of innovating new knowledge.
- Knowledge analysis: evaluate the efficiencies of knowledge management methods during the process of applying knowledge into work.

In the Launch Vehicle Design case study, efficiencies of both manual and AVD^{KBS} approaches are compared in all of the three aspects: knowledge manipulation, knowledge trends and knowledge analysis. In the Rotorcraft Vehicle Design case study, efficiencies of both manual and AVD^{KBS} approaches are compared in two aspects: knowledge trends and knowledge manipulation. The comparisons are based on the AVD knowledge evaluation criterion proposed in Chapter 4.

A case study overview can be found in Table 6-1. It illustrates the Purposes, Demonstrated Advantages, Involved AVD Systems, Knowledge Resources, Resource Evaluation and Efficiency Quantification Parameters of each case study.

- Purpose: the primary goal of the case study.
- Demonstrated Advantages: from which aspects the efficiency advantages of AVD^{KBS} approach are demonstrated: knowledge manipulation, knowledge trends and knowledge analysis.
- Involved AVD toolsets: which AVD toolsets are involved in the case study: AVD^{KBS}, AVD^{DBS}, or AVD^{PP}.
- Knowledge Sources: what knowledge is used in building the knowledge base in the case study.
- Efficiency Quantification Parameters: the definitions of the efficiency quantification parameters.

Highlights of the rotorcraft vehicle design case study:

- A short period (three weeks) project;
- Start from zero knowledge accumulation;
- Utilize the AVD^{KBS} to swiftly build up a knowledge base through deducing the design trend knowledge from collected vehicle data;
- Utilize the deduced knowledge to accelerate the research progress and educate novice engineers.

Highlights of the launch vehicle design case study:

- Build a knowledge base based on the most comprehensive and profound knowledge accumulations;
- Revive the legacy wisdom and apply it into research practices;
- Introduce the process of AVD^{KBS} accomplishing the parametric sizing analysis through working with other AVD design toolsets;

- Deduce design trend knowledge based on the parametric sizing results, and use it to educate novice designers.

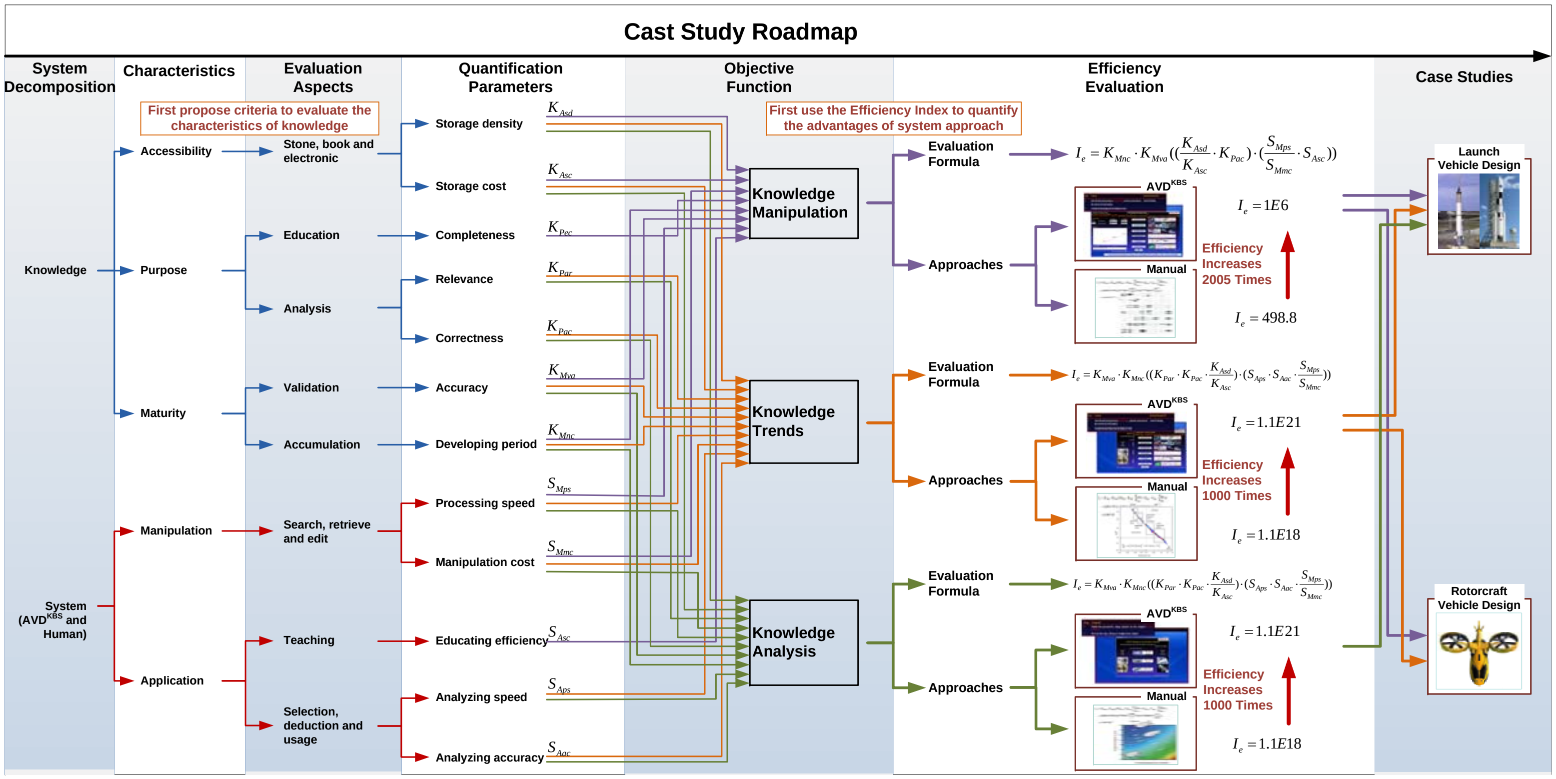


Figure 6-1 Case Study Roadmap

Table 6-1 Case Studies Overview

	Rotorcraft Vehicle Design	**Launch Vehicle Design**
Purpose	– Demonstrate how to quickly identify the developing trend and achieve the system level understanding – Support the configuration selection during conceptual design stage in achieving a much faster rotorcraft: single rotor vs. coaxial rotor	– Establish the launch vehicle design knowledge pool – Aid the launch vehicle design knowledge learning and retention – Revive the legacy launch design knowledge and innovate new knowledge based on past design experiences – Use the knowledge to guide future design
Demonstrated Advantages	– Knowledge Trends Accomplish the trend analysis – Knowledge Management Fast knowledge search and edit	– Knowledge Analysis Finish parametric sizing analysis – Knowledge Trends Accomplish the trend analysis – Knowledge Management Fast knowledge search and edit
Involved AVD toolsets	AVD^{KBS}+ AVD^{DBS}	AVD^{KBS}+ AVD^{DBS}+ AVD^{PP}
Knowledge Sources	AVD LLC	– P. Czysz – Hypersonic Convergence and Propulsion Sharpens the Focus for Hypersonic Design
Resource Evaluation	Poor	Rich
Efficiency Quantification Parameters	Knowledge Quantification Parameters K_{Asd} 10240(AVD^{KBS}) 1200 (Manual); K_{Asc} 1.1(AVD^{KBS}) 68.8(Manual); K_{Pec} 100 K_{Par} 1; K_{Pac} 100; K_{Mva} 50 K_{Mnc} 0.06 User Quantification Parameters S_{Mps} 0.1(AVD^{KBS}) 1(Manual); S_{Mmc} 0.02(AVD^{KBS}) 50(Manual); S_{Asc} 0.01(AVD^{KBS}) 100(Manual) S_{Aps} 2.4(AVD^{KBS}) 0.8(Manual); S_{Aac} 100(AVD^{KBS}) 97.5(Manual)	 K_{Asd} 10240(AVD^{KBS}) 1200 (Manual)); K_{Asc} 1.1(AVD^{KBS}) 68.8(Manual); K_{Pec} 100 K_{Par} 1; K_{Pac} 100; K_{Mva} 100 K_{Mnc} 11 S_{Mps} 0.002(AVD^{KBS}) 0.00013(Manual); S_{Mmc} 0.02(AVD^{KBS}) 50(Manual); S_{Asc} 0.01(AVD^{KBS}) 100(Manual) S_{Aps} 1.09E11(AVD^{KBS}) 2.2E15(Manual); S_{Aac} 100(AVD^{KBS}) 97.5(Manual)

6.2 Rotorcraft Vehicle Design

In 1906, Jacques and Louis Breguet [147] began to develop the first modern rotorcraft, *Gyroplane NO.1.* Rotorcrafts have developed for more than a hundred years since then and have been broadly used around the world, such as for transportation, medical care, and surveillance. Many rotorcraft configurations have been developed, such as: coaxial and single rotor, and compound configurations.

However, the quest for efficiency and speed has never stopped. AVD Laboratory has been contracted for a three-week project by Airbus Helicopters. The objective has been to develop a methodology to evaluate prospective cutting-edge rotorcraft configurations. This CTO motivated task required the implementation of a methodology capable to consistently evaluate and compare promising rotorcraft configurations against each other for future investments. This case study documents a problem scenario which requires the custom development of AVD^{KBS} without any previous helicopter-related data, knowledge and process. In contrast to the launch launch vehicle case study which is based on cutting edge proficiency, this case study illustrates how a novice team is capable, within a short turn-around time, to build-up a data, knowledge and process framework to reliably answer the customer quest. Clearly, this case study demonstrates the AVD^{KBS} efficiency advantages in knowledge management whilst building the helicopter foundation up from zero initial rotorcraft proficiency.

The case study consists of four sections:

1. Research Motivation: identify the necessity of supporting industry executives to correctly identify rotorcraft development trends during the conceptual design stage.
2. Research Background: introduce the work of AVD^{KBS} in the AVD contract project with Airbus Helicopter.
3. Research Steps: explain the steps as to how AVD^{KBS} helps the researchers quickly discover the disk loading development trend.

4. Research Contributions: validate the AVD^{KBS} generated trend knowledge by comparing it to the past projects and introduce other contributions of AVD^{KBS} in the project.

6.2.1 Research Motivation

Through the historical development of rotorcrafts, efficiency and speed are the two primary lines of improvement. Efficiency includes range-payload performances, fuel consumption, and aerodynamics; speed is the need to shorten the transit time in carrying operational payloads. A successful rotorcraft development is always an optimal balance between the two.

However, to achieve the balance, a system level understanding during the conceptual design stage is required to aid the strategic decision-making process. This system level understanding needs to comprehensively consider all of the technical areas, which requires a vast amount of information to be collected and processed. Unfortunately, the critical early conceptual design stage is frequently conducted with a minimal time allowance compared to the other design stages. As a result, a systematic approach is necessary to accelerate the learning progress within a shortest timeframe. This very case study demonstrates such 'explosive' learning exercise – the ability to accumulate, organize, process and utilize available knowledge within a short amount of time. The primary enabling ingredient to project success has been the availability of the generic suite of tools, consisting of AVD^{DBS}, AVD^{KBS} and AVD^{PP}. Clearly, all three modules were customized from project day #1 onwards for the first time with rotorcraft specific elements.

6.2.2 Research Background

The current case study represents an industry contract with Airbus Helicopter. The contract tasked to develop a rotorcraft configuration evaluation methodology which delivers offers state-of-the-art configuration suggestions during the early conceptual design stage.

The research project has been executed throughout a three-week period, consisting of three phases. The first phase, *DB/KB/PP Preparatory*, involves outlining the research plan and gathering data and knowledge from past rotorcraft projects. It serves as a foundation for the following project phases. The second phase, *Vehicle Configuration Assessment & Comparisons*, extracts useful information from the data/knowledge collection and analyzes them to form rotorcraft development trends. The third phase, *Conclusions & Report*, uses the development trends to evaluate rotorcraft configuration performances and offers suggestions for future rotorcraft configuration investment portfolios.

Throughout the first phase, the collected knowledge and data are managed using the existing generic AVD toolsets: AVD^{KBS} and AVD^{DBS}. AVD^{DBS} is an integrated data management system, focusing on data extraction, reuse, and capitalization of existing data assets.

There are six research steps defined for this phase. The first step is *Attribute Identification*. During this step, researchers identify the important gross design drivers for the rotorcraft development based on collected knowledge and data. The second step is *Attribute Filtering*. From those collected design drivers, this step involves the identification of the attributes that are related to the decision making process during the conceptual design stage. The third step is *Attribute Effect Assessment*. This step involves the deduction of key design driver development trends. The fourth step is *Constraint Identification/Application*. This step involves searching and defining the limitations on those selected drivers for current and future design work, such as industry capabilities. The fifth step is *Vehicle Assessment* (Technical only). This step compares the selected rotorcrafts' performances in terms of the designated drivers in each technical field. The sixth step is *Vehicle Assessment* (Total Vehicle). It summarizes the comparison results from the previous step and analyzes them in a comprehensive view to conclude the overall rotorcraft performance attributes. In Figure 6-18, the entire process is described. Step three, indicated with the red box outline below, is where AVD^{KBS} helps researchers accelerate the research progress

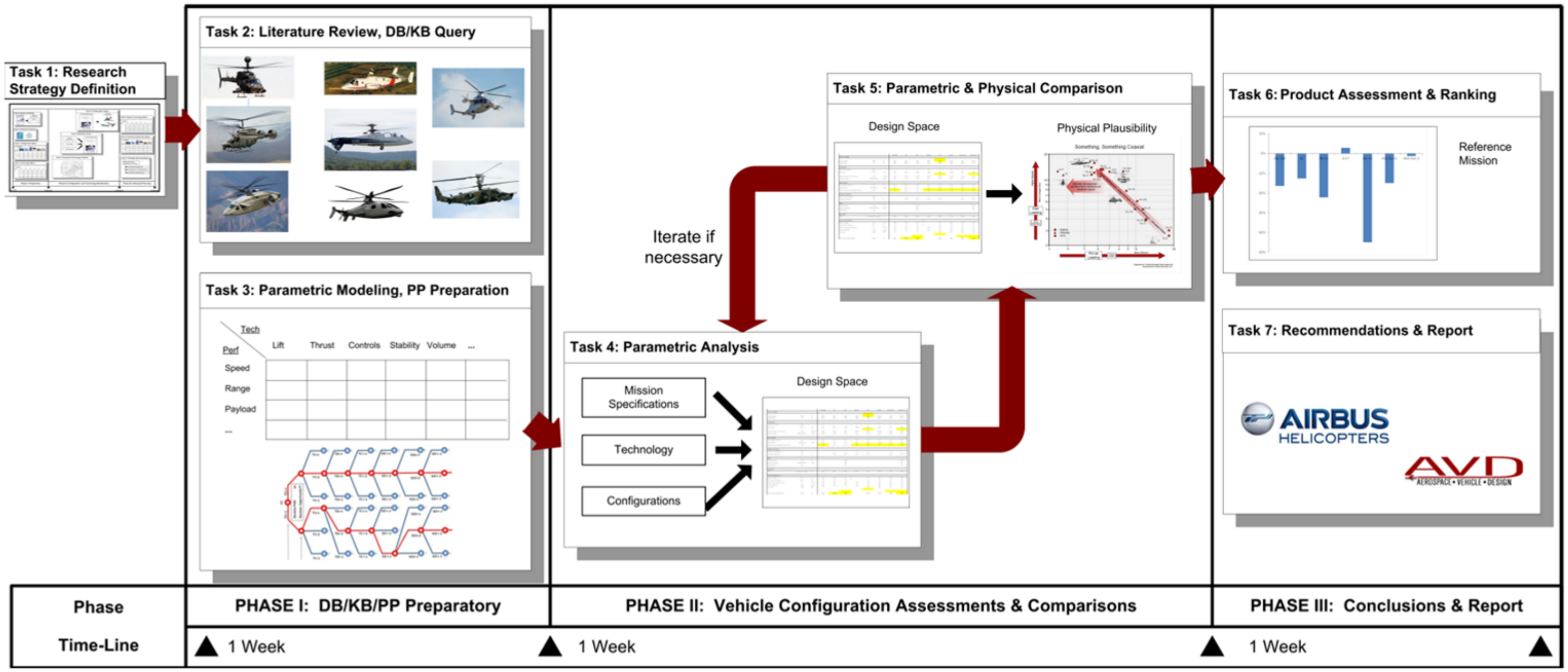


Figure 6-2 Research Stages of AVD Laboratory Contract with Airbus Helicopter

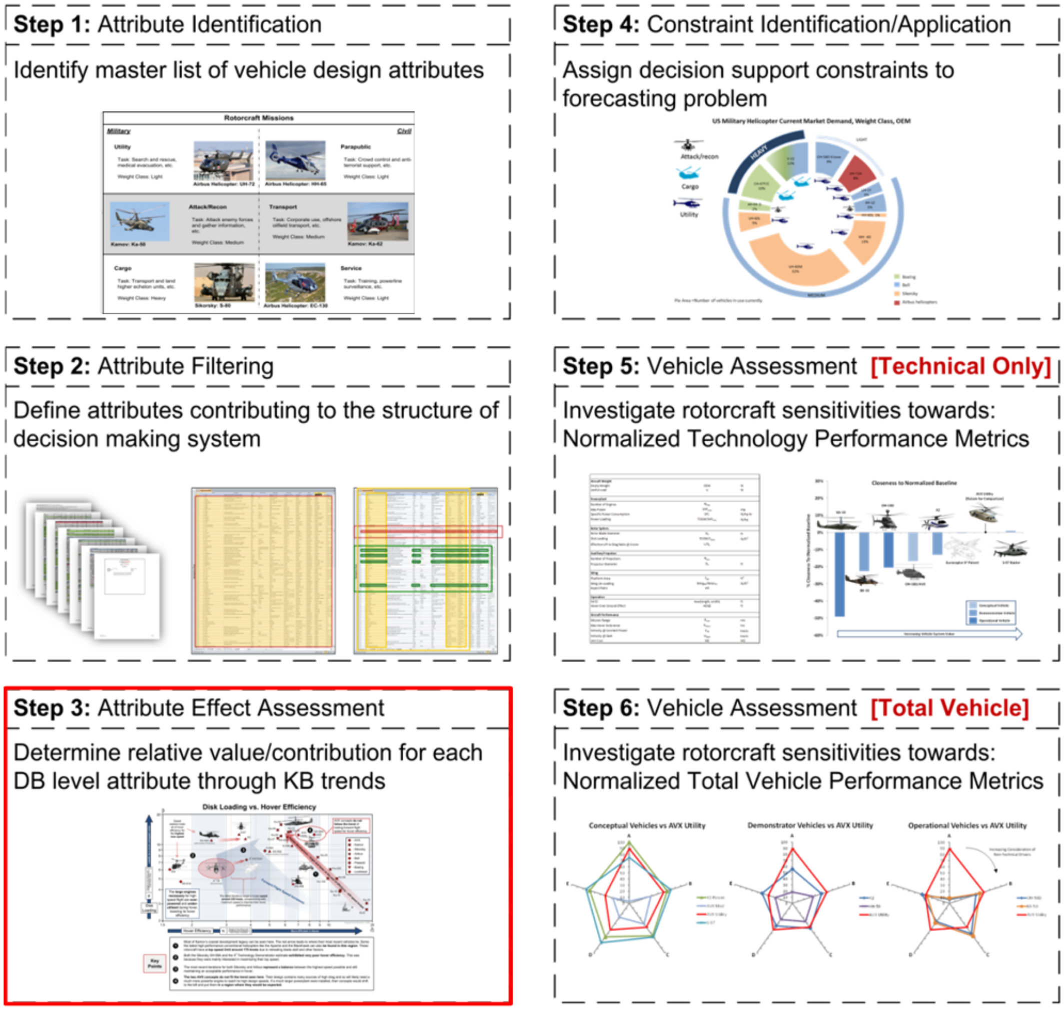


Figure 6-3 Research Steps in the Second Phase

After all of those development steps, the third phase concludes with rotorcraft configuration selection arguments the have been formulated based on those findings.

6.2.3 Research Steps

In this section, the deduction of the rotorcraft disk loading development trend is introduced. Primary rotorcrafts configurations from industry leaders are considered, including Sikorsky, Airbus Helicopters and Kamov. The efficiency advantages of the AVD^{KBS} knowledge management approach are demonstrated through knowledge trends and knowledge manipulation aspects.

In order to evaluate the knowledge management efficiencies, the definitions of the user efficiency quantification parameters are listed in Table 6-7:

Table 6-2 Definitions of User Efficiency Quantification Parameters

Quantification Parameter	**Symbol**	**AVD^{KBS}**	**Manual**
Processing Speed (GB/s)	S_{Mps}	0.002	0.00013
Manipulation Cost ($/GB)	S_{Mmc}	0.02	50
Analyzing Speed (flops)	S_{Aps}	1.09E11	2.2E15
Analysis Accuracy (%)	S_{Aac}	100	97.5
Teaching Efficiency (%)	S_{Asc}	0.01	100

The manipulating speed refers to the speed of AVD^{KBS} or humans manipulating knowledge, such knowledge searching and retrieving. A test of locating a randomly selected piece of knowledge in the knowledge base is used to estimate the manipulating speed of humans and AVD^{KBS}. The size of the knowledge base is 0.0002 GB, it takes the AVD^{KBS} about 0.1 s to locate a required knowledge entry; while in order to estimate the time cost of humans, five tests of locating a randomly selected piece of knowledge have been done (Table 6-4), and the average time cost is 1.6 s. As a result, the manipulating speed of AVD^{KBS} is 0.002 GB/s($\frac{0.0002}{0.1}$), and that of humans is 0.000125 GB/s($\frac{0.0002}{1.6}$).

Table 6-3 Tests of Humans Locating a Required Knowledge

Test	1	2	3	4	5	Average
Time Cost(s)	1.4	1.7	1.5	1.4	1.8	1.6

The manipulation cost refers to the expenditure during the process of AVD^{KBS} or humans manipulating knowledge. The cost of AVD^{KBS} is mainly electricity, whose rate is 0.12 $/hour [148], so its cost is estimated around $ 0.000003 ($\frac{0.12}{60*60} * 0.1$). The average hourly employee earning is $ 25 [149], so the cost of humans manipulating is $ 0.01 ($\frac{25}{60*60} * 1.6$). As a result, the manipulating cost of AVD^{KBS} is 0.02 \$/GB ($\frac{0.000003}{0.0002}$), and that of humans is 50 \$/GB ($\frac{0.01}{0.0002}$).

The analyzing speed refers to the speed of AVD^{KBS} or humans finishing all the other kinds of knowledge management activities except knowledge manipulating. The human brain is concluded as a massive complex parallel machine [(150)]. Researchers analyze the working mode, storage capacity, interconnections and number of neurons of the human brain, and estimate its analyzing speed to be 2.2E15 flops [(151)], while the analyzing speed of computer at AVD Laboratory, on which AVD^{KBS} is built, is 1.09E11 flops in comparison [(152)].

The analyzing accuracy measures the chances of a mistake during the analyzing processes. The computer rarely makes any mistake, so AVD^{KBS} analyzing accuracy is estimated as 100%. The GPA of the tester (author) is used as a measurement in evaluating humans analyzing accuracy, and the tester's GPA is 3.9, so the humans analyzing accuracy is evaluated as 97.5% ($\frac{3.9}{4.0}$).

The teaching efficiency measures the instructing effectiveness of AVD^{KBS} or humans. Dr. Robert A. Barry lists eight criteria for an effective teacher [(153)]:

- "Have high expectations for student learning."
- "Provide clear and focused instruction."
- "Closely monitor student learning progress."
- "Reteach using alternative strategies when students don't learn."
- "Use incentives and rewards to promote learning."
- "Highly efficient in their classroom routines."
- "Set and enforce high standards for classroom behavior."
- "Maintain excellent personal interactions with their students."

These criteria emphasize the interactions between students and teachers, and require teachers to dynamically change teaching strategies upon students' feedback. However, AVD^{KBS}

can only teach through displaying stored knowledge, which is a passive and predetermined teaching method. It does not satisfy any of the above criteria, so its teaching efficiency is estimated to be the minimum value 0.01. While humans teaching efficiency is estimated to be 100.

The definitions of the knowledge efficiency quantification parameters are:

Table 6-4 Definitions of Knowledge Efficiency Quantification Parameters

Quantification Parameter	**Symbol**	**AVD^{KBS}**	**Manual**
Storage Density (GB/m^3)	K_{Asd}	10240	1200
Storage Cost ($/GB)	K_{Asc}	1.1	68.8
Relevance (0/1)	K_{Par}	1	1
Correctness (%)	K_{Pac}	100	100
Accuracy (%)	K_{Mva}	50	50
Developing Period (Years)	K_{Mnc}	0.06	0.06

The storage density and storage cost are different for the two approaches because their storage media are different. The AVD^{KBS} approach uses hard drives as the knowledge storage medium, while the manual approach conventionally uses books as the knowledge storage medium.

The AVD^{KBS} is built in a desktop computer, whose space volume is 0.05 m^3 ($0.23 * 0.48 * 0.496 = 0.05$), and its storage capacity is 512 GB, so its storage density is 10240 GB/m^3 ($\frac{512}{0.05}$). In order to estimate the storage density of a book, the book Mechanics of Flight [154] is taken as an example. Its storage capacity is 2.4 GB and its space volume is 0.002 m^3 ($0.16 * 0.24 * 0.06 = 0.002$), so its storage density is 1200 GB/m^3 ($\frac{1.2}{0.002}$).

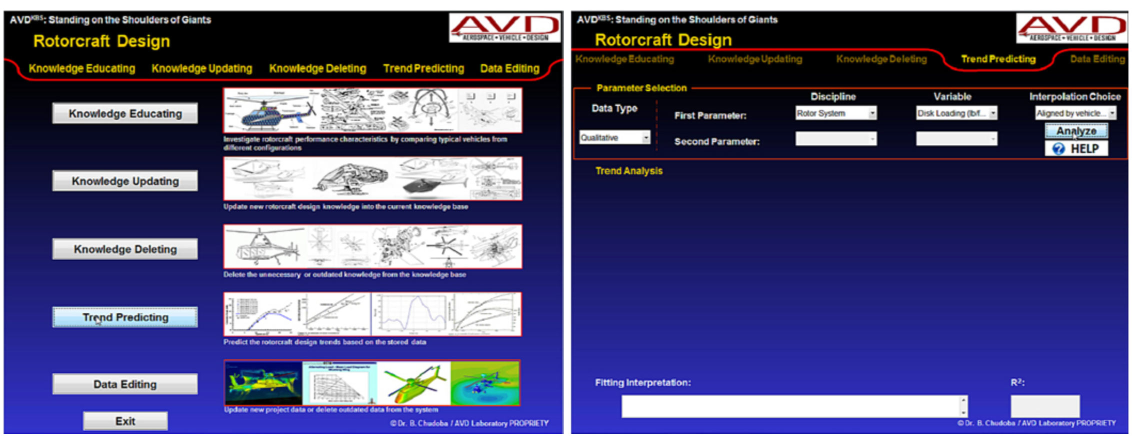
The price of the desktop on which the AVD^{KBS} is built is around $ 549 [155], so its storage cost is 1.1 $/GB ($\frac{549}{512}$). The price of the Mechanics of Flight book is $ 165, so its storage cost is 68.8 $/GB ($\frac{165}{2.4}$).

The rotorcraft design trend knowledge is deducted by AVD researchers based on data collected from reports, journals and conference papers; it has not been applied previously to any project practices, so its relevance, correctness and accuracy are estimated to be 1, 100% and 100%, respectively, and its developing period is 0.06 year (3 weeks).

6.2.3.1 Knowledge Trends

The first section demonstrates the AVD^{KBS} efficiency advantages in knowledge trends. The main goal is to use AVD^{KBS} to deduce the rotorcraft disk loading developing trend. The following are the research steps:

1. Choose the parameters of interest.
    - Open the Trend Predicting GUI through the Rotorcraft Vehicle Design starting panel.
    - Choose the Data Type as Qualitative.
    - Select the First Parameter's Discipline Rotor System.
    - Choose the Variable Disk Loading (lb/ft^2).
    - Use the 'Aligned by Vehicle Configuration' Interpolation Choice.



(a) (b)

Figure 6-4 (a) Select the Trend Predicting GUI, (b) Select the Parameters of Interests

2. Trend Prediction.
    - After finishing with all the inputs, press 'Analyze'.

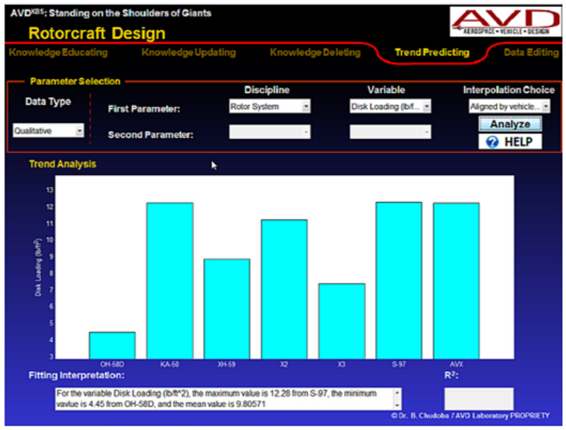
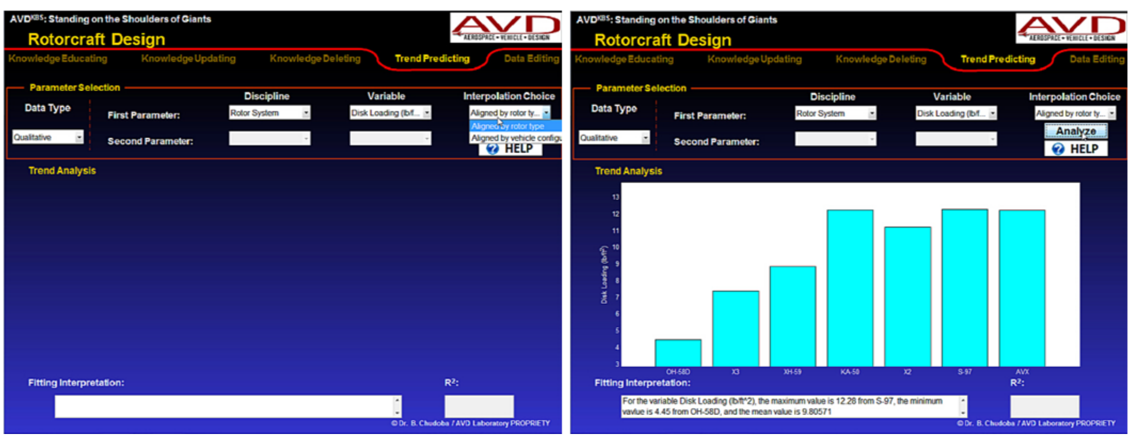


Figure 6-5 Fitting Result by Choosing Aligned by Vehicle Configuration.

Then, AVD^{KBS} will finish the development trend prediction. The design trend figure is displayed in the Trend Analysis window, and the fitting explanations show up in the fitting interpretation textbox.

However, from the above selections, there is no obvious developing trend that shows up, and the prediction is not successful. Change the interpolation choice, and choose 'Aligned by Motor Type' for the interpolation choice. After that, run the analysis again.



(a) (b)

Figure 6-6 (a) Change Fitting Method, (b) Choose Aligned by Motor Type

Then, an increasing trend shows up for the disk loading when the rotorcrafts configurations are aligned according to rotor types.

The above steps are the AVD^{KBS} approach in accomplishing the knowledge trends part in the rotorcraft vehicle design case study. If the task is accomplished by traditional manual approach, all of the fitting deduction processes must be done by hand.

The efficiency index formula for the knowledge trend applications is used to evaluate the efficiencies of the AVD^{KBS} and manual approaches.

The efficiency for the AVD^{KBS} approach is:

$$\begin{aligned} I_e &= \frac{K_{Asd}}{K_{Asc}} * K_{Mva} * K_{Mnc} * ((K_{Par} * K_{Pac}) * (\frac{S_{Mps}}{S_{Mmc}} * S_{Aps} * S_{Aac})) \\ &= \frac{10240}{1.1} * 100 * 0.06 * ((1*100) * (\frac{0.002}{0.15} * 1.09E11 * 100)) \\ &= 8.2E17 \end{aligned} \tag{6.1}$$

The efficiency for the manual approach is:

$$\begin{aligned} I_e &= \frac{K_{Asd}}{K_{Asc}} * K_{Mva} * K_{Mnc} * ((K_{Par} * K_{Pac}) * (\frac{S_{Mps}}{S_{Mmc}} * S_{Aps} * S_{Aac})) \\ &= \frac{1200}{68.8} * 100 * 0.06 * ((1*100) * (\frac{0.00013}{50} * 2.2E15 * 97.5)) \\ &= 5.6E15 \end{aligned} \tag{6.2}$$

The efficiency of the AVD^{KBS} approach is 146 ($\frac{8.2E17}{5.6E15}$) times that of the manual approach. This demonstrates the AVD^{KBS} approach's efficiency advantages in knowledge trend applications.

The efficiency advantage of AVD^{KBS} is exhibited through the following aspects:

– Shorter time in accomplishing the design trend deducing analysis;

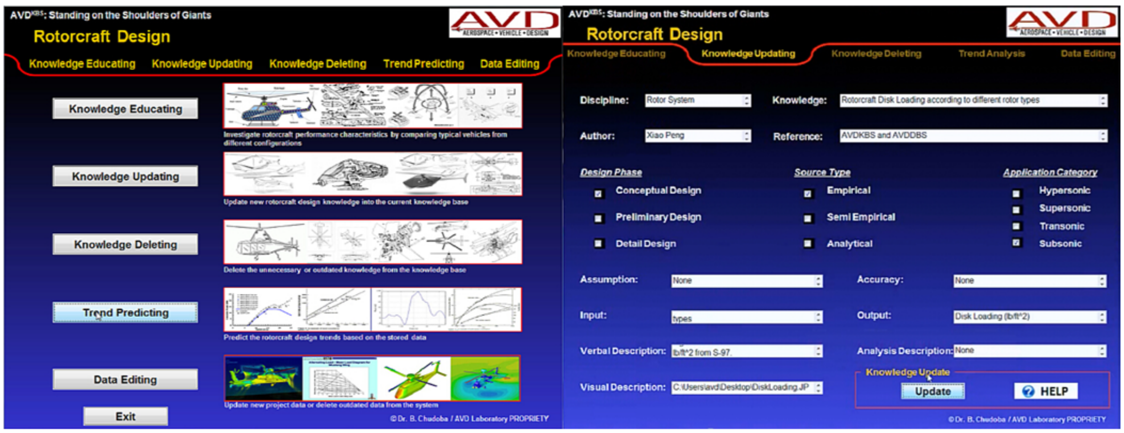
– Accurate analysis result with no mistake during the analysis process;

These advantages are mainly due to AVD^{KBS}'s higher analyzing speed and analyzing accuracy.

6.2.3.2 Knowledge Manipulation

This section tries to demonstrate the AVD^{KBS} efficiency advantages in knowledge manipulation. The main goal is to use AVD^{KBS} to finish the disk loading development trend knowledge updating and education processes. The following are the research steps:

1. Update the knowledge into AVD^{KBS}.

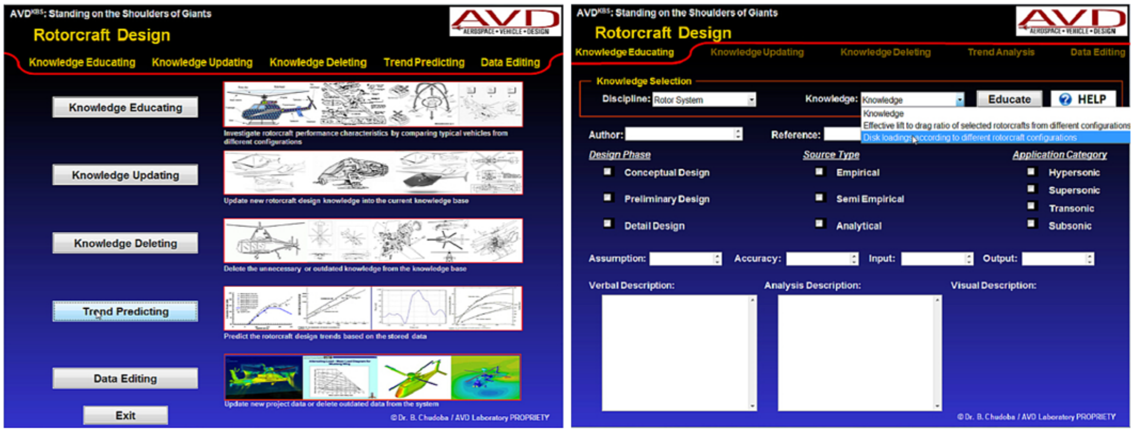


(a) (b)

Figure 6-7 (a) Select the Knowledge Updating GUI, (b) Input the Summarized Knowledge Information

- Open the knowledge updating GUI through the rotorcraft vehicle design starting panel.
- Input all the knowledge information summarized from the trend predicting process: Discipline, Knowledge, Author, Reference, Design Phase, Source Type, Application Category, Assumption, Accuracy, Input, Output, Verbal Description, Analysis Description and Visual Description.
- After finishing inputting all the knowledge information, press the “Update” button. The knowledge will be input into the system.

2. Knowledge Selection.



(a) (b)

Figure 6-8 (a) Select the Knowledge Educating GUI, (b) Make Selections

- o Open the knowledge educating GUI through the rotorcraft behicle design panel.
- o Select “Rotor System” from the discipline pull-down menu.
- o Choose “Disk loadings according to different rotorcraft configurations” from the Knowledge pull-down menu.

3. Knowledge Education
   - o After finish the selections, press the “Educate” button.

Figure 6-9 Knowledge Educating Result

Then, AVD^{KBS} will search and retrieve the knowledge from the knowledge base and display it for review and education.

The above steps are the AVD^{KBS} approach in accomplishing the knowledge manipulation part in the rotorcraft vehicle design case study. If the task is accomplished by the traditional manual approach, all of the search processes must be done by hand.

The efficiency index formula for the knowledge education applications is used to evaluate the efficiencies of the AVD^{KBS} and manual approaches.

The efficiency for the AVD^{KBS} knowledge management approach is:

$$\begin{aligned} I_e &= \frac{K_{Asd}}{K_{Asc}} * ((K_{Pac} * K_{Mva} * K_{Mnc}) * (\frac{S_{Mps}}{S_{Mmc}} * S_{Asc})) \\ &= \frac{10240}{1.1} * ((100*100*0.06) * (\frac{0.002}{0.02} * 0.01)) \\ &= 5585.46 \end{aligned} \tag{6.3}$$

The efficiency for the manual knowledge management approach is:

$$\begin{aligned} I_e &= \frac{K_{Asd}}{K_{Asc}} * ((K_{Pac} * K_{Mva} * K_{Mnc}) * (\frac{S_{Mps}}{S_{Mmc}} * S_{Asc})) \\ &= \frac{1200}{68.8} * ((100*100*0.06) * (\frac{0.00013}{50} * 100)) \\ &= 2.72 \end{aligned} \tag{6.4}$$

The efficiency of the AVD^{KBS} approach is 2053 ($\frac{5585.46}{2.72}$) times that of the manual approach. It demonstrates the AVD^{KBS} approach's efficiency advantages in knowledge education applications.

The efficiency advantage of AVD^{KBS} is exhibited through the following aspects:

- Shorter time in locating and retrieving the design trend knowledge;

This advantage is mainly due to AVD^{KBS}'s higher manipulating speed.

6.2.4 Research Contributions

Following the disk loading development trend predicted by AVD^{KBS}, researchers surveyed all of the historical rotorcrafts from Sikorsky, Airbus Helicopter and Kamov. After aligning them according to their rotor types, a clear increasing developing trend shows up (Figure 6-10).

The developing trend shows that the coaxial rotorcraft has a much higher disk loading than the other configurations in the same period. However, in different developing periods, even the disk loading of the single rotor configuration in a later developing period is higher than that of the coaxial configuration in an earlier developing period because of a significant progress in materials and structural design technologies.

From the overall disk loading development history, it generally shows three stages:

- Before 1974, the disk loading had a slowly increasing pattern. It only increased from 2 lb/ft^2 to 4.5 lb/ft^2 over thirty years.
- From 1974 to 1990, the disk loading increased quickly. It almost tripled from 4.5 lb/ft^2 to 12 lb/ft^2 in those sixteen years.
- From 1990 to the present, the disk loading has stayed at almost the same level, and no significant progress has been made. It might be because of technology constraints and may need a breakthrough to further increase the rotorcraft disk loading.

The data collection is done in form of a group effort, and the AVD^{KBS} gives suggestions on the development trend of the rotorcraft disk loading. Then the researchers can easily complete the development trend result by aligning the data of a big number of rotorcrafts according to the predicted trend.

In addition to the disk loading trend, other developing trends are deduced with the help of AVD^{KBS}, such as trends for maximum speed (Figure 6-11) and hover efficiency. From the maximum speed trend, it can be seen that the speed plateaus in both conventional and coaxial configuration rotorcraft. The conventional rotorcraft has a 180 kts speed limit, while the coaxial rotorcraft has a 170 kts speed limit. However, some high performance vehicles can reach up to 250 kts. The reason of the speed plateau is that both the conventional and coaxial configuration rotorcrafts show very high drag and have a lower speed, as well as the structural limit at high speed. Although their speeds increase significantly in history, they both have difficulties in further increasing the speed.

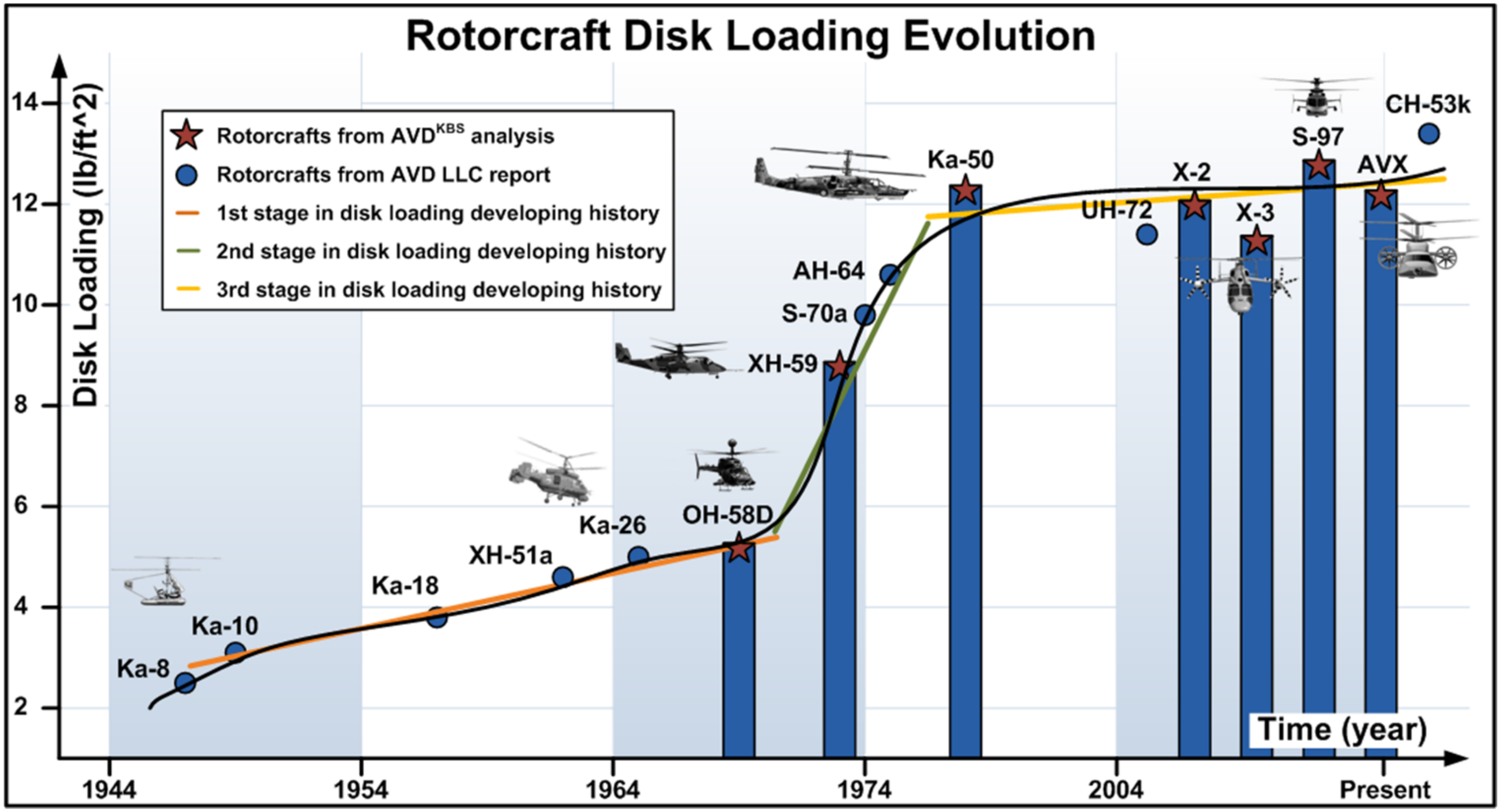


Figure 6-10 Rotorcraft Disk Loading Evolution

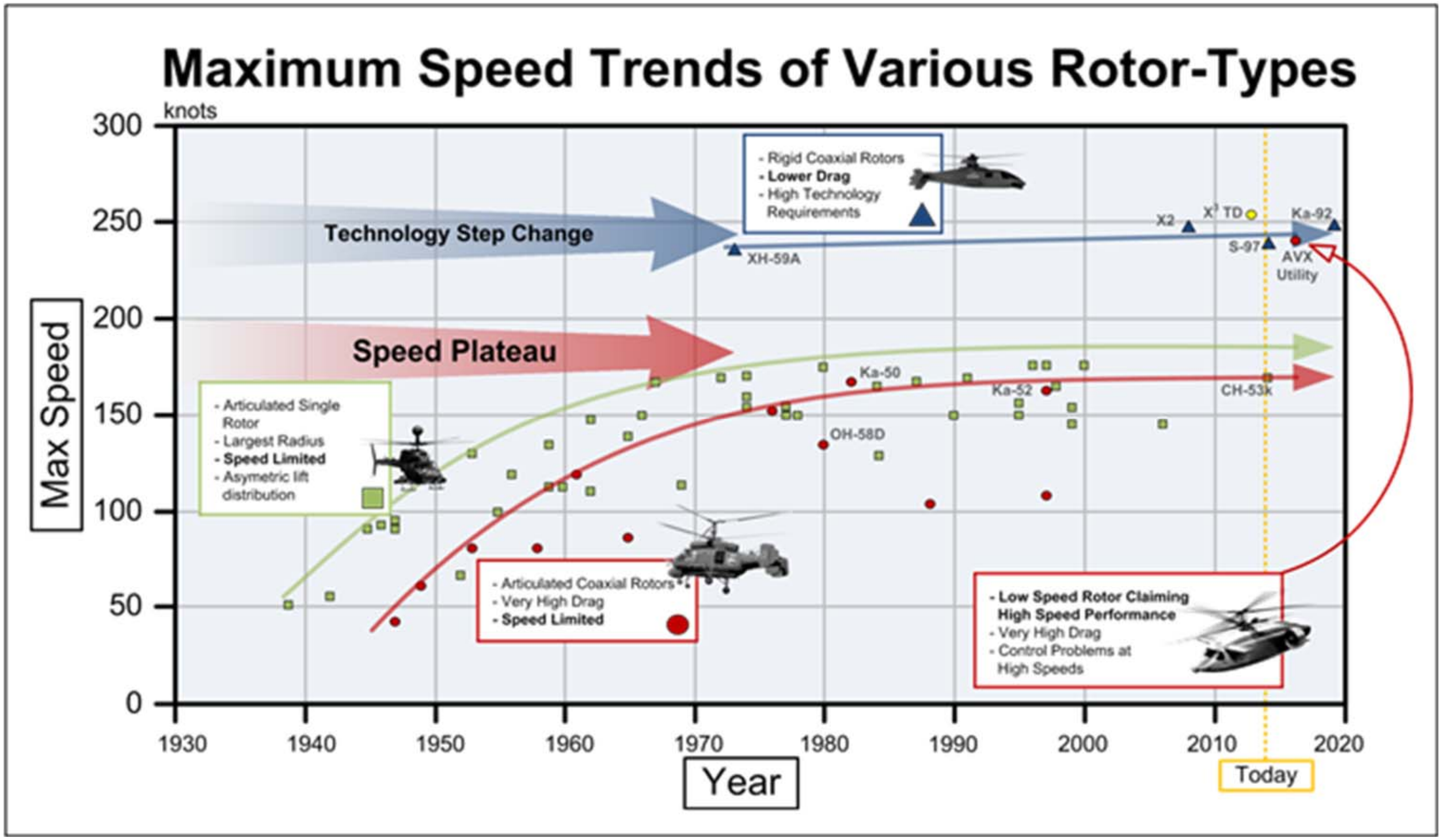


Figure 6-11 Maximum Speed Trends of Various Rotor-types

6.3 Launch Vehicle Design

The launch vehicle design case study consists of four sections:

1. Research Motivation: note the opportunity of employing past project data to aid modern launch vehicle design work.
2. Research Background: introduce the advantages of AVD Laboratory in launch vehicle design knowledge accumulations.
3. Research Steps: explain the new design knowledge (the relationship between take-off gross weight and launch vehicle length) generation process in detail and demonstrate the AVD^{KBS} efficiency advantages in knowledge management.
4. Research Contributions: conclude the research findings by validating the new generated knowledge.

6.3.1 Research Motivation

Expendable launch vehicles have evolved for more than fifty years, and a great number of them have been developed, forming many launch vehicle families, such as Atlas, Falcon, Zenit and Long March [(156)]. Accordingly, a vast quantity of project reports have been produced to document the design experiences and lessons learned during the project developments. As a result, report servers have been established to organize them, for instance, the NASA Technical Reports Server (NTRS) [(157)].

However, those reports are hard to use because of the difficult accessibility, and researchers may be even not aware of their existences. The difficulty of accessing past research experiences and knowledge has not gone unnoticed. NASA has recently stated plans to use the design experiences and lessons learned from past launch vehicle programs to aid the new space transportation system development [(158)]. It can

> "… leverage existing technologies and applying lessons learned to work smarter, and build an accountable team that is dedicated to implementing aerospace best practices, including rigorous systems engineering and systems management, and to mitigate the risks inherent; deliver complex

> prototype space transportation systems that fulfill stakeholder and customer requirements, including reduced operations costs from system inception to retirement. …”[158]

An ideal solution concept to implement such plan is a dedicated knowledge base. However, no progress has been reported until now. AVD researchers have been utilizing AVD^{KBS} to implement the plan, reviving legacy knowledge and using it to guide future launch vehicle development. The Mercury-Redstone launch vehicle is selected as the research object in the present context, which was designed for NASA’s Project Mercury, from 1958 to 1963 [159]. The Mercury-Redstone launch vehicle was the first American manned space booster. It was also the first effort to develop a recoverable launch vehicle through utilizing parachute and reach the testing phase. Overall this legacy development and knowledge does match the latest launch vehicle developing trend being tested by the SpaceX company today [160]. Consequently, the Project Mercury case study carries the value to explore and retrieve the design experiences and lessons learned from the legacy Mercury-Redstone launch vehicle. It will be demonstrated how valuable thus useful such legacy project is for guiding the current launch system design teams.

The take-off gross weight (TOGW) and launch vehicle length are selected parameters to deduce a new knowledge-based design trend stemming from this case study. The TOGW of a launch vehicle is a critical design parameter in evaluating its lifting capabilities [161]. Launch vehicles can be classified into small, medium, heavy and super-heavy lift launch vehicles in general. The launch vehicle length is an important geometry parameter in launch vehicle design. A smaller launch vehicle length is easier for transportation and results in a lower requirement for the launch pad facilities. Moreover, it also leads to less drag loss [162].

As a result, it will be interesting to find out whether there is a relationship between the two and what conclusions can be drawn.

6.3.2 Research Background

Legacy design trends are a powerful tool for generating new design knowledge based on past project data. Trends are derived stemming from the design continuum among projects [131]. The design continuum is based on the fact that projects with similar design missions show similar properties. In this way, researchers are able to interpolate an extrapolate the unknown data for a current project by deducing design trend from the available data of similar past projects. As a result, for the vehicles developed throughout history, their data include valuable knowledge for current and future design work.

However, to produce a design trend, large amounts of past project data and knowledge are required. Fortunately, AVD Laboratory has one of most comprehensive data and knowledge accumulations in launch vehicle conceptual design. Introduction to AVD knowledge accumulations has been made in Chapter 4 *AVD Knowledge Accumulation* section. The inheritance knowledge from Paul is employed in launch vehicle design case study.

The knowledge is documented in a matrix format using Microsoft Excel. The columns of the matrix are the constituents of the knowledge, such as author, reference, design phase and assumptions. Each row of the matrix contains a piece of knowledge. There are total 35 pieces of knowledge collected for the launch vehicle design case study. A glance of the knowledge content can be found in Figure 6-12 & 6-13.

1	Discipline	Content Name	Author	Reference	Design phase	Categoriz	Speed	Assur	Accuracy	Input	Output	Verbal	Analytical	Visual
2	Propulsion	Specific impulse variation for f	Jr. H.D.	Fusion-Ele	Conceptual Des	Analytical	Hypersoni	Excluc	Data taker	Mach number	Specific Impulse	The fusion	SI = -0.0002	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
3	Geometry	Wing sweep angle versus macl	Paul A.	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Mach number - M	Wing sweep angle - Lambda	The wing s	Lambda = 0.	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
4	Cost Estimati	Cost of payload versus flights	Paul A.	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Flights per year - fpy	Cost of payload - cop	The cost o	If fpy < =10	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
5	Propulsion	Propulsion index versus mach	Paul A.	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Mach number - M	Propulsion index - Ip	Propulsior	Ip = 106.2*	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
6	Propulsion	Propellant volume/area (Planf	Paul A.	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Propulsion index - Ip	Propellant volume/planform Area	The prope	For planforr	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
7	Geometry	Structure index versus kuchem	Paul A.	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Kuchemann's tau - tau	Structure index - Kstr	Structure i	Kstr = 0.317	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
8	Weight	OEW versus total volume	Paul A.	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Total volume - Vtot	OEW - oew	OEW is an	oew = 0.56	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
9	Geometry	Geometry characteristic versu	Paul A.	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Kuchemann's tau - tau	Geometry characteristic - K_tau	The geom	K_tau = exp	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
10	Geometry	Engine minimum height versus	Paul A.	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Planform Area - Sp (ft^2)	Engine minimum height - h2 (ft)	The engin	For Sp < 22	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
11	Geometry	Spatular nose width paramete	Paul A.	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Planform Area - Sp (ft^2)	Spatular nose width parameter - C	The spatul	Cs = 0.0002	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
12	Aerodynamic	Zero lift drag characteristic ver	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Kuchemann's tau - tau	Zero lift drag characteristic - Cd0	The zero li	Cd0 = 0.14*	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
13	Aerodynamic	L/D increment versus mach nu	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Mach number - M	L/D increment - delta_ld	The L/D in	delta_ld = -	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
14	Trajectory	Climb distance versus cruise sp	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Cruise speed - cs (ft/sec)	Climb distance - cd (nautical mile)	The climb	cd = 185.53	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
15	Trajectory	Descent distance versus cruise	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Cruise speed - cs (ft/sec)	Descent distance - dd (nautical mil	The desce	dd = 164.06	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
16	Aerodynamic	Lift to drag ratio versus drag c	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Drag coefficient - Cd	Lift to drag ratio - ld	The lift to	ld = 0.17*C	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
17	Propulsion	Weight ratio of TOGW to burni	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Incremental airbreathing	Weight ratio of TOGW to burningc	The weigh	Tobw = 7.5	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
18	Propulsion	Weight ratio at takeoff versus	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Maxium airbreathing mac	Weight ratio at takeoff - wrto	The weigh	wrto = -9.0	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
19	Trajectory	Weight ratio required to chang	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Maxium airbreathing mac	Weight ratio required to change fr	The weigh	wrcc = -2.3	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
20	Trajectory	Thrust drag ratio versus maxiu	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Maxium airbreathing mac	Thrust drag ratio - TD	The thrust	For mab<8	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
21	Trajectory	Oxidizer fuel ratio versus maxi	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Maxium airbreathing mac	Oxidizer fuel ratio - OF	The oxidiz	For mab<1.	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
22	Trajectory	Weight ratio from takeoff to gi	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Mach number - M	Weight ratio from takeoff to given	The weigh	For M<1.3	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
23	Propulsion	Frictional thrust loss versus w	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Wetted area (ft^2) - Swet	Frictional thrust loss (%) - ftl	The frictio	ftl = 0.675*	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
24	Propulsion	Average transonic Isp versus v	Paul A.	Hypersoni	Conceptual Des	Empirical	Transonic	None	Summariz	Vehicle average transonic	Average transonic Isp - ati	The avera	For ttw<0.5	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
25	Propulsion	Thrust loss versus planform ar	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Planform Area - Sp (ft^2)	Thrust loss - tl	The thrust	tl = 449.73*	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
26	Weight	Launch gross weight versus pr	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Propulsion system thrust	Launch gross weight - lgw (Mg)	The launch	For 20 lbm/	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
27	Weight	Launch gross weight versus m	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Mach number at rocket In	Launch gross weight - lgw (Mg)	The launch	For tau = 0.	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
28	Weight	Launch gross weight versus pa	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Payload - pl (Mg)	Launch gross weight - lgw (Mg)	The launch	lgw = 8.69*	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
29	Propulsion	Test time versus velocity	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Velocity/1000 - V (kiloft/s	Test time - tt (milliseconds)	The test ti	For model l	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
30	Propulsion	Driven tube diameter versus v	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Velocity/1000 - V (kiloft/s	Driven tube diameter - Dtd (in)	The driven	For combus	C:\Xiao\AVD_research\AVDKB\KBS_GUI\
31	Trajectory	Lateral range versus lift-to-dra	Paul A.	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Lift to drag ratio - ld	Lateral Range - lr (nautical range)	The lateral	lr = 221.88*	C:\Xiao\AVD_research\AVDKB\KBS_GUI\

Figure 6-12 Documentation Format of Knowledge Base in Launch Vehicle Design Case Study

Figure 6-13 A Glance of Collected Knowledge in Launch Vehicle Design Case Study

6.3.3 Research Steps

The goal of the launch vehicle design case study is to revive Project Mercury legacy design knowledge and innovate new design knowledge based on past design experiences. It is accomplished through deducing a new design trend between the launch vehicle length and the take-off gross weight based on the past design data and knowledge accumulated in AVD Laboratory. The efficiency advantages of AVD^{KBS} are demonstrated in the process through the three aspects: *knowledge analysis, knowledge trend* and *knowledge manipulation.*

Definitions of the user characteristic quantification parameters are listed as:

Table 6-5 Definitions of User Efficiency Quantification Parameters

Quantification Parameter	**Symbol**	**AVD^{KBS}**	**Manual**
Manipulating Speed (GB/s)	S_{Mps}	0.002	0.00013
Manipulating Cost ($/GB)	S_{Mmc}	0.02	50
Analyzing Speed (flops)	S_{Aps}	1.09E11	2.2E15
Analyzing Accuracy (%)	S_{Aac}	100	97.5
Teaching Efficiency (%)	S_{Asc}	0.01	100

The definitions are the same as the ones used for the rotorcraft vehicle design case study, which have been explained, because the performances of either AVD^{KBS} or humans are stable and will not change from one case study to another.

The definitions of the knowledge efficiency quantification parameters are summarized in Table 6-5:

Table 6-6 Definitions of Knowledge Efficiency Quantification Parameters

Quantification Parameter	**Symbol**	**AVD^{KBS}**	**Manual**
Storage Density (GB/m^3)	K_{Asd}	10240	1200
Storage Cost ($/GB)	K_{Asc}	1.1	68.8
Relevance (0/1)	K_{Par}	1	1
Correctness (%)	K_{Pac}	100	100
Accuracy (%)	K_{Mva}	100	100
Developing Period (Years)	K_{Mnc}	11	11

The storage density and storage cost definitions have not changed either from the rotorcraft vehicle design case study values. The reason is that those parameters are only related with knowledge documentation media, which are the same for both case studies.

The rest of the knowledge quantification parameters have the same values because both AVD^{KBS} and manual approaches are supposed to use the exact same knowledge to finish the task. The launch vehicle design knowledge collected in AVD^{KBS} has been applied to many projects and demonstrated to be correct, so its relevance, correctness and accuracy are 1, 100% and 100%, respectively.

It is hard to determine the birth date of each piece of knowledge, so the publication date of the report Hypersonic Convergence is selected as the developing starting date [(8)]. Accordingly, its developing period is 11 years.

In the following sections, knowledge management efficiencies of AVD^{KBS} and manual approach will be evaluated and compared through three aspects: *knowledge analysis, knowledge trend* and *knowledge manipulation.*

6.3.3.1 Knowledge Analysis

The first section tries to demonstrate the AVD^{KBS} efficiency advantages in knowledge analysis. The main goal is to use AVD^{KBS} to finish the parametric sizing analysis. The following are the research steps:

1. Launch the Parametric Sizing GUI.
    - Start from the main starting panel.
    - Click the 'Hypersonic Vehicle Design' button.

- o Then click the ‘Parametric Sizing’ button.

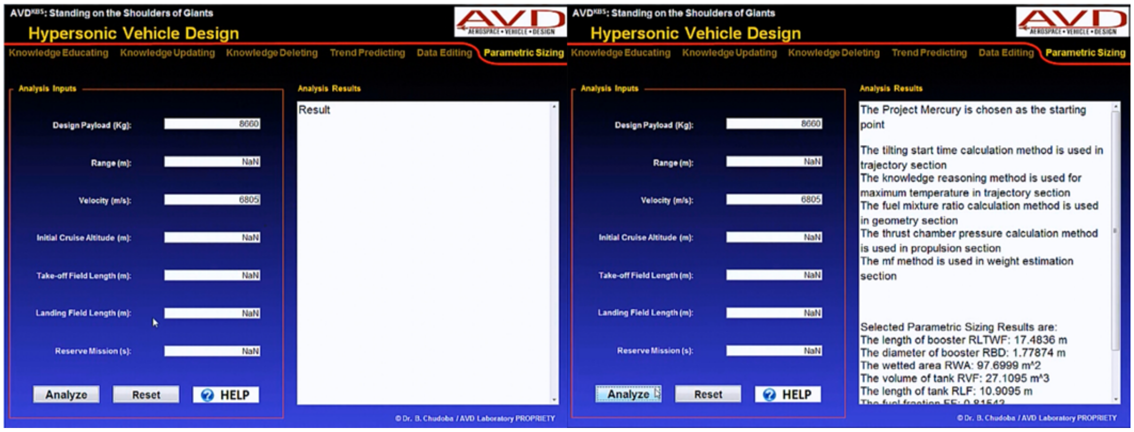
Figure 6-14 (a) Main Starting Panel, (b) Launch Vehicle Design Staring Panel, (c) Parametric Sizing Analysis GUI

2. Run the parametric sizing analysis for the original Project Mercury Redstone launch vehicle.

   - o Input the design mission requirements.
   - o Hit the ‘Analyze’ button to start the parametric sizing analysis process. The analysis process has been explained in Chapter 5 Parametric Sizing Analysis.

3. Update the Take-Off Gross Weight into the database.

   - o After the analysis process is finished, find the Take-Off Gross Weight (TOGW) from the output.



(a) (b)

Figure 6-16 (a) Input Mission Requirements, (b) Parametric Sizing Analysis Results

(a) (b)

(c)

Figure 6-15 (a) Find TOGW, (b) Open Data Editing GUI, (c) Update TOGW.

- Open the 'Data Editing' GUI from the 'Launch Vehicle Design' staring panel.

- o Update the TOGW into the database through the ‘Data Editing’ GUI.

4. Change the vehicle length

   - o In the ‘Data Editing’ GUI, change Project Mercury Redstone’s vehicle length (RLTWF).

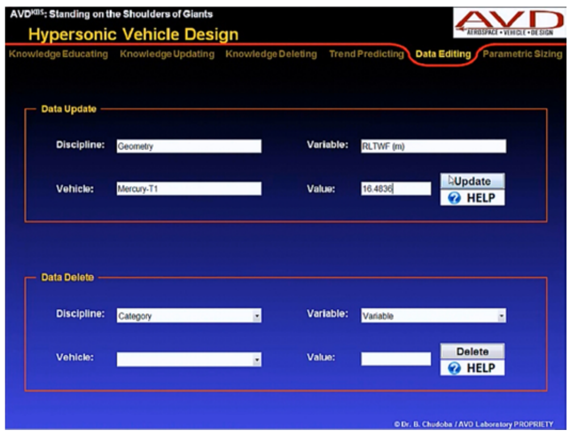
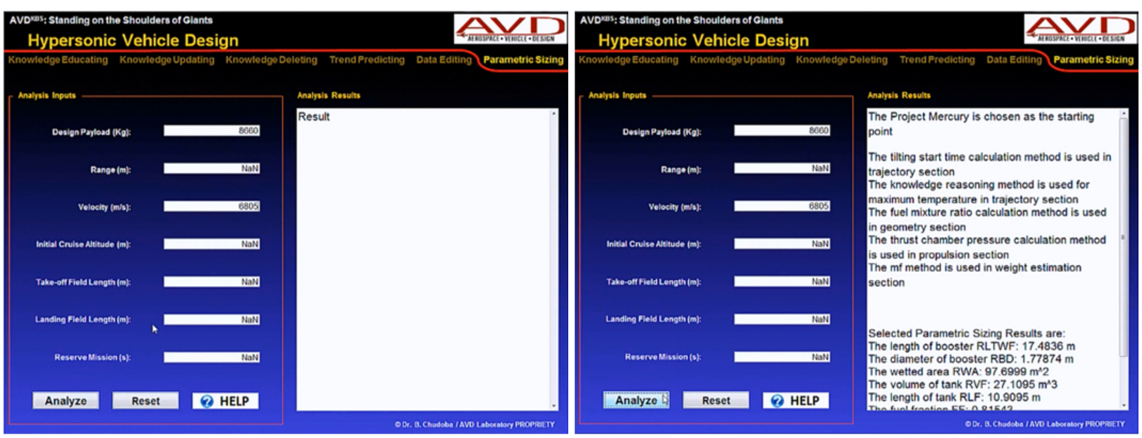


Figure 6-17 Change the Vehicle Length and Name it as Mercury-t1

   - o Name it as a new vehicle: Mercury-T1.



(a) (b)

Figure 6-18 (a) Input Mission Requirements for Mercury-T1, (b) Finish the Parametric Sizing Analysis

5. Finish the parametric sizing analysis for Mercury-T1.

   - o Use the same mission requirements to run another parametric sizing analysis through the ‘Parametric Sizing’ GUI.

6. Update the new Take-Off Gross Weight into the database.

- o Update the TOGW into the database through the 'Data Editing' GUI.

7. Repeat Steps 4-6.
   - o Repeat Steps 4-6 to produce five sets of TOGW-RWLTF data for Mercury, Mercury-T1, Mercury-T2, Mercury-T3 and Mercury-T4.

The above seven steps are the AVD^{KBS} approach in accomplishing the knowledge analysis part. If the same task is accomplished in manual approach, all of the calculating and data editing processes are going to be done by hand.

The efficiency index formula for the knowledge analysis applications is used to evaluate the efficiencies of both AVD^{KBS} and manual approaches.

The efficiency for the AVD^{KBS} approach is:

$$\begin{aligned} I_e &= \frac{K_{Asd}}{K_{Asc}} * K_{Mva} * K_{Mnc} * ((K_{Par} * K_{Pac}) * (\frac{S_{Mps}}{S_{Mmc}} * S_{Aps} * S_{Aac})) \\ &= \frac{10240}{1.1} * 100 * 11 * ((1*100) * (\frac{0.002}{0.02} * 1.09E11 * 100)) \\ &= 1.1E21 \end{aligned} \quad (6.5)$$

The efficiency for the manual approach is:

$$\begin{aligned} I_e &= \frac{K_{Asd}}{K_{Asc}} * K_{Mva} * K_{Mnc} * ((K_{Par} * K_{Pac}) * (\frac{S_{Mps}}{S_{Mmc}} * S_{Aps} * S_{Aac})) \\ &= \frac{1200}{68.8} * 100 * 11 * ((1*100) * (\frac{0.00013}{50} * 2.2E15 * 97.5)) \\ &= 1.1E18 \end{aligned} \quad (6.6)$$

The efficiency of the AVD^{KBS} approach is 1000 ($\frac{1.1E21}{1.1E18}$) times that of the manual knowledge management approach, which demonstrates the AVD^{KBS} approach's efficiency advantages over manual approaches in knowledge analysis.

The efficiency advantage of AVD^{KBS} is exhibited through the following aspects:

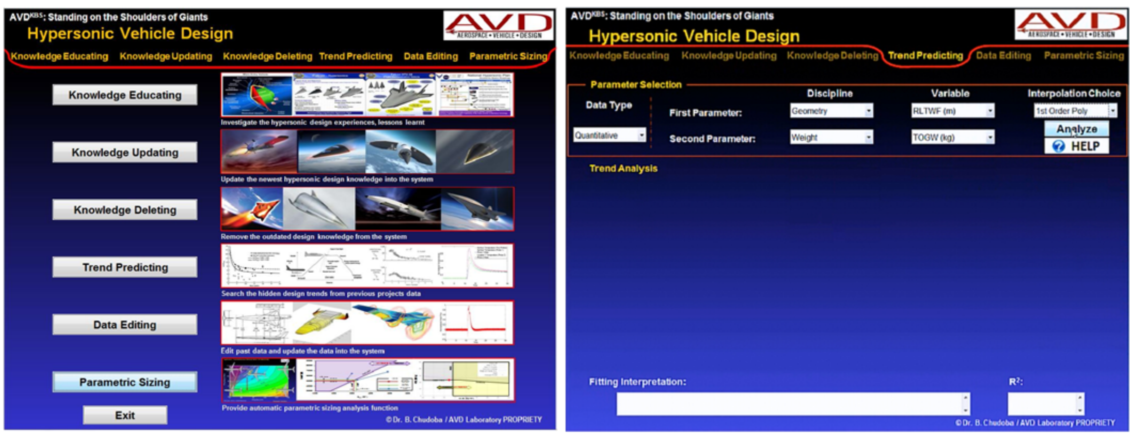
- Shorter time in accomplishing the parametric sizing analysis;
- Accurate analysis result with no mistake during the analysis process;

These advantages are mainly due to AVD^{KBS}'s higher analyzing speed and analyzing accuracy.

6.3.3.2 Knowledge Trends

This section demonstrates the AVD[KBS] efficiency advantages in knowledge trends. The main goal is to use AVD[KBS] to predict the design trend between TOGW and launch vehicle length. The following are the research steps:

1. Choose the parameters of interest.



(a) (b)

Figure 6-19 (a) Open Trend Preidicting GUI, (b) Selecte Parameters of Interests

- Open the Trend Predicting GUI through the Hypersonic Vehicle Design starting panel.
- Choose the Data Type as ‘Quantitative’.
- Select the First Parameter’s Discipline to be ‘Geometry’, and choose the Variable ‘RLTWF(m)’.
- For the second parameter, choose the Discipline ‘Weight’, and select the Variable ‘TOGW(kg)’.

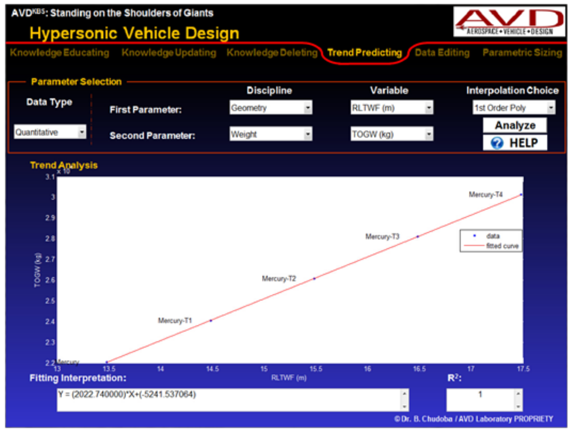


Figure 6-20 Trend Predicting of TOGW and RLTWF

- o Choose the '1st Order Poly' Interpolation Choice.

2. Trend Prediction

- o After finishing all the inputs, press 'Analyz'.

Then, AVD^{KBS} finishes the design trend prediction. The design trend figure is displayed in the *trend analysis* window, the fitting expression will show up in the *fitting interpretation* textbox, and the coefficient of determination will be shown in the R^2 textbox.

The above steps are the AVD^{KBS} approach for accomplishing the knowledge trends part of the hypersonic vehicle design case study. If the task is accomplished by the traditional manual approach, all of the fitting deduction processes must be done by hand.

The efficiency index formula for the knowledge analysis applications is used to evaluate the efficiencies of both AVD^{KBS} and manual approaches.

The efficiency for the AVD^{KBS} approach is:

$$
\begin{aligned}
I_e &= \frac{K_{Asd}}{K_{Asc}} * K_{Mva} * K_{Mnc} * ((K_{Par} * K_{Pac}) * (\frac{S_{Mps}}{S_{Mmc}} * S_{Aps} * S_{Aac})) \\
&= \frac{10240}{1.1} * 100 * 11 * ((1 * 100) * (\frac{0.002}{0.02} * 1.09E11 * 100)) \\
&= 1.1E21
\end{aligned}
\tag{6.7}
$$

The efficiency for the manual approach is:

$$
\begin{aligned}
I_e &= \frac{K_{Asd}}{K_{Asc}} * K_{Mva} * K_{Mnc} * ((K_{Par} * K_{Pac}) * (\frac{S_{Mps}}{S_{Mmc}} * S_{Aps} * S_{Aac})) \\
&= \frac{1200}{68.8} * 100 * 11 * ((1*100) * (\frac{0.00013}{50} * 2.2E15 * 97.5)) \\
&= 1.1E18
\end{aligned} \tag{6.8}
$$

The efficiency of the AVD^{KBS} approach is 1000 ($\frac{1.1E21}{1.1E18}$) times that of the manual approach. This demonstrates the AVD^{KBS} approach's advantages in knowledge analysis.

The efficiency advantage of AVD^{KBS} is exhibited through the following aspects:

- Shorter time in accomplishing the design trend deducing analysis;
- Accurate analysis result with no mistake during the analysis process;

These advantages are mainly due to AVD^{KBS}'s higher analyzing speed and analyzing accuracy.

6.3.3.3 Knowledge Manipulation

This section demonstrates the AVD^{KBS} efficiency advantages in knowledge manipulation. The main goal is to use AVD^{KBS} to finish the deduced design trend knowledge updating and education processes. The following are the research steps:

1. Update the knowledge into AVD^{KBS}.

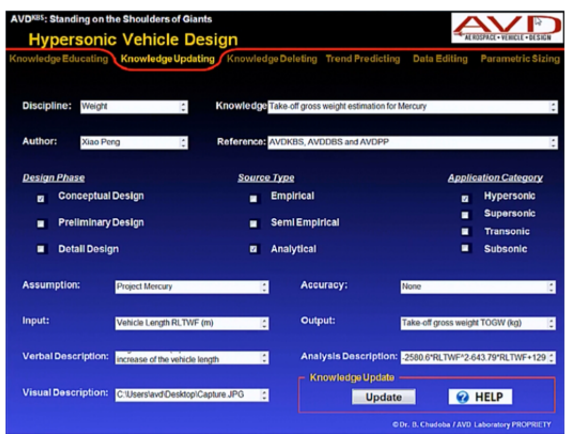
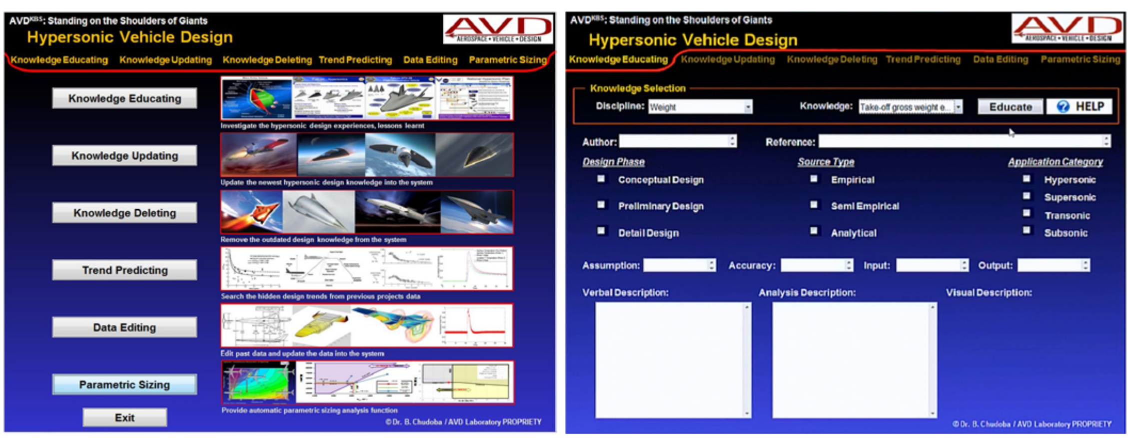


Figure 6-21 Update Summarized Knowledge

- o Open the Knowledge Updating GUI through the Hypersonic Vehicle Design starting panel.
- o Input all the knowledge information summarized from the trend predicting process: Discipline, Knowledge, Author, Reference, Design Phase, Source Type, Application Category, Assumption, Accuracy, Input, Output, Verbal Description, Analysis Description and Visual Description.
- o After finishing inputting all the knowledge information, click the “Update” button. The knowledge will be input into the system.

2. Knowledge Selection.
   - o Open the Knowledge Education through the Hypersonic Vehicle Design GUI.
   - o Select ‘Weight’ from the Discipline menu.
   - o Choose ‘Take-off gross weight estimation versus vehicle length’ from the Knowledge menu.



(a) (b)

Figure 6-22 (a) Select Knowledge Educating GUI, (b) Make Selections

3. Knowledge Education.

- After finishing with the selections, press the 'Educate' button.

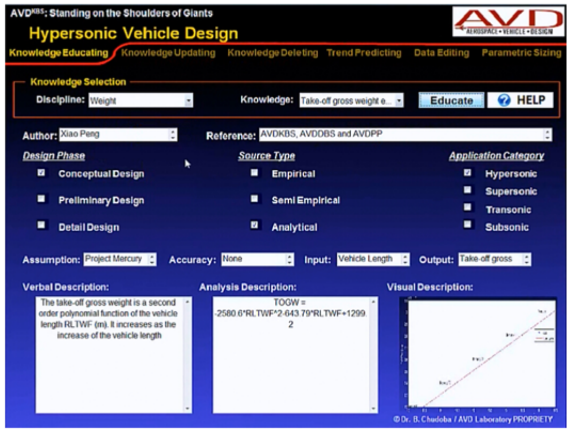


Figure 6-23 Knowledge Educating Results

Then, AVD^{KBS} searches and retrieves the knowledge and displays it for review and education.

The above steps are the AVD^{KBS} approach for the knowledge manipulation part of the launch vehicle design case study. If the task is accomplished in a manual approach, all of the search processes must be done by hand.

The efficiency index formula for the knowledge education applications is used to evaluate the efficiencies of the AVD^{KBS} and manual approaches.

The efficiency for the AVD^{KBS} approach is:

$$\begin{aligned} I_e &= \frac{K_{Asd}}{K_{Asc}} * ((K_{Pac} * K_{Mva} * K_{Mnc}) * (\frac{S_{Mps}}{S_{Mmc}} * S_{Asc})) \\ &= \frac{10240}{1.1} * ((100*100*11) * (\frac{0.002}{0.02} * 0.01)) \\ &= 1E6 \end{aligned} \quad (6.9)$$

The efficiency for the manual approach is:

$$\begin{aligned} I_e &= \frac{K_{Asd}}{K_{Asc}} * ((K_{Pac} * K_{Mva} * K_{Mnc}) * (\frac{S_{Mps}}{S_{Mmc}} * S_{Asc})) \\ &= \frac{1200}{68.8} * ((100*100*11) * (\frac{0.00013}{50} * 100)) \\ &= 498.8 \end{aligned} \quad (6.10)$$

The efficiency of the AVD^{KBS} approach is 2005 ($\frac{1E6}{498.8}$) times that of the manual approach. This demonstrates the AVD^{KBS} approach's advantages in knowledge education.

The efficiency advantage of AVD^{KBS} is exhibited through the following aspects:

- Shorter time in locating and retrieving the design trend knowledge;

This advantage is mainly due to AVD^{KBS}'s higher manipulating speed.

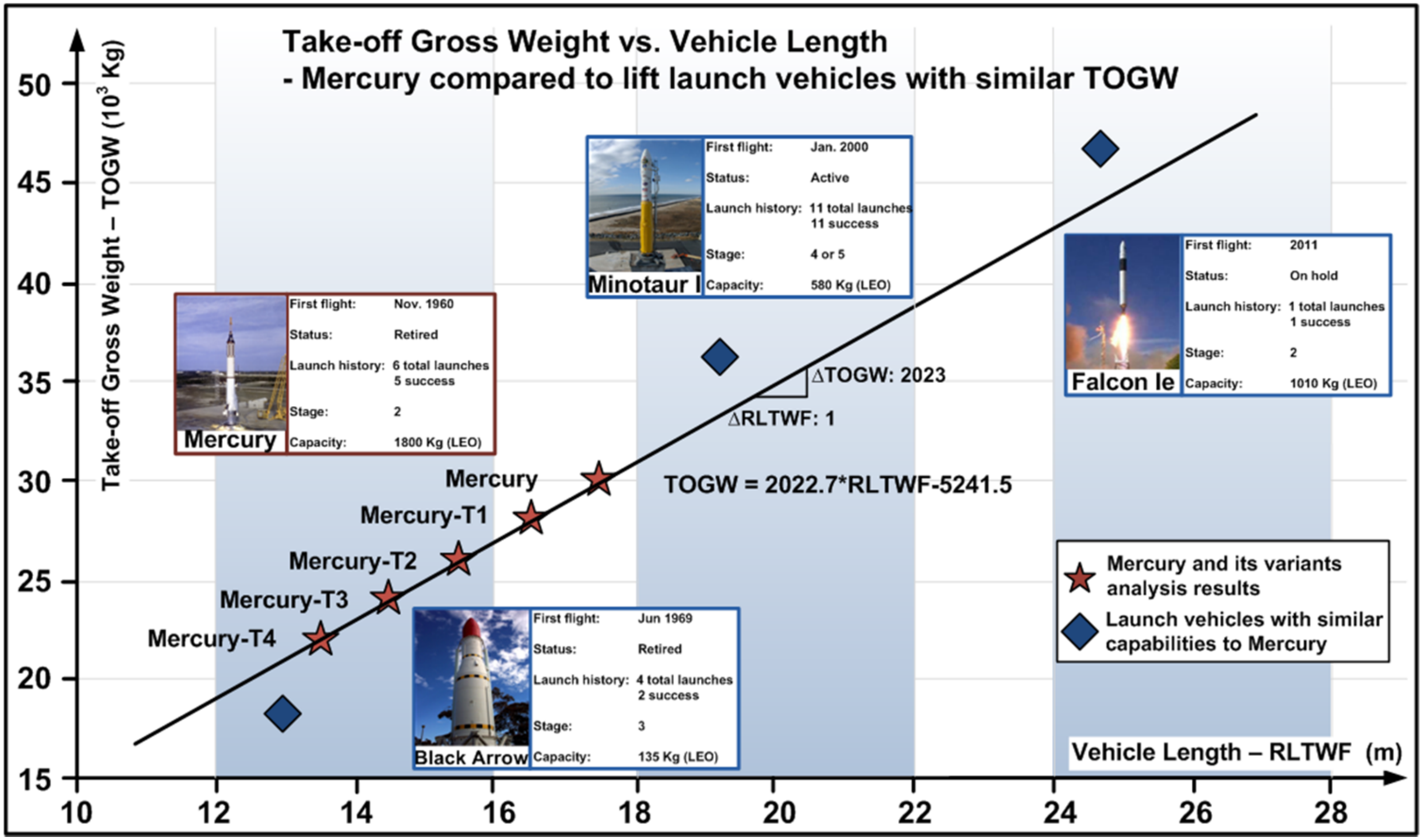


Figure 6-24 Compare Project Mercury Launch Vehicle to the Ones with Similar TOGW

6.3.4 Research Contributions

From the above design trend prediction process, the relationship between the take-off gross weight (TOGW) and launch vehicle length (RLTWF) is concluded to be a linear function:

$$TOGW = 2022.7 * RLTWF - 5241.5 \quad (6\text{-}11)$$

To validate the knowledge trend-line derived from involved design synthesis based on a legacy project, the launch vehicles with similar take-off gross weights to Project Mercury are first selected. They are added in the same figure with Project Mercury, see Figure 6-24. The launch vehicles selected and their related information are:

Table 6-7 Launch Vehicles with Simliar TOGW to Project Mercury Launch Vehicle

Launch Vehicle	**TOGW (10^3 Kg)**	**First Flight**	**Status**
Mercury	30	1960	Retired
Black Arrow	18.1	1969	Retired
Minotaur 1	36	2000	Active
Falcon 1e	46	2011	On

From the results, it can be concluded that they all have a reasonable match (correlate well) with the predicted design trend. Note that, these launch vehicles do not belong to the same era: Mercury and Black Arrow were developed in the early space exploration age (1960s), while Minotaur 1 and Falcon 1e were developed in the 21st century. In this case, the knowledge-trend derived is still valid for launch vehicles developed half a century later.

As a result, it can be concluded that the overall industry capability for expendable launch vehicles has not changed significantly during the past fifty years. In specific fields, such as propellant and structural materials, there may have been considerable progress. However, from the point of view of system engineering, the overall industry capability for expendable launch vehicle design has not progressed significantly.

The AVD^{KBS} demonstrate its capabilities of accomplishing the tasks a more efficient manner, compared to traditional manual approaches.

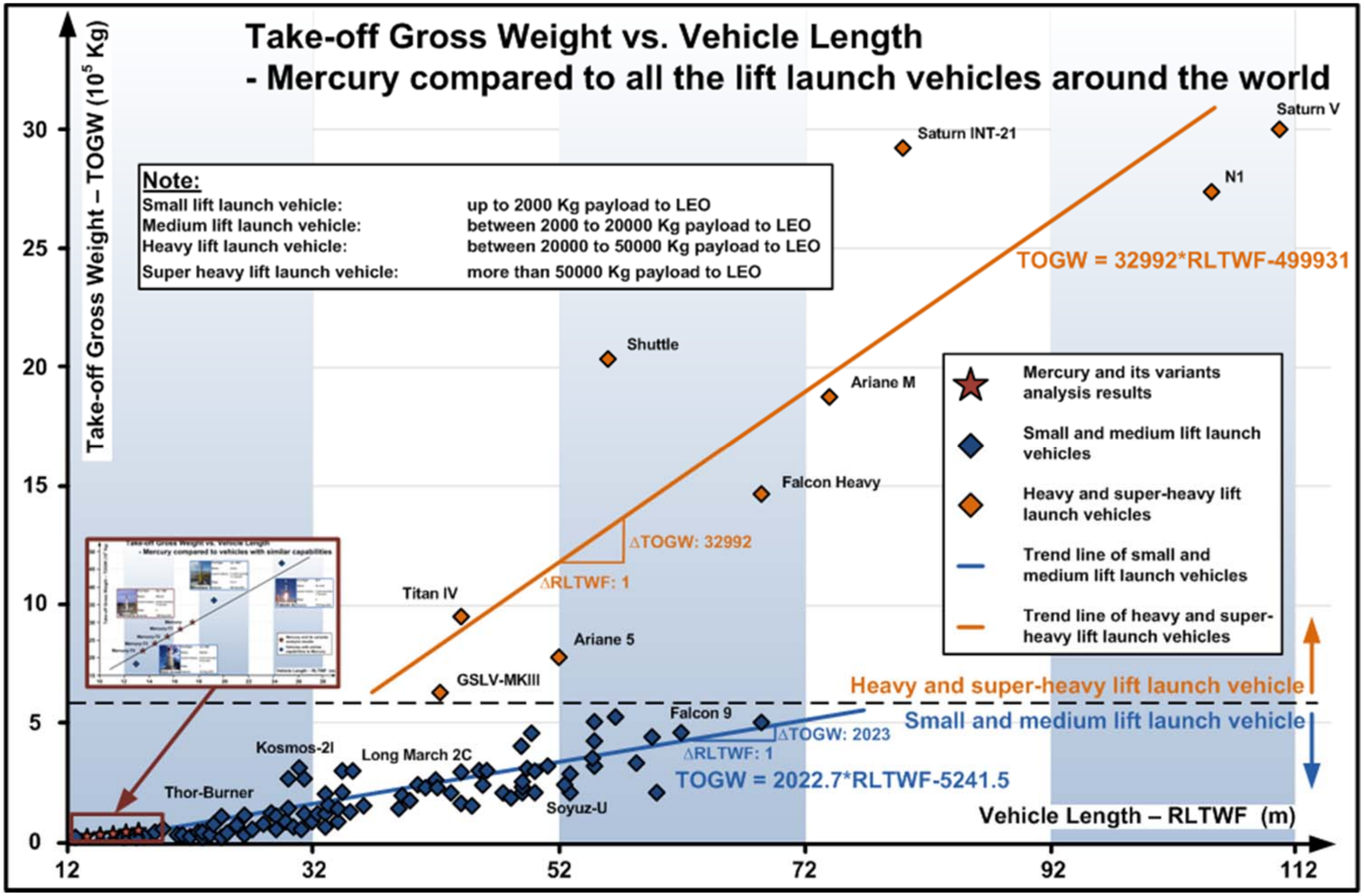


Figure. 6-25 Compare Project Mercury launch vehicle to All of the Launch Vehicles Developed around the World

Having compared expendable launch vehicles with similar take-off gross weights like the Project Mercury expendable launcher, the correlation is expanded to survey all expendable launch vehicles weight classes that have been developed around the world, see Figure 6-25.

In the figure, the launch vehicles are categorized into two weight groups:

- Small and medium launch vehicles (payload less than 20000 Kg to LEO);
- Heavy and super heavy launch vehicles (payload more than 20000 Kg to LEO).

Small and medium launch vehicles lie around the predicted design trend; while heavy and super heavy launch vehicles show a quite different pattern, and they have a much steeper slope for take-off gross weight over vehicle length. A logical reason might be that, for the same vehicle length, the mass of the heavy and super heavy launch vehicles must be much larger than that of the small and medium launch vehicles because of the high payload requirements. This is frequently achieved by increasing the radius of the launch vehicles or modifying the structural design.

On examination, each category of launch vehicle has a single design trend. Furthermore, the trend lines extend through the design eras. This indicates that, for the past half century, the industry capabilities in launch vehicle design have not progressed significantly. In this manner, the design knowledge deduced from past project data can be used to guide our current and future design work.

6.4 Contribution Summary

The original research contributions from Chapter 6 are as follows:

1. The launch vehicle design case study explicitly demonstrates the efficiencies increases brought by AVD^{KBS} during the processes of (a) parametric sizing analysis, (b) design trend knowledge deduction and (c) knowledge education. In addition, the comprehensive and profound design knowledge accumulations at AVD Laboratory is important to AVD^{KBS} applications.

2. The rotorcraft vehicle design case study demonstrates efficiencies increases brought by AVD^{KBS} during processes of (a) design trend knowledge deduction and (b) knowledge education. Moreover, this case study resembles a short course to teach users how to quickly get started with AVD^{KBS}, how to use AVD^{KBS} to accelerate the research progress, especially when there is no previous knowledge accumulation available as a starting point.

Chapter 7

Conclusion and Summary of Contributions

Humans have made significant progress throughout the history of development. At the beginning, humans could only satisfy their basic living needs at a very low level, such as living in caves, eating uncooked food and wearing leaves. Currently, humans not only satisfy their living needs at quite a high level but also explore the unknown world well beyond their living environment, such as using robotics to explore Mars and sending satellites to explore the depths of outer space. All of those achievements are obtained through the discoveries and applications of large quantities of knowledge.

However, until now, humans are struggling with knowledge management issues. For example, researchers still suffer from problems such as knowledge loss and unawareness of existing knowledge.

The presented research is based on and expanded from the best practices of KBS. It proposes the first systematic approach to form a closed loop for knowledge management instead of just focusing on one or two knowledge management functions.

Conclusions derived from this research investigation are organized into (1) a research summary and (2) a Ph.D. contribution summary.

7.1 Research Summary

7.1.1 Knowledge-based System (KBS) Development [Chapter 3]

1. ACHIEVEMENT: The survey has produced a unique cross-section of the KBS development history from 1984 to the present. These literatures are consistently documented, analyzed and presented to show a clear development pattern during the history of KBSs.
2. ACHIEVEMENT: Consistent documentation of KBS past research work provides an overview of the KBS development stages: (1) Early Preparation; (2) Independent System; (3) Integrated System; and (4) New Frontiers. KBSs evolved from system methodology proposals, to systems

working alone for knowledge storage and education, to systems cooperating with other processing tools to finish numerical analysis, to systems being broadly applied in almost every industry.

3. ACHIEVEMENT: The literature survey notes the research opportunity in the KBS field. Until now, no KBS research work has taken knowledge as the key concern and formed a closed loop of knowledge management process, including knowledge storage, education, application and innovation. Existing KBS work only employs one or several knowledge management functions based on the available technologies.

7.1.2 Methodology of AVD^{KBS} Knowledge Management Functions [Chapter 4]

1. ACHIEVEMENT: For the first time, knowledge is categorized according to its formats and representations: literal knowledge, qualitative knowledge and quantitative knowledge. These categorizations are the basis for the development of the following knowledge management functions.

2. ACHIEVEMENT: Three groups of knowledge management functions are proposed according to the three knowledge categories: literal knowledge management functions, qualitative knowledge management functions and quantitative knowledge management functions.

3. ACHIEVEMENT: The characteristics of the knowledge and the users involved in the knowledge application process (AVD^{KBS} and humans) are analyzed. For the first time, an efficiency evaluation criterion is proposed to quantify the efficiencies for knowledge management methods.

7.1.3 Development of AVD^{KBS} Knowledge Management Functions [Chapter 5]

1. ACHIEVEMENT: Users are classified into three groups. This aims to help them identify their current status and teach them how to start using the AVD^{KBS} knowledge management functions.

Suggestions are also given on how to make new discoveries based on their current knowledge accumulations.

2. ACHIEVEMENT: Knowledge management functions are built through MATLAB (the inference engine), MATLAB's GUI-creation functionalities (the GUI) and Microsoft Excel (the knowledge base). The function method logics and the GUI buildups are introduced in detail. As a result, a fully functional knowledge-based system, AVD^{KBS}, has been established.

7.1.4 Case Studies [Chapter 6]

1. ACHIEVEMENT: The efficiencies of knowledge management methods are measured in three aspects: knowledge manipulation, knowledge trend and knowledge analysis.

2. ACHIEVEMENT: The launch vehicle design case study demonstrates the AVD^{KBS} efficiencies in knowledge analysis, knowledge trends and knowledge manipulation for a researcher proficiency-rich product category. It aims at reviving the legacy launch vehicle design knowledge and innovating new knowledge based on past project data and design experiences.

3. ACHIEVEMENT: The launch vehicle design case study employs the launch vehicle design knowledge inherited from Paul A. Czysz's accumulations at McDonnell Douglas Corp. to build the knowledge base. It deduces the design trend knowledge between the launch vehicle length and the take-off gross weight, and it updates the design trend as a new piece of knowledge into AVD^{KBS}. It demonstrates AVD^{KBS}'s advantages by concluding the parametric sizing analysis and design trend deductions.

4. ACHIEVEMENT: The rotorcraft vehicle design case study demonstrates the AVD^{KBS} efficiencies in knowledge trends and knowledge manipulation for an initially researcher proficiency-poor product category; the proficiency had to be build-up throughout the project period. It aims at helping the user quickly identify the rotorcraft developing trends.

5. ACHIEVEMENT: The rotorcraft vehicle design case study uses the AVD contract with Airbus Helicopter to teach the users how to quickly establish a functional knowledge base starting from zero knowledge accumulation. It helps researchers quickly identify the rotorcraft disk loading development history to accelerate the rotorcraft configuration evaluation processes. It demonstrates AVD^{KBS}'s advantages by completing the design trend deductions.

7.2 Original Research Contribution

This research contributes to aerospace science by addressing the following fundamental research objectives:

1. Objective: Survey, investigate, and categorize the past KBS developments from the earliest developments in 1984 to the present.

Contribution: Conclude KBS development patterns and note the necessity of making knowledge as the key concern in knowledge management. It proposes the conception of forming a closed loop process for knowledge management, consisting of knowledge storage, education, application and innovation.

2. Objective: Propose the methodology for developing AVD^{KBS} and implement it by developing a functional KBS.

Contribution: For the first time, categorize knowledge into three groups according to its formats and representations. Propose and develop three groups of knowledge management functions according to the three knowledge categories. Those knowledge management functions are implemented through AVD^{KBS} both working alone and working with existing AVD toolsets.

3. Objective: Validate and demonstrate the efficiency advantages of AVD^{KBS} through case studies.

Contribution: In order to evaluate the efficiency differences of knowledge management methods, a quantification parameter, the *Efficiency Index*, has been derived. This index has been proposed based on the analysis of the characteristics of the parties involved in the knowledge application processes. The efficiencies of knowledge management methods are compared in three aspects: knowledge analysis, knowledge trend and knowledge manipulation. The launch vehicle design and rotorcraft vehicle design case studies use concrete knowledge application examples to demonstrate the efficiency advantages of AVD^{KBS} in knowledge management.

7.3 Research Outlook

Future AVD^{KBS} developments are classified into two categories: near term development and long term development.

7.3.1 Near Term Development

The near term development refers to the AVD^{KBS} upgrades which can be finished within a comparatively short period, like half a year.

The first proposed upgrade is knowledge reasoning. Although the current existing AVD^{KBS} prototype is equipped with a trend predicting function, which helps a user to predict the potential design trend based on past project data, this trend predicting process is not completely automatic. A user needs to select parameters for the trend predicting, then AVD^{KBS} can finish the successive design trend deduction process. The proposed knowledge reasoning is a knowledge innovating process during which AVD^{KBS} independently identifies parameters with potential relationships and finishes the design knowledge deduction process. After that, it can either apply the new knowledge into parametric sizing analysis process or update it into the knowledge base as a reference.

The second proposed upgrade is intelligent advising. The AVD^{KBS} prototype process and software can only passively accept requests from a user, and finishes the assigned tasks. However, it is possible that the requests from the user are not always reasonable because of either personal deficiencies, like lack of profound understandings of the design missions, or external factors, like carelessness. An improved AVD^{KBS} system should be able to actively interact with the user about unreasonable requests, which are judged by the comprehensive knowledge accumulations in the knowledge base.

7.3.2 Long Term Development

The long term development refers to the AVD^{KBS} upgrades which are planned but cannot be finished in a comparatively short period because of lack of necessary technologies.

Like other AI researcher being inspired by HAL 9000 from *2001: A Space Odyssey*, which "… *is capable of speech, speech recognition, facial recognition, natural language processing, lip reading, art appreciation, interpreting and reproducing emotional behaviors, automated reasoning, and playing chess* …" [(163)], AVD researchers work on implementing an AI design environment to intelligently support the decision making process of aerospace vehicle development during the early conceptual design stage. AVD^{KBS} is an important component in AVD AI design environment. It should be equipped with advanced knowledge enriching mechanism, consisting of automatic documents screening, text parsing and knowledge extracting technologies. However, these technologies are still under development, like AeroText [(125)]. If AVD^{KBS} can be upgraded with the advanced knowledge enriching mechanism based on the above technologies, it can independently utilize the huge amount of aerospace vehicle design documents and become the most powerful tool in supporting the conceptual design decision making process.

Appendix A

Knowledge-Based System Literature Search

Table A-1 KBS Early Preparation literature search

Title	Year	Author	Field	Contribution
Knowledge base system in computer aided technology [101]	1984	Gilmore, John F.	Computer science	System requirements discussion of a KBS and their relevance with computer-aided technology
Architectures and hardware systems: parallel inference machine and knowledge base machine [164]	1984	Murakami, Kunio et al	Computer science	Preliminary research on inference engine and knowledge base for forming the core of the fifth generation computer systems
On the development of a knowledge base for the general systems problem solver [165]	1985	Hai, Abdul	Computer science	Research on framework of the general systems problem solver - reconstructability analysis for the study of relationships between wholes and their various parts
Experimental distributed microprocessor-based knowledge base system [166]	1985	Fu Tong	Computer science	Investigate the developing environment for KBS supporting knowledge sorting/merging, retrieving, joining, inference, and ultimately automatic programming
A Model and an architecture for a relational knowledge base [167]	1986	Yokota, Haruo; Itoh, Hidenori	Computer science	Propose architecture of a knowledge base, supporting retrieval and a variety of knowledge representations
Profile of a geometrical knowledge base for CAD-system [168] s	1986	Bigelmaier, Anton	Computer science	Investigate the descriptions of geometrical knowledge in CAD-system knowledge base building, including rule knowledge and method knowledge
Research and development of knowledge base system at ICOT [169]	1986	Itoh, Hidenori	Computer science	Propose several models for building knowledge base from viewpoint of logic programming
Knowledge base for structural design [170]	1986	Das, Mukti L. et al	Mechanical Engineering	Discuss knowledge base formalization and the components of the expert system for structural engineering design
Xplane, a knowledge-based driven process planning expert system [171]	1986	Erve, A.H et al	Mechanical Engineering	Propose prototype structure and functions of a knowledge-based system on automatic process and planning in part manufacturing
Toward an expert system for chromosome analysis [102]	1987	Q. Wu et al	Electrical Engineering	Propose a framework for the automatic chromosome classification analysis based on knowledge based system
KRINE: a knowledge base system with frame-based logic programming mechanisms [103]	1987	Ogawa, Yutaka et al	Industrial Engineering	Invent a knowledge representation and inference environment KRINE, mainly introduces its design objectives and mechanisms
On creating the scientific knowledge base for computer-assisted analysis and design of electric apparatus [172]	1988	Tozoni, O.V.	Electrical Engineering	Investigate the purposes and functions, structure and content of a knowledge base in scientific theoretical research in the electromagnetic fields
Generalized knowledge base [173]	1989	Rui, Zhang et al	Civil Engineering	Present a structure for generalized knowledge base
Outline of a knowledge-base model for an intelligent information retrieval system [174]	1989	Marie-France Bruandet	Computer science	Propose an outline to automatic construct a knowledge base, including methods and a domain knowledge model
Framework for building rule-based machine diagnostic expert systems [175]	1989	Francis Cheong et al	Mechanical engineering	Propose a rule-based machine diagnostic expert system architecture for diagnosis of sophisticated equipment in microchip manufacturing
Systematic knowledge base design for medical diagnosis [176]	1989	Senyk, Oksana	Biomedical Engineering	Propose a methodology for building knowledge base for medical knowledge
Framework of knowledge-based systems - Multiple meta-level architecture for representing problems and problem-solving [177]	1990	Setsuo Ohsuga	Computer science	Propose a framework of a knowledge-based system for dealing with various problems, focusing on nature of problem representation and process representation

Table A-2 KBS Independent System literature search

Title	Year	Author	Field	Contribution
VLSI logic design with logic programming and knowledge base technology (178)	1988	Hamada, Nobuhiro et al	Electrical Engineering	An knowledge-based system with logic programming and object oriented frame together for MPU-type VLSI logic design
A knowledge base system for power cable design (104)	1990	El-Kady, M.A. et al	Electrical Engineering	Build a knowledge base system for power cable design with two purposes: aiding experienced designer and educate novice engineers
Integrating human factors/ergonomics in facilitating the design/analysis of consumer products. A computerized knowledge-based system (179)	1990	Diaz, Eileen et al	Industrial engineering	Build a knowledge base system for consumer products design, providing design information, guidelines and dimensions
Knowledge base for retaining wall rehabilitation design (106)	1990	Adams, Teresa M et al	Geotechnical engineering	Build a knowledge base system for storing knowledge on diagnostic knowledge for infer failure mechanisms, design knowledge for identify rehabilitation strategies and evaluation knowledge for analyze design adequacy and estimate costs
DRILL: a standardized radiology-teaching knowledge base (180)	1991	Rundle, Debra A. et al	Bio-engineering	Build a knowledge-based digital radiology image learning system
Integrated electronic knowledge base/workstation (181)	1991	Lindenlaub, John C.	Electric engineering	Build a knowledge base system for teaching electronic courses
Knowledge base design for flexible assembly robots (182)	1991	Offodile, O. Felix et al	Mechanical engineering	Build a knowledge base system for choosing assembly robot for mechanical assembly.
Knowledge-based system for material selection for design with new materials (183)	1991	Hans-Jiirg Bullinger et al	Mechanical engineering	A knowledge-based system to supports the designer in selecting the optimal material, observing given technical standards of the cured component.
Knowledge base for designing casing strings (184)	1992	Heinze, Lloyd R.	Petroleum Engineering	Build a knowledge based system for casing design, helping select proper casing elements
A Knowledge-based Expert System for Unsteady Open Channel Flow (185)	1992	K. W. CHAU et al	Civil Engineering	Build a knowledge-based system to aid engineers in design the open channel flow modeling
A knowledge-based system for power system weekly scheduling (105)	1992	Stipe Fustar et al	Electric engineering	A knowledge-based system for weekly power system operation scheduling, including load prediction, inflow prediction, storage hydro production, unit commitment and so on.
A knowledge base for alloy and process selection for casting (186)	1993	Sirilertworakul, N. et al	Mechanical Engineering	Build a knowledge based system for selecting casting alloys and process
Heuristic knowledge-based approach to runoff estimation in Midwestern states using a SCS curve number method (187)	1994	Yoon, Jaewan et al	Civil Engineering	Build a knowledge base containing regional rainfall parameters for runoff estimation
A knowledge base for finite element mesh design (188)	1994	Dolsak, Bojan et al	Mechanical Engineering	Build a knowledge based system on deciding the appropriate mesh resolution
Knowledge-base management system for mine design and evaluation (189)	1994	Huang, Xin et al	Mining Engineering	Build a knowledge based system on design of backfill mining operations, using hydraulic transportation system design as an example
Knowledge-based cabin crew pattern generator (190)	1994	Lam-For Kwok et al	Computer science	A knowledge-based system for designing cabin crew patterns according to flight schedules
Speech understanding and dialog system with a homogeneous linguistic knowledge base (191)	1994	Marion Mast et al	Computer science	Presents a speech understanding and dialog knowledge-based system EVAR

Continued Table A-2

Generation of operation sequences for accident restoration of primary substations based on a re-usable knowledge base [192]	1995	Qianren Zhang et al	Computer science	Propose a knowledge-based system to generating operation sequences for accident restoration in primary substations
Knowledge Base for Chip Management System [193]	1995	X.D. Zhang et al	Mechanical engineering	Construct a knowledge base to predict the extent of chip breaking
Improving design and fabrication of bridges using knowledge base [194]	1995	Amin Hammad et al	Civil Engineering	Build a knowledge base to support the decision-making process for improving both bridge design and fabrication
Establishing a knowledge base for bridge aesthetics [195]	1996	Moore, C.J. et al	Structural engineering	Build a preliminary knowledge base for assessing the aesthetics of small to medium size road bridges
A knowledge based advisory system for acid/base titrations in non-aqueous solvents [196]	1996	M. Bos et al	Chemical engineering	Build a knowledge-based system to aid the choose of solvent and titrant for acid/base titrations in nonaqueous media
A fuzzy knowledge base for dynamic image understanding [197]	1996	Yukiko Nakagawa et al	Computer science	Build a knowledge-based system to aid the picture understanding process, abstract moving objects and its dynamic movements
An integrated knowledge-based system for urban planning decision support [198]	1997	Feng Shan et al	System engineering	Build a knowledge-based system to make the urban planning decisions
Knowledge-based expert system for damage assessment and vulnerability analysis of structures subjected to cyclones [199]	1997	T.L. Murlidharan et al	Structure Engineering	Build a knowledge-based system to provide advice for damage assessment and vulnerability analysis of structures subjected to cyclones
A fuzzy knowledge-based system for railway traffic control [200]	2000	Alexander Fay	Information engineering	Build a knowledge-based system to help railway operation control service
A knowledge-base for electronics soldering [201]	2000	S.M. Darwish et al	Mechanical Engineering	Knowledge-based system for electronics soldering, including: materials for soldering, soldering processes, cleaning for soldering, and trouble shooting for soldering
Development of a knowledge-base for automatic monitoring of renal function of intensive care patients over time [202]	2000	Bernhard Heindl et al	Mechanical Engineering	Developed a knowledge-base for the dynamic monitoring of renal function of critically ill patients to detect any significant deterioration of kidney function
EULE: A Knowledge-Based System to Support Business Processes [203]	2000	U. Reimer et al	Computer science	Develop a knowledge-based system to increase the efficiency and quality of office task performance
Construction of a knowledge base for ergonomic design with human models [204]	2000	Jung, Eui S. et al	Industrial Engineering	Develop a knowledge base to evaluate the ergonomic design, providing designers with design alternatives
Method for designing CAM system based on feature and knowledge base [205]	2000	Qiao, Liang et al	Mechanical engineering	Build a knowledge-based system to aid the design of CAM systems, which consists of four parts: tools, manufacturing parameters, thread manufacturing and manufacturing features and operations
Systematization of design knowledge on failure and construction of knowledge base for aiding design [206]	2001	Tamura, Yasuhiko et al	Mechanical engineering	Build a knowledge base system for preventing design failures
CKB - The Compound Knowledge Base: A Text Based Chemical Search System [207]	2002	Matthew J. Walker et al	Chemical engineering	Build a compound knowledge base system to quickly provide compound information to researchers based on queries
The Development of Object-Oriented Knowledge Base and Adaptive Motion Planning for Autonomous Mobile Robots [208]	2001	Ren C. et al	Electrical Engineering	Present a knowledge-based system to aid the Motion planning for autonomous mobile robot
Knowledge-based system for alternative design, costing estimating and scheduling [107]	2002	Abdulrezak Mohamed et al	Civil engineering	Develop a knowledge-based system for construction cost estimating and scheduling, including on line schematic drawing, material selection, crew selection and productivity analysis

Table A-3 KBS Integrated System literature search

Title	Year	Author	Field	Contribution
Knowledge-based systems in the design of a new parceling (142)	1996	A.M. Buis et al	Geodetic Engineering	Develop a knowledge-based system to be combined with an existing Geographical Information System to support increasingly difficult parceling design task
Knowledge-based assessment of watershed condition (209)	2000	Keith M. Reynolds et al	Forest Ser6ice	Develop a knowledge-based system to work with a geographic information system to provide an analytical tool for environmental assessment and monitoring
Knowledge-based engineering in the mold base design and its key technology (210)	2002	Lou, Zhen-Liang et al	Mechanical engineering	Build a knowledge based system for mold design, integrated with database and using neural network as the process method
Study and realization of the knowledge base system supporting collaborative design and simulation (211)	2004	Wang, Danni et al	Mechanical engineering	Build a knowledge based system using object-oriented method, data mining, XML technologies for collaborative design and simulation
Energy based decision support system for facilities management: integration of data/web mining, knowledge base and thermal simulation (108)	2007	Malkawi, Ali et al	Civil engineering	Integrate existing KBS with a thermal simulation engine and local databases to provide a decision support function for the selection of replacement building features.
A common sense geographic knowledge base for GIR (212)	2008	Zhang Yi et al	Geographic engineering	Propose a whole geographic system including database, knowledge base, and inference engine.
Design and Implementation of Knowledge Base for Target Recognition in Remote Sensing Images (109)	2010	Shaobin Chen et al	Mechanical Engineering	Build a knowledge-based system to work with remote sensing module to perform target recognition tasks
Knowledge base of computer-aided system for design of safe ship power plants (213)	2010	Kowalewski, Tomasz et al	Naval Engineering	Build a knowledge base system to work with a hazard zone identification system for the ship power plants
Foundation of near-miss knowledge base for metro projects (214)	2010	Xiaopeng Deng et al	Civil engineering	Develop a knowledge-based system to work with database to help improve the safety management capability of metro construction and avoid metro accidents
Document based knowledge base engineering method for ship basic design (215)	2011	Ying-Han Wun et al	Naval engineering	Build a knowledge-based system for basic ship design, including user interface, knowledge base, inference engine, database
Research on the knowledge base system of rolling bearings (216)	2011	Xianzhao Jia et al	Mechanical engineering	Build a knowledge based system for rolling bearings intelligent design, including KBS,DBS, process
A knowledge-based decision support system for shipboard damage control (217)	2012	F. Calabrese, A. Corallo et al	Information engineering	Present a knowledge-based system incorporated in the damage control systems to assist crew members in the effective handling of dangerous events and accidents

Table A-4 KBS New Frontier literature search

Title	Year	Author	Field	Contribution
A knowledge-based systems for marking professional IT skills examinations[218]	2003	Stewart Long et al	Computer Science	Develop a knowledge-based system to automatically assess IT skills
Construction of the knowledge-based of a web-based analysis system for stamping process [219]	2003	Zheng Sui et al	Mechanical engineering	Develop a web-based knowledge-based system to satisfy different users' stamping process
Implementing a web-based knowledge base for a construction company: industry-academia collaboration [220]	2004	Suckariech, George et al	Construction Management	Build a web-based knowledge base for documenting and transferring internal knowledge within a company
Municipal solar energy knowledge base for policy making [221]	2005	Pavlovski, A. et al	Solar Energy	Build a knowledge base on solar energy with three spatial scales: regional, municipal and local for renewable energy policy decision making
Ideological conflict – notes on the development of a commonsense knowledge base about ideologies [222]	2006	Todorova, Yana	Computer Science	Use the knowledge representation language A-Prolog to build a commonsense knowledge base for ideologies conflict
Knowledge Base Design for Network Service Composition Using Semantic Web Languages [223]	2006	Nobuhide Nishiyama et al	Computer Science	Build a knowledge base using Semantic Web languages for QoS service
Popcorn: the personal knowledge base [224]	2006	Stephen Davies et al	Mechanical Engineering	Propose rationale and build knowledge base for documenting mental knowledge to help record and retrieve mental conceptions
Design of a clinical knowledge base for heart disease detection [225]	2007	Kim, Kihyeon et al	Information Technology	Build a knowledge base system for diagnosing ECG and heart disease using semantic web technology
A web-based customer support knowledge base system [111]	2008	Wood, S. et al	Computer Science	Build an on-line help support system based on a KBS to diagnose users' problems
Automatic determination of sleep stage through bio-neurological signals contaminated with artifacts by a conditional probability of the knowledge base [226]	2008	Bei Wang et al	Information Engineering	Presents a knowledge-based system an automatic sleep-stage determination
A mobile knowledge management decision support system for automatically conducting an electronic business [110]	2008	W. Wen et al	Business Management	Presents a mobile knowledge management decision support system for automatically providing efficient solutions for decision making and managing an electronic business
Development of Knowledge Base of Fault Diagnosis System in Solar Power Tower Plants [227]	2009	S. Guo et al	Power Engineering	A knowledge-based system of Fault Diagnosis System is designed and developed to use in Solar Power Tower plants according to the characteristics of structure and operation of Solar Power Tower plant
A Formal Model of User Knowledge Base Systems in Intelligent Tutoring Systems [228]	2010	SUN Yu et al	Information Engineering	Presents a knowledge-based system for intelligent tutoring
A daylighting knowledge base for performance driven façade design exploration [229]	2011	Naudet, Yannick et al	Illuminating Engineering	A knowledge-based system contains information on climate-based luminance and glare metrics to aid façade design in both visual performance and visual comfort of daylighting performance
Construction of knowledge base for clothing sensory design [230]	2011	Hong Lu et al	Textile Engineering	Build a knowledge base system for clothing sensory design, and a case study for man's suit is conducted
Detection emotion in social affective situations using the emotinet knowledge base [231]	2011	Balahur, Alexandra et al	Computer Science	Build a knowledge base system to detect social affective situations from texts and chains of actions, gathering knowledge from international survey
Emotional Knowledge Base Based on Information Granule [232]	2011	Jun Hu, Chun Guan	Computer Science	Develop a knowledge-based system to express the emotional knowledge

Continued Table A-4

Design of fertilization recommendation knowledge base and application (233)	2012	Ren, Zhouqiao et al	Agriculture	Build a knowledge based system to provide easily customized advice to different location production practices on the needed amount of nutrition during crop growth
Design of artificial climate chamber control system for food crops cultivation based on expert knowledge base (234)	2012	Li, Zhihui et al	Information Engineering	Build a knowledge based artificial climate chamber control system for food crops cultivation
A Knowledge-based Customization System for Supply Chain Integration (235)	2012	C.F. Cheung et al	Information Engineering	Develop a knowledge-based system to obtain quantified actionable information and formulate strategies for supply chain configuration leading to the long term success
Constructing a nutrition diagnosis expert system (236)	2012	Yuchuan Chen et al	Biomedical Engineering	Build a web-based knowledge-based system to help researchers adapt to the newly introduced concept of nutrition diagnosis

Table A-5 Aerospace Engineering KBS literature search

Title	Year	Author	Contribution
Knowledge-based analysis and design systems for aerospace structures [114]	1985	J.R. Zumsteg et al	Investigate the integrating problems of linking knowledge-based system with existing analysis code
A knowledge-based system engineering process for obtaining engineering design solutions [237]	2005	Brian Pradad et al	Propose a knowledge-based system architecture for obtaining engineering design solution in a commercial setting.
A knowledge-based engineering approach to automation of conceptual design option selection [238]	2007	E.J. Schut et al	Propose a partial automation approach for multidisciplinary analysis and optimization steps based on knowledge-based system
A knowledge-based engineering tool to estimate cost and weight of composite aerospace structures at the conceptual stage of the design process [116]	2007	Jin-Woo Choi et al	Develop a knowledge-based system for estimating manufacturing cost and weight of a composite structure
Enhancing product development through knowledge-based engineering [239]	2009	Angelo Corallo et al	Investigate knowledge-based systems potentiality in new product development, showing the performance improvement when knowledge-based systems involved
Knowledge-based engineering approach to support aircraft multidisciplinary design and optimization [115]	2009	Gianfranco La Rocca et al	Discuss the architecture and functionalities of knowledge-based system to record and automate complex engineering design process
Enhancing knowledge sharing in "Fuzzy Front End" of NPD: an aerospace case study [240]	2010	Corallo, Angelo et al	Develop a knowledge-based system for knowledge transfer within an aerospace company
A knowledge-based approach to design automation of wire and pipe routing through complex aerospace structures [241]	2011	Christian Van Der Velden et al	Present a knowledge-based system for automatic path-finding for aircraft electrical harness and pipe routing

Appendix B

AVD^{KBS} User Guide

This document details the most common ways to use the knowledge management functions in AVD[KBS]. It mainly consists of the manipulation introductions to the AVD[KBS] GUIs in which the knowledge management functions are built.

1. Start

In order to use AVD[KBS] knowledge management functions, the user needs to get to the Matlab **Main Starting Panel** at first**.** There are two methods to start the **Main Starting Panel**.

i). From Matlab **Command Window**

- In the **Command Window**, type **guide**.
- Go to the **Open Existing GUI** tab in the **GUIDE Quick Start** window and click the **Browse** button.

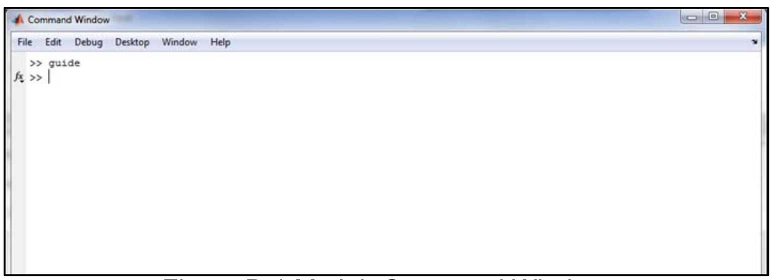
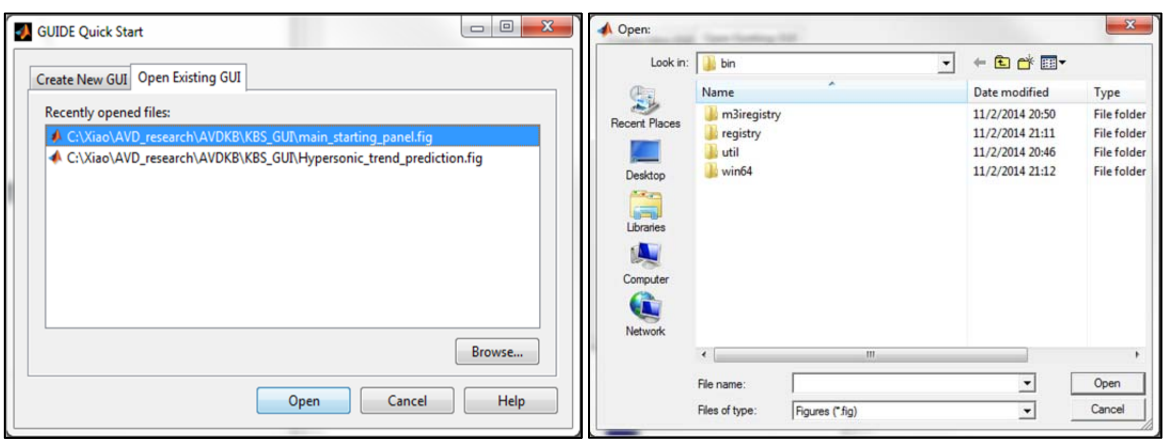


Figure B-1 Matlab Command Window

- In the Open window, locate and select the **main_starting_panel.fig file**.
- Then click **Open** button.



(a) (b)

Figure B-2 (a) GUIDE Quick Start Window, (b) Locate Main-starting-panel in Open Window ii). From Matlab **Editor**

- In Matlab Editor, Click **File** and select **Open…**
- Locate the script **main_starting_panel.m** file in the Open window.
- Click the **Open** button and run it.

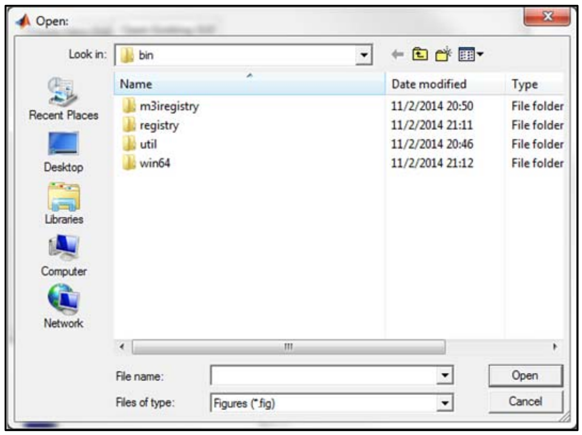
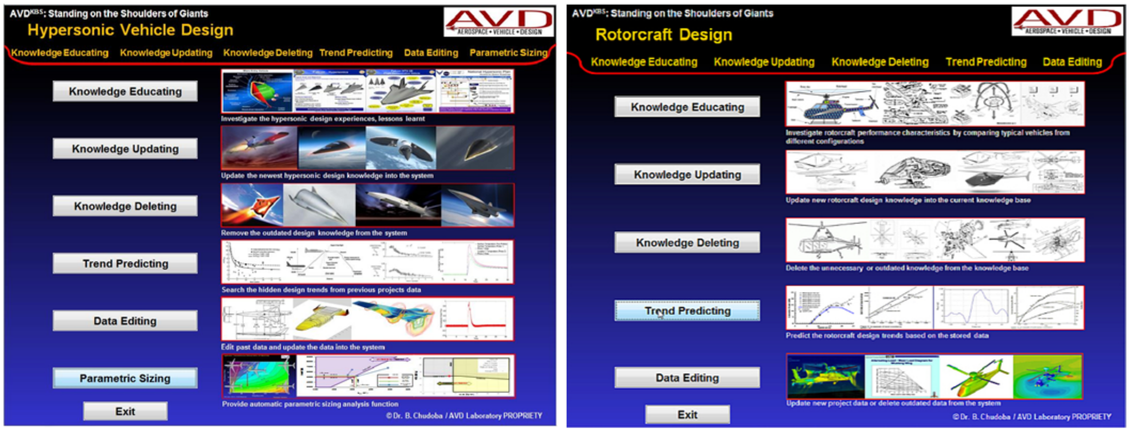


Figure B-3 Use Open Window to Locate main_staring_panel.m File

After the above processes, the Main Starting Panel pops up.

Figure B-4 Main Starting Panel

Choose from either of the two case studies: Hypersonic Vehicle Design and Rotorcraft Vehicle Design. It will lead the user to the case study starting panel. From the case study panel, the user can choose the knowledge management functions: Knowledge Educating, Knowledge Updating, Knowledge Editing, Trend Predicting, Data Editing and Parametric Sizing Analysis.



(a) (b)

Figure B-5 (a) Hypersonic Vehicle Design Starting Panel, (b) Rotorcraft Vehicle Design Staring Panel

2. Knowledge Management Functions

There are seven knowledge management functions in AVD[KBS].

i). Knowledge Educating.

Knowledge Educating helps the user search and retrieves the current knowledge from AVD[KBS] for knowledge education and reference purposes.

The function process is:

Figure B-6 Knowledge Educating GUI

- o Select the knowledge field from the **Discipline** pull-down menu
- o Select the knowledge of interest from the **Knowledge** pull-down menu
- o Click **Educate** button.

Then the content of the selected knowledge will pop up.

The detailed GUI function explanations can be found in the help document by clicking **HELP** button.

ii). Knowledge Updating.

Knowledge Updating helps the user update new knowledge into AVD^{KBS} to keep it up-to-date.

The function process is:

- Input all of the knowledge content into the according textboxes in the **Knowledge Updating** GUI, such as **Discipline**, **Author**, **Reference**, **Design Phase**, and so on.
- Click **Update** button to finish the update process.

The detailed GUI function explanations can be found in the help document by clicking **HELP** button.

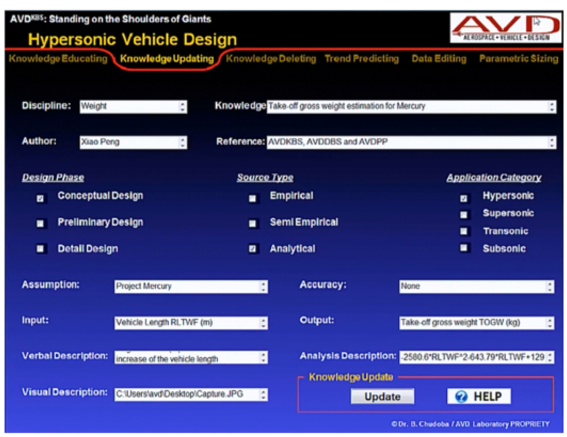


Figure B-7 Knowledge Updating GUI

iii). Knowledge Deleting

Knowledge Deleting helps the user remove the outdated or unnecessary knowledge from AVD^{KBS}.

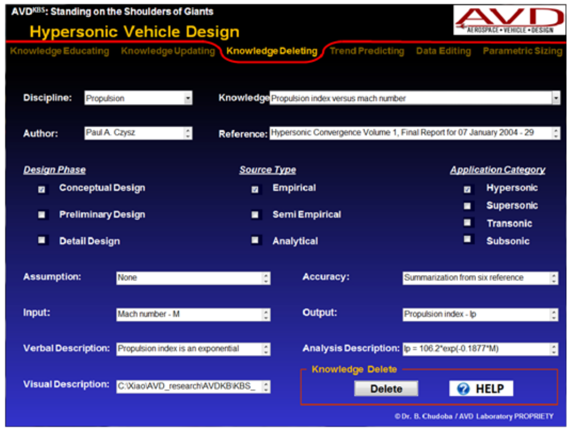


Figure B-8 Knowledge Deleting GUI

The function process is:

- Select the knowledge field from the **Discipline** pull-down menu
- Select the piece of knowledge from the **Knowledge** pull-down menu
- Check the knowledge content to confirm it is the knowledge to be deleted
- Click **Delete** button to remove the knowledge from AVD^{KBS}.

The detailed GUI function explanations can be found in the help document by clicking **HELP** button.

iv). Trend Predicting

Trend Predicting helps the user deduct the design trend based on past project data and design experiences.

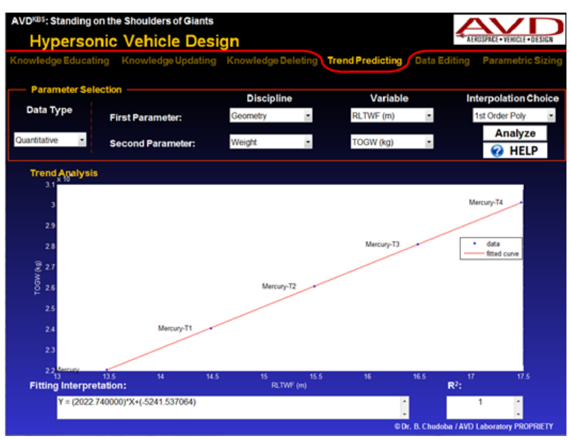


Figure B-9 Trend Predicting GUI

The function process is:

- Select the data type from **Data Type** pull down menu: **Qualitative** or **Quantitative.**
- Select the first parameter discipline from the **Discipline** pull-down menu.
- Select the first parameter from the **Variable** pull-down menu.
- If necessary, finish the same process for the second parameter.
- Choose the interpolation method from the **Interpolation Choice** pull-down menu.
- Click **Analysis** button to start the design trend prediction process.
- After the prediction process is finished, the fitting figure will be displayed in the **Trend Analysis**, and the fitting explanations will be displayed in the **Fitting Interpretation** textbox, and coefficient of determination will be displayed in from **R^2** textbox.

The detailed GUI function explanations can be found in the help document by clicking **HELP** button.

v). Data Updating

Data Updating helps the user update the new data into AVD^{DBS} to keep the project data up-to-date.

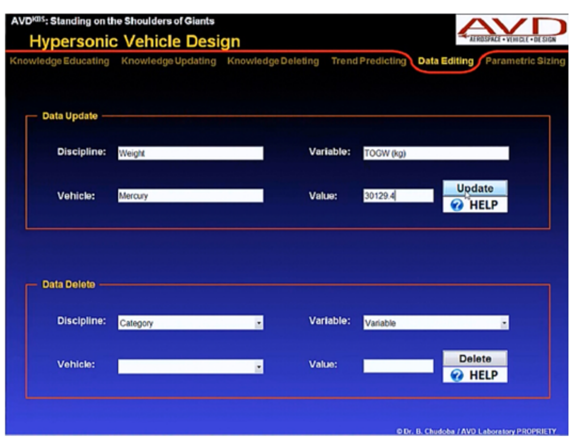


Figure B-10 Data Updating GUI

The function process is:

- o Input the necessary data information into the according textboxes: **Discipline**, **Variable**, **Vehicle** and **Value**.
- o Click the **Update** button to update it into AVD^{DBS}.

The detailed GUI function explanations can be found in the help document by clicking **HELP** button.

vi). Data Deleting

Data Deleting helps the user remove the outdated or wrong data from AVD^{KBS}.

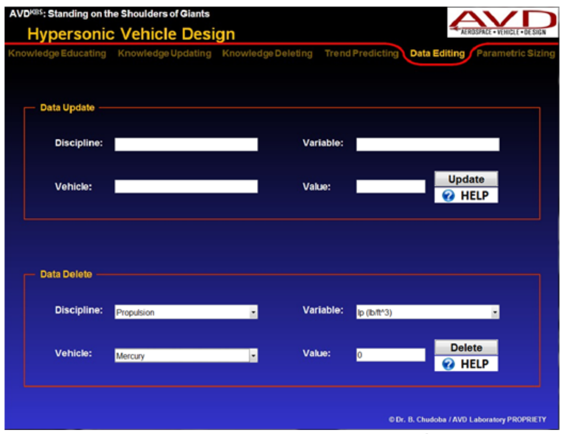


Figure B-11 Data Deleting GUI

The function process is:

- o Select the discipline of the data from the **Discipline** pull-down menu
- o Select the parameter from the **Variable** pull-down menu
- o Select the vehicle to which the data belongs from the **Vehicle** pull-down menu
- o Check the numerical value of the data in the **Value** textbox to confirm the selected data is the one to be removed.
- o Click the **Delete** button to delete it from AVD^{KBS}.

The detailed GUI function explanations can be found in the help document by clicking **HELP** button.

vii). Parametric Sizing Analysis

Parametric Sizing Analysis helps the user finish the parametric sizing analysis.

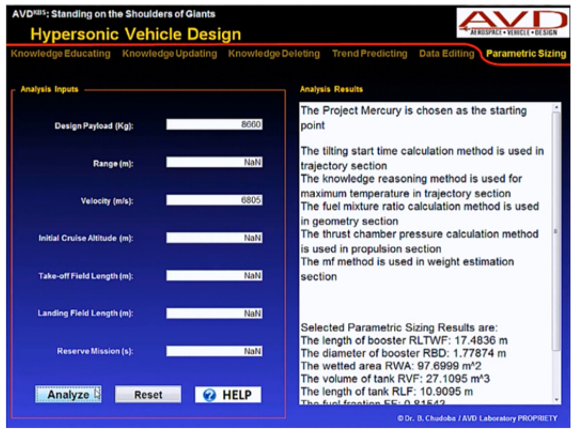


Figure B-12 Parametric Sizing Analysis GUI

The function process is:

- Fill in the mission requirements in the according textboxes, including **Design Payload, Range, Velocity, Initial Cruise Altitude, Take-off Field Length, Landing Field Length** and **Reserve Missions.**
- If the user needs to restart the design mission input process, click **Reset** button
- Click the **Analyze** button to start the parametric sizing analysis process.
- Check the analysis results from the **Analysis Results** textbox.

The detailed GUI function explanations can be found in the help document by clicking **HELP** button.

An overview of the AVD^{KBS} GUIs is the following:

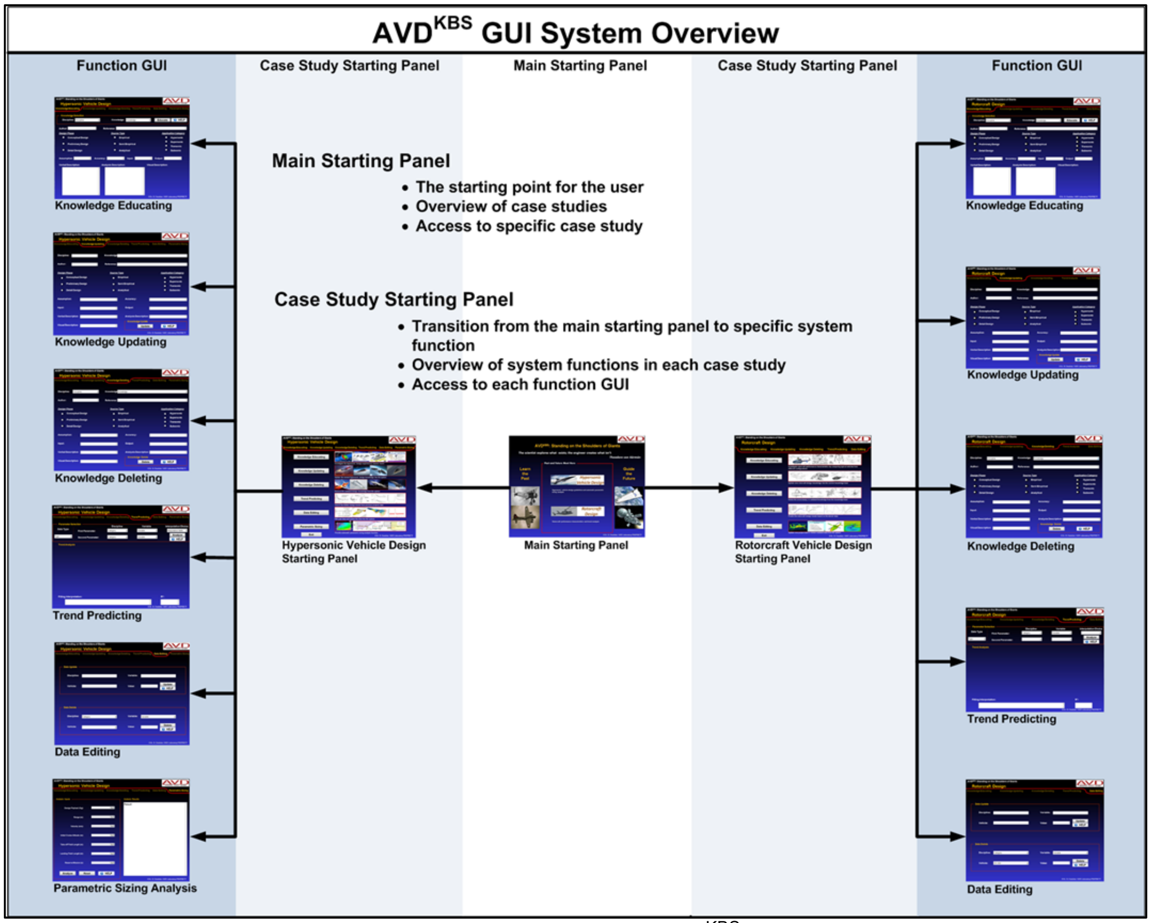


Figure B-13 Overview of AVD^{KBS} GUI

3. Combined Functions

When those basic knowledge management functions work together, more complex knowledge management functions can be achieved.

i). Knowledge Editing.

Knowledge Editing aims at helping the user change the content of the current knowledge in AVD^{KBS}.

The function process is:

- o Delete the current knowledge from the knowledge base using the **Knowledge Deleting** function.

- Prepare the edited knowledge.
- Update it into AVD^{KBS} using the **Knowledge Updating** function as a new piece of knowledge.

ii). Data Editing

Data Editing aims at helping the user change the value of the current data in AVD^{DBS}.

The function process is:

- Delete the current data from the system using the **Data Deleting** function.
- Prepare the edited data.
- Update the edited data into the system using the **Data Updating** function as a new data.

iii). New knowledge generation through trend predictions.

It aims at helping the user update new knowledge, which is generated through the trend predicting process, into AVD^{KBS}.

The function process is:

- Deduct the design trend knowledge based on past project data and design experiences using the **Trend Predicting** function.
- Summarizing the knowledge content.
- Update it into AVD^{KBS} using the **Knowledge Updating** function

iv). New knowledge generation through parametric sizing analysis

It aims at helping the user update new knowledge, which is generated through the parametric sizing analysis, into AVD^{KBS}.

The function process is:

- Finish the parametric sizing analysis using the **Parametric Sizing Analysis** function.
- Update the analysis results into the system using the **Data Updating** or **Knowledge Updating** functions.

- Deduct the new design trend knowledge based on past project data and design experiences using the **Trend Predicting** function
- Summarizing the knowledge content.
- Update it into AVD^{KBS} using the **Knowledge Updating** function

4. HELP document

In order to explain the GUI setup to the user in detail, for each GUI, a **HELP** document is prepared. It can be accessed through the **HELP** button in the GUI.

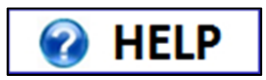


Figure B-14 HELP Button

In the following sections, the **HELP** documents for each knowledge management function will be introduced.

i). Knowledge Educating GUI HELP document

This GUI is for the **Knowledge Educating** function. It aims at helping fresh engineers quickly learn the stored knowledge from AVD^{KBS}.

Figure B-15 Knowledge Selection Section

For the **Knowledge Selection** section, it helps the user select the knowledge of interest: it uses two steps to locate a piece of knowledge, including **Discipline** and **Knowledge**. The **Discipline** pull down menu specifies the category to which the Knowledge belongs to, and the **Knowledge** pull down menu lists the title of the knowledge.

Figure B-16 Educate Button

After the user finishes the selection and hits the **Educate** button, the knowledge content will be displayed in the knowledge details section.

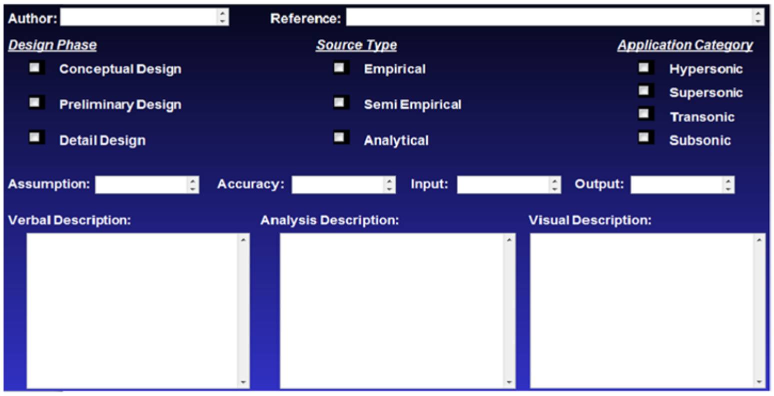


Figure B-17 Knowledge Details Section

Knowledge Details shows the detail information of the selected knowledge. It shows the **Author**, **Reference**, **Design Phase**, **Source Type**, **Application Category**, **Assumption**, **Accuracy**, **Input**, **Output**, **Verbal Description**, **Analysis Description** and **Visual Description** of the knowledge.

ii). Knowledge Updating GUI HELP document

This GUI is for the **Knowledge Updating** function. It aims at helping the user update new knowledge into the AVD^{KBS}.

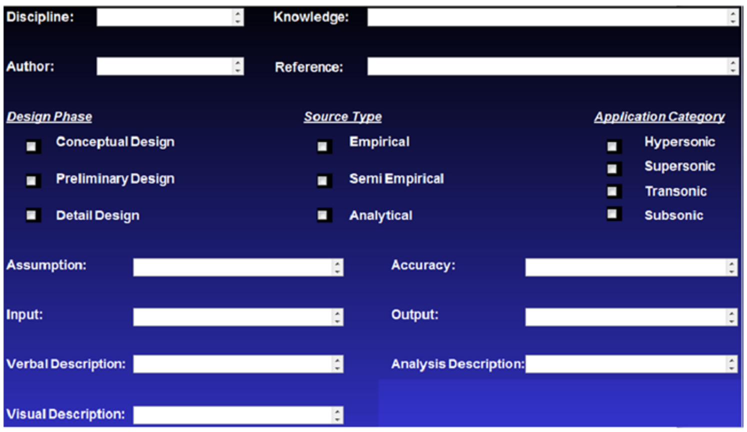


Figure B-18 Knowledge Update Section

In the update area, eleven textboxes and ten checkboxes are used to fill in all of the knowledge content, which is going to be updated into the system. The user can choose to fill out all or some of them.

Figure B-19 Update Button

After inputting all the necessary information, the user should click the **Update** button. Then the new knowledge will be updated into AVD^{KBS}.

iii). Knowledge Deleting GUI HELP document

This GUI is for the **knowledge deleting** function. It aims at helping user remove the unnecessary knowledge from AVD^{KBS}.

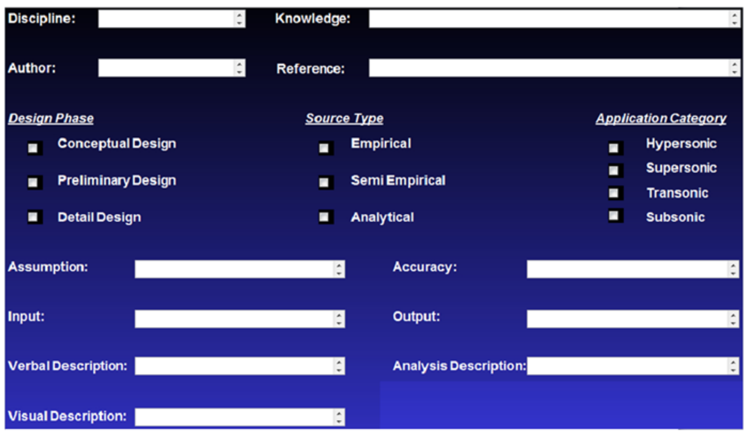


Figure B-20 Knowledge Selection and Confirmation Section

The user follows the two-step selection process: the **Discipline** and **Knowledge**, to locate a specific knowledge. The **Discipline** pull down menu specifies the category to which the knowledge belongs; The **Knowledge** pull down menu lists the title of the knowledge. After the user selects the knowledge, its content will be displayed, which helps the user confirm whether it is the knowledge to be deleted.

After the confirmation, the user needs to click the **Delete** button and the selected knowledge will be removed from AVD^{KBS}.

Figure B-21 Delete Button

iv). Trend Predicting GUI HELP document

This GUI is for the **Trend Predicting** function. It aims at helping the user to deduct the unknown design trend from the past project data.

It has two sections: **Parameter Selection** and **Trend Analysis**.

Figure B-22 Parameter Selection Section

For the **Parameter Selection**, the user needs to choose **Data Type** at first. If the **Qualitative Data** type is chosen, the user just needs to choose one parameter in the following parameter selection process. The parameter selection process has two steps: **Discipline** and **Variable**. The **Discipline** pull down menu lists the category to which the **Variable** belongs to; the **Variable** pull down menu specifies the parameters of interest. The user follows the two steps to locate the parameter. If the **Quantitative Data** type is chosen, the user needs to choose two parameters. After that, the user needs to select the **Interpolation Method**. It provides five interpolation methods: **1st order polynomial, 2nd order polynomial, 3rd order polynomial, exponential** and **power**. After finishing the **Interpolation Method** selection, the user needs to click the **Analyze** button. Then the AVD^{KBS} will finish the trend analysis process and make trend predictions. The prediction results will be displayed in the **Trend Analysis**

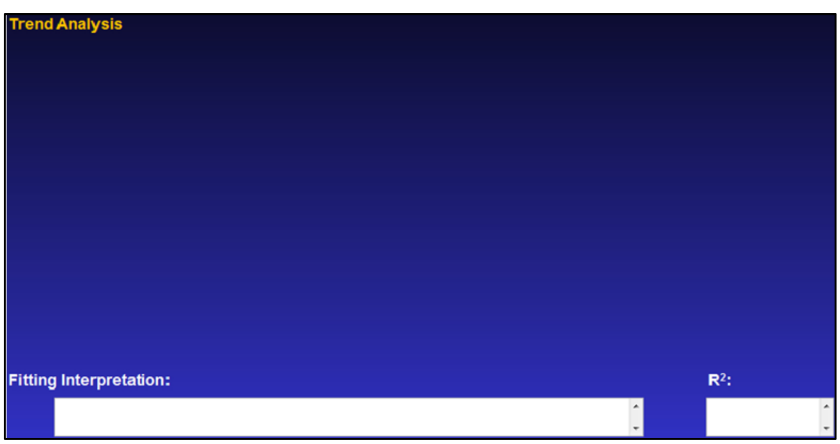


Figure B-23 Trend Analysis Section

section.

In the **Trend Analysis** section, the system displays the predicted trend curve.

For **Qualitative Data Type**, the **Fitting Expression** shows the AVD^{KBS} observations of the selected **Variable**: maximum value, minimum value and average value; for the **Quantitative Data Type**, the **Fitting Expression** displays the fitting equation of the selected two variables, and the $\mathbf{R^2}$ shows how good the fitting is.

v). Data Editing GUI HELP document

This GUI is for the **Data Editing** function. It aims at helping the user to update or remove the vehicle data from AVD^{DBS}.

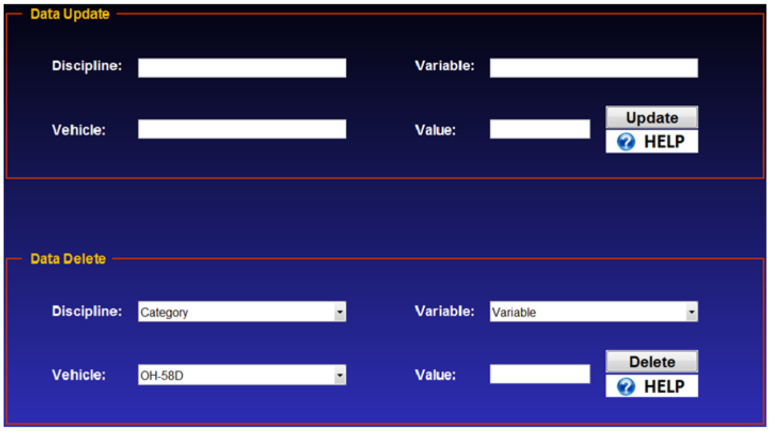


Figure B-24 Data Update and Data Delete

It has two sections: **Data Update** and **Data Delete**.

For the **Data Update** section, the user should fill out all of the blanks for the new vehicle data, including **Discipline**, **Variable**, **Vehicle** and **Value**: **Discipline** specifies the field to which the **Variable** belongs; **Variable** stands for the parameter name of the data; **Vehicle** shows the project name to which the data belongs; **Value** is the numerical description of the **Variable**. After the input, the user clicks the **Update** button and the new data will be updated into AVD^{KBS}.

Figure B-25 Update Button.

In the **Data Delete** section, the user selects the unnecessary vehicle data and deletes it. The user selects the data by choosing **Discipline**, **Variable** and **Vehicle**. After the user selected the **Vehicle**, the according numerical value will be displayed in the **Value** blank. Then the user can double check whether it is the data that needs to be deleted. Once it is confirmed, the user needs to hit the **Delete** button to remove the selected data from AVD^{DBS}.

Figure B-26 Delete Button.

vi). Parametric Sizing HELP document

This GUI is for the **Parametric Sizing Analysis** function. It aims at helping the user finish the parametric sizing analysis.

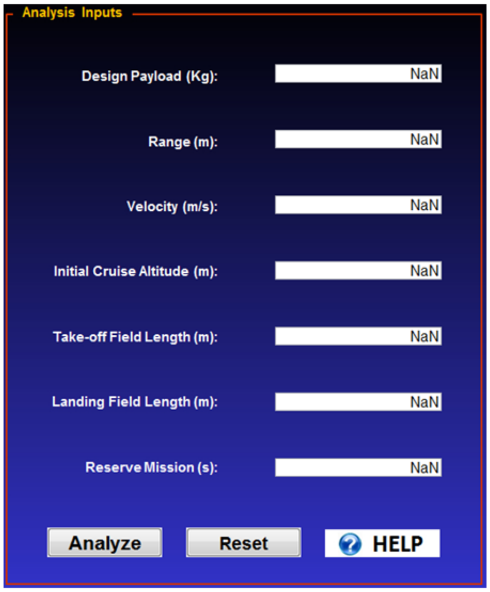


Figure B-27 Analysis Inputs Section

It has two sections: the **Analysis Inputs** and the **Analysis Results**

In the **Analysis Inputs** section, the user needs to input the mission requirements for the analysis, including **Design Payload (Kg)**, **Range (m)**, **Velocity (m/s)**, **Initial Cruise Altitude (m)**, **Take-off Field Length (m)**, **Landing Field Length (m)** and **Reserve Missions (s)**. The user is not required to fill out all of them, and he/she can just select the ones which are important to the mission. After that, the user clicks the **Analyze** button and the system will start the analysis process. The **Reset** button helps the user to clear all of the previous inputs.

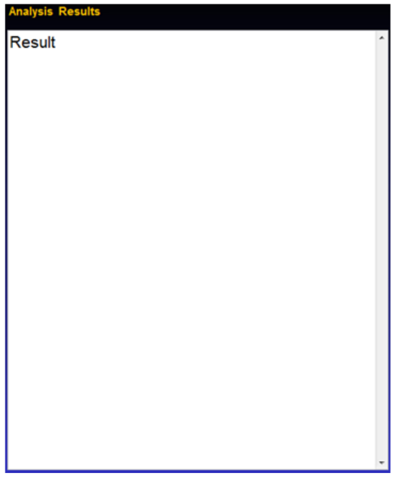


Figure B-28 Analysis Results Section.

In the **Analysis Results** section, it displays the analysis results. The results consist of three parts: the first part illustrates which vehicle is selected as the starting point; the second part states the knowledge that has been used in the current analysis process; the third part introduces the parametric sizing results.

Appendix C

AVD^{KBS} Developer Guide

The developer guide introduces the technical development approaches used in building the AVD^{KBS}. It includes the programming logic, GUI setup and decoration methods, and knowledge base structure definitions. All of those development detail explanations are organized in three sections: Development in Matlab GUI, which explains the development techniques used in building the GUI; Development in Matlab, which illustrates the development techniques used in building the inference engine; Development in Excel, which introduces the development techniques used in building the knowledge base.

1. Development in Matlab GUI

This section introduces the GUI setup methods and decoration techniques.

i). Start building the GUI

In order to start building the Matlab GUI, it needs to open a blank GUI at first. The method is:

- Start Matlab, and in the command window, type **guide**.
- Go to the **Create New GUI** tab, and select the **Blank GUI(Default)** from the **GUIDE Quick Start** window.
- Then click **OK** at the bottom right corner of the panel.

Figure C-1 Use Command Window to Start the Black Matlab GUI

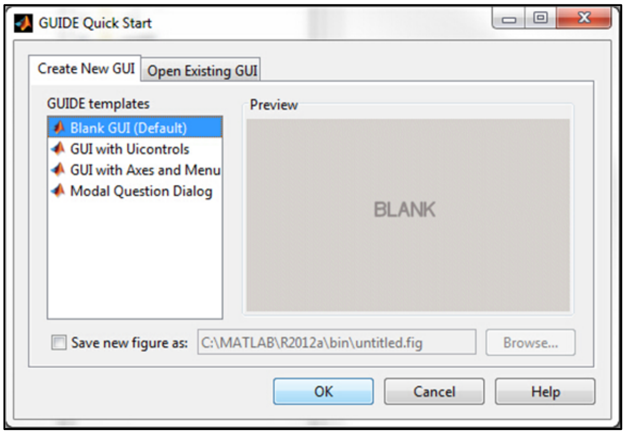


Figure C-2 Select the Blank GUI from the GUIDE Quick Start Window

ii). GUI Components used in AVD^{KBS}

In the black Matlab GUI, the following GUI components are used in the AVD^{KBS} development process.

a). Push Button

Figure C-3 Push Button

It is a trigger button for certain function. It receives the command from the user and begins the function implementation process, such as searching the desired knowledge, starting the analysis process, and removing the knowledge from AVD^{KBS}.

The name of **Push Button** can be changed to any word that the user wants.

b). Textbox

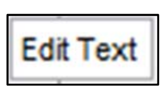


Figure C-4 Edit Text

It is an input place for the user and output place for the AVD^{KBS}. It receives the input from the user and transfers it to AVD^{KBS}, such as mission requirements and knowledge update information; it also receives the output from AVD^{KBS} and displays it to the user, such as parametric sizing analysis results, analysis interpretation, and knowledge searching results.

c). Check Box

Figure C-5 Check Box.

It is an on/off selection GUI for both the user and the AVD^{KBS}. It receives the selection from the user and transferred it to AVD^{KBS}, and it also displays the AVD^{KBS} analysis results and shows them to the user. It is mainly used to specify the certain property of the vehicle, such as the design stage: conceptual design, preliminary design or detail design.

The name of **Check Box** can be changed to any word that the user wants.

d). Pop-up Menu

Figure C-6 Pop-up Menu

It provides the user with a series of choices to select. It receives the selection from the user and transfers it to the system. It is mainly used to take the user's selection, such as the knowledge of interest.

The content of the **Pop-up Menu** can be edited by user, and it can be any word.

e). Axes

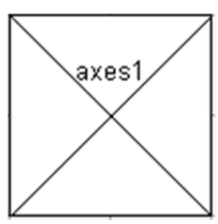


Figure C-7 Axes

It provides a place to displace the output from AVD^{KBS}, such as searching or analysis results and the trend predicting figure.

it's the other function is to decorate the other GUI tools, such as the GUI background and push buttons. It can use other figures to cover the previous Matlab plain

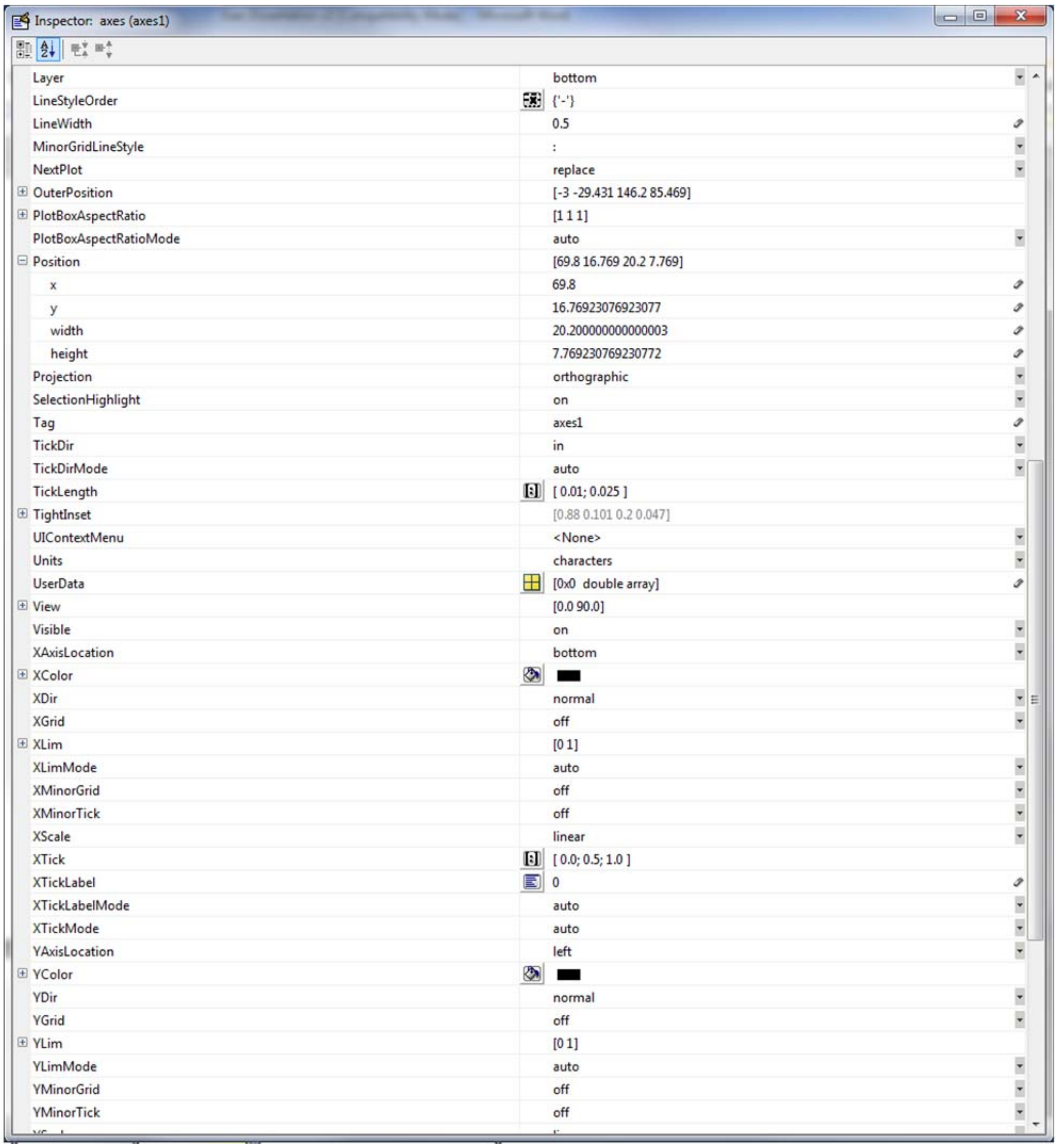


Figure C-8 GUIs Editor – Inspector

backgrounds, which makes the GUIs look much better.

The edit tool for those GUI components is labeled **Inspector**, and it can be activated by double clicking the GUI component.

The most used items in the Inspector are:

- **Positon**: it uses x and y to specify the location of GUI component, and uses width and height to determine the size of the GUI component.
- **Units**: it is used to determine the unit in measuring the location and size of the GUI. It offers six choices: **centimeters, inches, normalized, pixels, points** and **characters**.
- **Font**: it offers the developer the freedom to choose the font size, weight and type.
- **Color**: it allows the developer to determine the color of the GUI component.

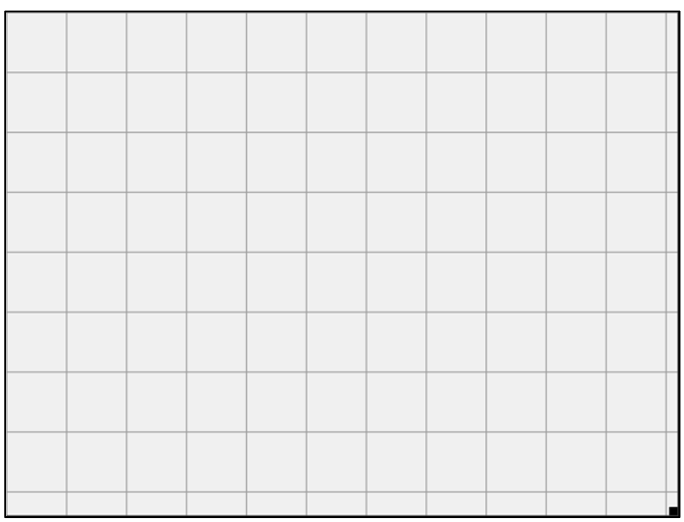


Figure C-9 Original GUI Background

There are also many other properties, which help the developer to customize the GUI component, and they are different from component to component. The developer can change them according to their needs.

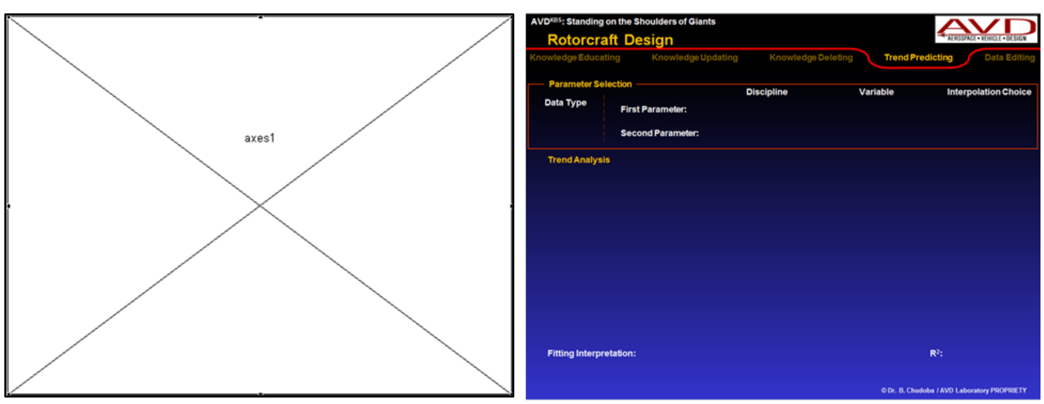
iii). GUI Decoration

The original GUI look is quite boring and can't display background information (Fig C-9). The GUI Decoration can replace the original backgrounds with the user defined pictures and display necessary background information.

The decoration process is:

- o Create an **Axes**, and adjust its size to the that of the GUI, which needs to be decorated.
- o Use it to cover the whole GUI.
- o Use the Matlab programming to choose the figure, which should be displayed as the new background. The detailed programming process will be introduced in the Development in Matlab section.

The following is an example of the background change.



(a) (b)

Figure C-10 (a) GUI before Decoration, (b) GUI after Decoration

From the example, it is obvious to see in the new background, its look improves considerably and it can display much more information.

The same decoration method can be applied to the **Push Buttons**, and it gives them a much better look.

Figure C-11 Push Button Decoration

2. Development in Matlab

This section introduces the Matlab programming techniques used in the AVD^{KBS} development and they are mainly used in the Matlab GUI and inference engine building.

i). Matlab GUI programming

The Matlab GUI programming includes the programming to implement the GUI component function and the GUI decoration.

a) Push Button

It is a trigger for certain function. The programming leads the analysis process to other functions. There are two types:

The first type is the **Push Button** is connected to another m. file. Then in the programming, the m. file name is directly included.

```
% --- Executes on button press in pushbutton2.
function pushbutton2_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
hypersonic_starting_panel;
handles = guihandles(gcf);
```
Figure C-12 Programming of Connecting the Push Button to Another m. File

In the Fig C-12's example, the 'hypersonic_starting_pannel' is the name of the m. file.

```
% --- Executes on button press in pushbutton1.
function pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
global content_var
[~,raw,~] = xlsread('C:\Xiao\AVD_research\AVDKB\KBS_GUI\hypersonic_knowledge_base.xlsx');
dataInfo = raw(2:end,:);
[a,b] = size(dataInfo);
i = 1;
while i <= a
    if strcmp(dataInfo(i,3),content_var)
        kno_fig = i;
        break;
    end
    i = i+1;
end

dataInfo = raw(2:end,4:end);
global con_aut
con_aut = dataInfo(kno_fig,1);
set(handles.edit1,'String',con_aut);
global con_ref
con_ref = dataInfo(kno_fig,2);
set(handles.edit2,'String',con_ref);
global con_def
con_def = dataInfo(kno_fig,3);
if strcmp(con_def,'Conceptual Design')
    set(handles.checkbox1,'Value',1)
elseif strcmp(con_def,'Preliminary Design')
    set(handles.checkbox2,'Value',1)
elseif strcmp(con_def,'Detail Design')
    set(handles.checkbox3,'Value',1)
end
global con_sty
con_sty = dataInfo(kno_fig,4);
if strcmp(con_sty,'Empirical')
    set(handles.checkbox4,'Value',1)
elseif strcmp(con_sty,'Semi Empirical')
    set(handles.checkbox5,'Value',1)
elseif strcmp(con_sty,'Analytical')
    set(handles.checkbox6,'Value',1)
end
global con_aca
con_aca = dataInfo(kno_fig,5);
if strcmp(con_aca,'Hypersonic')
    set(handles.checkbox7,'Value',1)
elseif strcmp(con_aca,'Supersonic')
    set(handles.checkbox8,'Value',1)
```

Figure C-13 Programming of the Push Button with Built-in Functions

The second type is the **Push Button** has the built-in functions. Once it is clicked, the functions are going to be run.

The Fig C-13 shows the programming of **Educate** push button which directly runs the searching process.

b) Textbox

It is an input place for the user and output place for the AVD^{KBS}. When it receives the input from the user, the programming is written to take the input. The programming process is:

- Define a parameter.
- Use the parameter to store the input information from the user.

```
function edit3_Callback(hObject, eventdata, handles)
% hObject    handle to edit3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
global con_tit
con_tit = get(hObject, 'string');
```

Figure C-14 Programming of the Textbox Receiving Input from the User

When the **Textbox** displays the output to the user, there is no programming necessary within the GUI itself. The content is directly assigned to the **Textbox** at the end of other analysis processes.

c) Check Box

It is an on/off selection function for both the user and AVD^{KBS}. It receives the selection from the user and transfers it to the system, and it also receives the AVD^{KBS} analysis results and displays them back to the user.

```
% --- Executes on button press in checkbox1.
function checkbox1_Callback(hObject, eventdata, handles)
% hObject    handle to checkbox1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
global con_cod;
con_cod = get(hObject,'Value');
% Hint: get(hObject,'Value') returns toggle state of checkbox1
```

Figure C-15 Programming of the Check Box Receiving Input from the User

When it is used to take the input from the user, the programming process is:

- Define a parameter.
- Use the parameter to store the input from the user.

When the **Check Box** displays the output to the user, there is no programming necessary within the GUI itself. The content is directly assigned to the **Check Box** at the end of other analysis processes.

d) Pop-up Menu

It provides the user with a series of choices to select. It receives the selection from the user and transfers it to the system. The programming is finished within the opening function of each GUI. In the opening function, the content of the pop-up menu is directly assigned.

```
% --- Executes just before hypersonic_knowledge_education is made visible.
function hypersonic_knowledge_education_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to hypersonic_knowledge_education (see VARARGIN)

% Choose default command line output for hypersonic_knowledge_education
handles.output = hObject;

h=imread('C:\Xiao\AVD_research\AVDKB\KBS_GUI\question-mark-150x150.jpg');
set(handles.pushbutton2,'CData',h);

[~,raw,~] = xlsread('C:\Xiao\AVD_research\AVDKB\KBS_GUI\hypersonic_knowledge_base.xlsx');
dataInfo = raw(2:end,2:end);
set(hObject,'UserData',dataInfo);
direction = dataInfo(:,1);
str1 = {'Discipline'};
str2 = {'Knowledge'};
i =1;
while ~isempty(direction)
    i = i+1;
    str1(i) = direction(1);
    direction(strcmpi(direction(1),direction)) =[];
end

set(handles.popupmenu2,'string',str1);
set(handles.popupmenu3,'string',str2{1});
setappdata(hObject,'str1',str1);
setappdata(hObject,'str2',str2);
```

Figure C-16 Programming of the Pop-up Menu

```
axes(handles.axes2)
[f,g] = fit(var11,var22,'power2');
equ = sprintf('Y = (%0.5g)*X^(%0.5g)+(%0.5g)',f(1),f(2),f(3));
set(handles.edit1,'String',equ);
set(handles.edit2,'String',g.rsquare);
plot(f,var11,var22);
```

Figure C-17 Programming of the Axes to Display a Figure

In the above example, the analysis process first reads the content from an Excel file “hypersonic_knoweldge_base,xlsx”. Then it assigns the content to the pop-up menu using the **set** function.

e) Axes

It provides a place to displace the figure from the system search or analysis results. It receives the output from AVD^{KBS} and displays it to the user. The programming method is:

- Define parameters to take the analysis output.
- Plot it in the axes using **plot** function.

Its another function is to decorate other GUI tools, such as the GUI background and **Push Button**s. It can use other figures to cover the previous backgrounds, which make the GUIs look much better. The programming method is:

- Import in the figure location information using **importdata** function.
- Display it using **image** function.

```
backgroundImage = importdata('C:\Xiao\AVD_research\AVDKB\KBS_GUI\hypersonic_knowledge_educaton.jpg');

axes(handles.axes1);

image(backgroundImage);

axis off
```

Figure C-18 Programming of the Axes to Decorate Push Buttons ii). Inference engine programming

The inference engine programming is the process of building the inference engine and implementing its functions, such as searching, logical judging, and reasoning.

a) Information transfer between GUIs

```
% --- Executes on selection change in popupmenu6.
function popupmenu6_Callback(hObject, eventdata, handles)
% hObject    handle to popupmenu6 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
global typ_sel
```

Figure C-19 An Example of Defining a Global Parameter in the GUI

The information transfer between GUIs is the process of one GUI passing information to another one. The method is to define the global parameter in both GUIs. In this way, the parameter can be used in both GUIs.

b) Retrieve information from knowledge base

The knowledge base is built in Excel, so the information retrieval process is to read information directly from Excel using **xlsread** function.

```
[~,raw,~] = xlsread('C:\Xiao\AVD_research\AVDKB\KBS_GUI\hypersonic_knowledge_base.xlsx');
dataInfo = raw(2:end,2:end);
```

Figure C-20 Programming of the retrieving knowledge from Excel file

Its application can be found in the Pop-up menu section.

```
while i <= a
    if strcmp(dataInfo(i,3),content_var)
        kno_fig = i;
        break;
    end
    i = i+1;
end
```

Figure C-21 Programming of the Searching Process using While Function

c) Search knowledge within knowledge base

The search process is a type of breadth-first search. It first searches the knowledge discipline. After it finds the matching discipline, it begins to search the knowledge. All of the search processes use the **while** function.

d) Update knowledge into the knowledge base

The update process inputs the knowledge from the user into AVD^{KBS}. The updating function here is **xlswrite**.

```
xlswrite('C:\Xiao\AVD_research\AVDKB\KBS_GUI\hypersonic_knowledge_base.xlsx',dataInfo,1,'B2')
```

Figure C-22 Programming of the Updating Process using xlswrite Function

e) Delete knowledge from the knowledge base

The knowledge deleting process includes two parts: firstly, it finds the knowledge that needs to be deleted, which is a searching process; secondly, it deletes the knowledge from the knowledge base. The deleting programming method is it replaces the previous knowledge content with the blanks **“”**.

```
for k = 1:b
    dataInfo(row,k) = cellstr('');
end
for i = row:a-1
    for j = 1:b
        dataInfo(i,j) = dataInfo(i+1,j);
    end
end

for j = 1:b
    dataInfo(a,j) = cellstr('');
end
```

Figure C-23 Programming of the Knowledge Deleting Process

f) Trend predicting

The trend predicting process uses the retrieved information from AVD^{KBS} to figure out a fitting expression for the unknown trend. The programming method is:

- o Use the **fit** function to calculate the fitting results.
- o Use **sprintf** function to display the fitting expression.
- o Uses **plot** function to display it in the GUI.

```
[f,g] = fit(var11,var22,'poly3');
equ = sprintf('Y = (%0.5g)*X^3+(%0.5g)*X^2+(%0.5g)*X+(%0.5g)',f(1),f(2),f(3),f(4));
set(handles.edit1,'String',equ);
set(handles.edit2,'String',g.rsquare);
plot(f,var11,var22);
```

Figure C-24 Programming of the Knowledge Predicting Process

g) Knowledge application

Knowledge application uses the stored knowledge to solve the unknown parameter during the parametric sizing analysis process. The programming method is:

- o Read the methods list from the knowledge base using **xlsread** function.

```
if isnan(TILT_START)
    [number,source,raw]=xlsread('C:\Xiao\AVD_research\AVDKB\variable_method.xlsx');
    variable = source(:,1);
    method = source(:,2);
    index = strmatch('TILT_START',variable);
    funcxx = method(index);
    funcxx = char(funcxx);
    funcxx = str2func(funcxx);
    TILT_START = funcxx();
    fid=fopen('C:\Xiao\AVD_research\AVDKB\output.txt','a');
    fprintf(fid,'The tilting start time calculation method is used in trajectory section\r\n');
    fclose(fid);
end
```

Figure C-25 An example of Knowledge Application Programming

- o Compare the unknown parameter with the methods list to figure out the right knowledge method using **strmatch** function.
- o Apply the selected method using **str2func** function.

All of the Matlab function explanations can be found by using the **help** function. In the Matlab command window, type **help** plus the function name to which you have questions, such as **help sprintf**. The detailed explanations will be displayed in the command window.

3. Development in Excel

This section introduces the knowledge base development process. The knowledge base is developed in Microsoft Excel and this section mainly talks about the structure of the knowledge base.

An overview of part of the current knowledge base is:

The whole knowledge base can be considered as a two-dimension matrix: for the column, it includes the content of each piece of knowledge, such as **Discipline, Author, Reference,** and **Design Stage**; for the row, each row stands for a piece of knowledge.

Based on this structure, the knowledge base can be easily expanded. The developer can add more content to each piece of knowledge by adding more columns to the knowledge base; and the developer can also add more pieces of knowledge into the

1	Project	Discipline	Content Name	Author	Reference	Design phase	Categoriz	Speed	Assur	Accuracy	Input	Output	Verbal	Analytical	Visual
2	TSTO	Propulsion	Specific impulse variation for f	Jr. H.D.	Fusion-Ele	Conceptual Des	Analytical	Hypersoni	Excluc	Data taker	Mach number	Specific Impulse	The fusion	SI = -0.0002	C:\Xiao\A
3	SSTO	Geometry	Wing sweep angle versus macl	Paul A. (	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Mach number - M	Wing sweep angle - Lambda	The wing s	Lambda = 0.	C:\Xiao\A
4	TSTO	Cost Estimati	Cost of payload versus flights	Paul A. (	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Flights per year - fpy	Cost of payload - cop	The cost o	If fpy < =10	C:\Xiao\A
5	SSTO	Propulsion	Propulsion index versus mach	Paul A. (	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Mach number - M	Propulsion index - Ip	Propulsior	Ip = 106.2*	C:\Xiao\A
6	TSTO	Propulsion	Propellant volume/area (Planf	Paul A. (	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Propulsion index - Ip	Propellant volume/planform Area	The prope	For planforr	C:\Xiao\A
7	SSTO	Geometry	Structure index versus kucherr	Paul A. (	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Kuchemann's tau - tau	Structure index - Kstr	Structure i	Kstr = 0.317	C:\Xiao\A
8	TSTO	Weight	OEW versus total volume	Paul A. (	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Total volume - Vtot	OEW - oew	OEW is an	oew = 0.56!	C:\Xiao\A
9	SSTO	Geometry	Geometry characteristic versu	Paul A. (	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Kuchemann's tau - tau	Geometry characteristic - K_tau	The geom	K_tau = exp	C:\Xiao\A
10	TSTO	Geometry	Engine minimum height versus	Paul A. (	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Planform Area - Sp (ft^2)	Engine minimum height - h2 (ft)	The engin	For Sp < 22	C:\Xiao\A
11	SSTO	Geometry	Spatular nose width paramete	Paul A. (	Hypersoni	Conceptual Des	Empirical	All speed r	None	Summariz	Planform Area - Sp (ft^2)	Spatular nose width parameter - C	The spatul	Cs = 0.0002	C:\Xiao\A
12	TSTO	Aerodynamic	Zero lift drag characteristic ver	Paul A. (	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Kuchemann's tau - tau	Zero lift drag characteristic - Cd0	The zero li	Cd0 = 0.14*	C:\Xiao\A
13	SSTO	Aerodynamic	L/D increment versus mach nu	Paul A. (	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Mach number - M	L/D increment - delta_ld	The L/D in	delta_ld = -C	C:\Xiao\A
14	TSTO	Trajectory	Climb distance versus cruise s	Paul A. (	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Cruise speed - cs (ft/sec)	Climb distance - cd (nautical mile)	The climb	cd = 185.53	C:\Xiao\A
15	SSTO	Trajectory	Descent distance versus cruise	Paul A. (	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Cruise speed - cs (ft/sec)	Descent distance - dd (nautical mil	The desce	dd = 164.06	C:\Xiao\A
16	TSTO	Aerodynamic	Lift to drag ratio versus drag c	Paul A. (	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Drag coefficient - Cd	Lift to drag ratio - ld	The lift to	ld = 0.17*Cc	C:\Xiao\A
17	SSTO	Propulsion	Weight ratio of TOGW to burni	Paul A. (	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Incremental airbreathing	Weight ratio of TOGW to burningc	The weigh	Tobw = 7.5!	C:\Xiao\A
18	TSTO	Propulsion	Weight ratio at takeoff versus	Paul A. (	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Maxium airbreathing mac	Weight ratio at takeoff - wrto	The weigh	wrto = -9.07	C:\Xiao\A
19	SSTO	Trajectory	Weight ratio required to chang	Paul A. (	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Maxium airbreathing mac	Weight ratio required to change fr	The weigh	wrcc = -2.3E	C:\Xiao\A
20	TSTO	Trajectory	Thrust drag ratio versus maxiu	Paul A. (	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Maxium airbreathing mac	Thrust drag ratio - TD	The thrust	For mab<8T	C:\Xiao\A
21	SSTO	Trajectory	Oxidizer fuel ratio versus maxi	Paul A. (	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Maxium airbreathing mac	Oxidizer fuel ratio - OF	The oxidiz	For mab<1.	C:\Xiao\A
22	TSTO	Trajectory	Weight ratio from takeoff to gi	Paul A. (	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Mach number - M	Weight ratio from takeoff to given	The weigh	For M<1.3w	C:\Xiao\A
23	SSTO	Propulsion	Frictional thrust loss versus w	Paul A. (	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Wetted area (ft^2) - Swet	Frictional thrust loss (%) - ftl	The frictio	ftl = 0.675*	C:\Xiao\A
24	TSTO	Propulsion	Average transonic Isp versus v	Paul A. (	Hypersoni	Conceptual Des	Empirical	Transonic	None	Summariz	Vehicle average transonic	Average transonic Isp - ati	The avera	For ttw<0.5	C:\Xiao\A
25	SSTO	Propulsion	Thrust loss versus planform ar	Paul A. (	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Planform Area - Sp (ft^2)	Thrust loss - tl	The thrust	tl = 449.73*	C:\Xiao\A
26	TSTO	Weight	Launch gross weight versus pr	Paul A. (	Hypersoni	Conceptual Des	Empirical	Hypersoni	None	Summariz	Propulsion system thrust	Launch gross weight - lgw (Mg)	The launch	For 20 lbm/	C:\Xiao\A

Figure C-26 A Partial Overview of the Knowledge Base current knowledge base by adding more rows into the knowledge base.

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