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Systems Thinker's Toolbox

Tools for Managing Complexity

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Contents

List of Figures

List of Tables

Preface

This is not another book about systems thinking; this is a book on how to actually do it. This book provides you with the tools for systems thinking and solving problems, and if you use them, you will have an advantage over those who are not using systems thinking.

This book is written for a wide audience. It's written for people like you who are struggling to deal with the day-to-day problems they face in life. If you're a student, a project manager, a systems engineer, or just somebody who needs to tackle problems, this book provides a desk reference of more than 100 tools and examples of how to use them.

Some of the tools are widely known, others have been around for a while but are not so widely known, several of the tools are not even associated with systems thinking, and some of the tools are original coming out of the research that I've been doing for the last 30 years.

The story begins in 1981 when I talked myself into my first job as a project manager. The project succeeded but according to all traditional approaches and measurements the project should have failed. It took me years to realise that the project succeeded because I was using the systems approach without realizing it.

All the tools, original and otherwise, have been used successfully in the real world as well as in the classroom. For example, after I introduced CRIP Charts in my postgraduate class on software engineering at University of Maryland University College, towards the end of the semester one of the students told me that she was using the charts in her work and her management was absolutely delighted with them. The tools and their predecessors helped me to achieve success in my project management and systems engineering endeavours. So in this book I show you how to use the tools and how they are linked to other tools.

What is the systems approach? It's basically a problem-solving approach that looks at the problematic or undesirable situation in its context from a number of different viewpoints and then works out the root cause of the symptoms causing the undesirable situation. It then goes on to conceptualize at least two different solutions that will remove the undesirability, selects the best one and then turns it into reality. Of course, all this is supposed to be done within schedule and budget. This book will give you the tools to do the job.

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- National University of Singapore, 2008–2009 Division of Engineering and Technology Management, Faculty of Engineering Innovative Teaching Award for use of magic in class to enrich the student experience.
- Best Paper, Systems Engineering Technical Processes track, at the 16th Annual Symposium of the INCOSE, 2006, and the 17th Annual Symposium of the INCOSE, 2007.
- United States Air Force (USAF) Office of Scientific Research Window on Science program visitor, 2004.
- Inaugural SEEC "Bust a Gut" Award, SEEC, 2004.
- Employee of the Year, SEEC, 2000.
- Distance Education Fellow, University System of Maryland, 1998–2000.

- Outstanding Paper Presentation, Systems Engineering Management track, at the 6th Annual Symposium of the INCOSE, 1996.
- Distinguished Service Award, Institute of Certified Professional Managers (ICPM), 1993.
- Manned Space Flight Awareness Award (Silver Snoopy) for quality and technical excellence, for performing and directing systems engineering, NASA, 1991.
- NASA Goddard Space Flight Center Community Service Award, 1990.
- The E3 award for Excellence, Endurance and Effort, Radio Amateur Satellite Corporation (AMSAT), 1981, and three subsequent awards for outstanding performance.
- Letters of commendation and certificates of appreciation from employers and satisfied customers, including the:

    - American Radio Relay League (ARRL).
    - American Society for Quality (ASQ).
    - Association for Quality and Participation (AQP).
    - Communications Satellite Corporation (Comsat).
    - Computer Sciences Corporation (CSC).
    - Defence Materiel Organisation (Australia).
    - Institution of Engineers (Singapore).
    - IET Singapore Nework.
    - Loral Corporation.
    - Luz Industries.
    - Systems Engineering Society of Australia (SESA).
    - University of South Australia.
    - United States Office of Personnel Management (OPM).
    - University System of Maryland.
    - Wireless Institute of Australia.

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1

INTRODUCTION

The best way of solving simple and complex problems is to use the systems approach based on systems thinking. However both the systems approach and systems thinking are not taught very well. In fact, there are many things that are not taught very well in the 20th-century problem-solving paradigm. While there are indeed many tools that are taught for problem-solving, project management, and systems engineering, they are all taught as separate tools. They are not taught as interdependent tools. For example, in project management, risk management is taught as a separate process from general management or project management. Similarly, in systems engineering, risk management is taught as a separate process from mainstream systems engineering. In the real systems approach, everything is related as part of a system. While these words are often used, they not really implemented.

The literature focuses on the "what" of the systems approach, namely what it is and the benefits it bestows. This book focuses on the "how": how to use the systems approach and how to apply systems thinking by providing a set of tools. The tools in this book consist of products such as Lists (Section 9.4), processes such as the Process for Tackling a Problem (Section 11.5), and templates such as the Problem Formulation Template (Section 14.3). Because the tools are grouped in the different chapters, Section 1.6 provides an alphabetical list to facilitate locating a specific tool quickly. This book:

- Contains more than 100 different conceptual tools for solving problems.
- Is different. Not only does it teach the tools for solving problems, it relates them together; you will notice many cross references in this book.
- Provides examples of how to use many of the tools.
- Provides a number of original tools that were developed as part of the research into systems engineering and systems thinking that led to a practical approach to teaching and applying systems thinking to solve problems. I could probably write a whole book on each of those tools, but I hope I've given enough information on how to use them in the appropriate sections of this book.
- Contains a number of items included because in the course of my teaching the systems approach paradigm I often heard myself saying, "And you won't find that in the textbooks." Well, now you can find it in at least one book.
- Is written for a project managers, systems engineers, and other problem

solvers as a desk reference to provide a reminder of the tools that are available for solving different types of problems so they won't rely on their usual problem-solving tool that may not be suitable for a specific problem.
- Is written for students because I've noticed that few postgraduate students have been taught how to deal with class exercises, and many do not have any idea of how to manage the time they have available in which to do exercises (which will reflect in the real world as managing the time they have available to do projects and other tasks) using Prioritization (Section 4.6.6) and other time management tools.
- Shows how many of the tools in use today are related, and you will recognize them. However, these tools are not thought of as being part of systems thinking because they were not taught as such.
- Mentions the current non-systems approach as well as the system approach in many sections since the systems approach is different to what is currently being taught.
- Can be used by the beginner as a cookbook of tools, but the advanced systems thinker can also use the individual tools to build custom complex tools.

1.1 How to Read and Use This Book

The first section to read is the section on Systems Thinking (Section 1.4) followed by the Holistic Thinking Perspectives (HTP) (Section 10.1) and the Problem Formulation Template (Section 14.3). This order is suggested because Section 1.3 discusses systems thinking and systematic and systemic thinking, and Section 10.1 discusses the HTPs which are used throughout this book. As explained later in this book, we often make sure that everybody is viewing something from the same perspective by saying something like, "Let's make sure everybody is on the same page" (Chapter 10). Well, the set of viewpoint pages in this book, in most instances, are the different HTPs. The Problem Formulation Template (Section 14.3) helps you think through the problem before beginning to tackle it, and you will find many examples of the Problem Formulation Template in different situations throughout this book.

Each section that describes an existing tool is a descriptive summary which should provide enough information on how to use the tool and is not intended to be comprehensive. For the more complex tools, many books and Internet pages have been written about them. The original tools developed in this research however are described in more detail. If you know the name of the tool, look it up and read about it. To learn about the other tools, remember that this is a reference book, so don't read this book sequentially in a linear manner, but prepare for several passes through it. This book is non-fiction. Non-fiction books are different to fiction; stories, novels, and thrillers that are designed to be read in a linear manner from start to finish. This book is designed to help you learn and use the content in the following manner:

1. **Skim this book.** Flip through the pages. If anything catches your eye and interests you, stop, glance at it, and then continue flipping through the pages. Notice how the pages have been formatted with dot points (bulleted lists) rather than in paragraphs to make skimming and reading easier.
2. For each chapter:
    1. Read the introduction.
    2. Skim the contents.
    3. Look at the drawings and photographs.
    4. Read the summary of the chapter.
    5. Go on to the next chapter.
3. **If you don't understand something, skip it on the first and second readings.** This book uses examples from many different disciplines and domains; don't get bogged down in the details.
4. Work though this book slowly so that you understand the message in each section of each chapter. If you don't understand the details of the example, don't worry about it as long as you understand the point that the example is demonstrating.
5. Refer to the list of acronyms in Table 1.1 as necessary.
6. Visualize (Section 7.11) and create innovative solutions to complex problems using the material you have gained from this book, your reading and experience.

TABLE 1.1 Acronyms Used in this Book

AC	Actual Cost (ACWP)
ACWP	Actual Cost of Work Performed (AC)
AHP	Analytical Hierarchy Process
ATM	Automatic Teller Machine
BAC	Budget at Completion
BCWP	Budgeted Cost of Work Performed (EV)
BCWS	Budgeted Cost of Work Scheduled
BPR	Business Process Reengineering
C3	Command, Control, Communications
C3I	Command, Control, Communications, and Intelligence
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
CASE	Computer Assisted Software Engineering
CDR	Critical Design Review
CM	Configuration Management
CONOPS	Concept of Operations
CONOPS	Concept of Operations Document

COTS	Commercial-Off-The-Shelf
CPI	Cost Performance Index
CPM	Critical Path Method
CQ	Looking for a contact (seek you)
CRIP	Categorized Requirements in Process
CSV	comma-separated values
CV	Cost Variance
DMSMS	Diminishing Manufacturing Sources and Material Shortages
DOD	Department of Defense
DRR	Delivery Readiness Review
DSM	Design Structure Matrix
DSTD	Defence Systems and Technology Department
dTRL	dynamic TRL
EAC	Estimate at Completion
EDF	Engaporean Defence Forces
EV	Earned Value (BCWP)
EVA	Earned Value Analysis
ETC	Estimate to Completion
ETL	Enhanced Traffic Light
EVA	Earned Value Analysis
FCFDS	Feasible Conceptual Future Desirable Situation
FDD	Feature Driven Development
FP	Function Point
FRAT	Functions Requirements Answers and Test
HKMF	Hitchins-Kasser-Massie Framework
HTP	Holistic Thinking Perspective
ICD	Interface Specification Document
INCOSE	International Council on Systems Engineering
IRR	Integration Readiness Review
ISM	Interpretive Structural Modelling
IST	Ideas Storage Template
IV&V	Independent Validation and Verification
JIT	Just in time
KISS	Keep it Simple Stupid
MBE	Management by Exception
MBO	Management by Objectives
MBUM	Micromanagement by Upper Management
MVA	Multi-attribute Variable Analysis
NGT	Nominal Group Technique
NUS	National University of Singapore
OARP	Observations, Assumptions Risks and Problems
OODA	Observe-Orient-Decide-Act
OT&E	Operational Test and Evaluation
PAM	Product Activity Milestone
PBS	Product Breakdown Structure
PDCA	Plan Do Check Act
PDR	Preliminary Design Review
PERT	Program Evaluation Review Technique

PP	Project Plan
PV	Planned Value
PWC	Pair-wise Comparison
RFP	Request for Proposal
RTM	Requirements Traceability Matrix
QSO	Contact (communications “Q” code) exchange of messages
SEAS	Systems Engineering and Services
SEBOK	Systems Engineering Body of Knowledge
SEEC	Systems Engineering and Evaluation Centre
SDP	System Development Process
SLC	System Lifecycle
SPARK	Schedules, Products, Activities, Resources and risKs
SPI	Schedule Performance Index
SRD	System Requirements Document
SRR	System Requirement Review
SSM	Soft Systems Methodology
SV	Schedule Variance
STALL	Stay calm, Think, Analyse and ask questions, Listen and Listen
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TAWOO	Technology Availability Window of Opportunity
TBD	To Be Determined
TLC	Traffic Light Chart
TPM	Technical Performance Measure
TQM	Total Quality Management
TRIZ	Theory of Inventive Problem-Solving
TRL	Technology Readiness Level
TRR	Test Readiness Review
UDP	User Datagram Protocol
UniSA	University of South Australia
US	United States
VAC	Variance at Completion
WBS	Work Breakdown Structure
WP	Work Package

Step 1 should give you something you can use immediately. Steps 2 and 3 should give you something you can use in the coming months. Step 4 should give you something you can use for the rest of your life. Step 6 is the rest of your life.

1.2 Thinking

Thinking is the action that underlies problem-solving and decision-making. Thinking can be divided into three parts:

1. Non-systems thinking.
2. Systems thinking.

3. Critical Thinking.

Auguste Rodin's bronze casting *The Thinker*, first presented to the public in 1904, shows a seated man in a thinking pose. What is he thinking about? Nobody knows. How does he think? Nobody knows. Where do ideas come from? Nobody knows. What we do know is that thinking is a cognitive act performed by the brain. Cognitive activities include accessing, processing, and storing information. The most widely used cognitive psychology information processing model of the brain based on the work of Atkinson and Shiffrin (Atkinson and Shiffrin 1968) cited by Lutz and Huitt (Lutz and Huitt 2003) likens the human mind to an information processing computer. Both the human mind and the computer ingest information, process it to change its form, store it, retrieve it, and generate responses to inputs (Woolfolk 1998). These days we can extend our internal memory using paper notes, books and electronic storage as shown in Figure 1.1. We use our mental capacity to think about something received from a sense (hearing, sight, smell, taste and touch). From a functional standpoint our mental capacities might be oversimplified as follows (Osborn 1963: p. 1):

- ***Absorptive*** – the ability to observe, and to apply attention.
- ***Retentive*** – the ability to memorize and recall.
- ***Reasoning*** – the ability to analyse and to judge.
- ***Creative*** – the ability to visualize, to foresee, and to generate ideas.

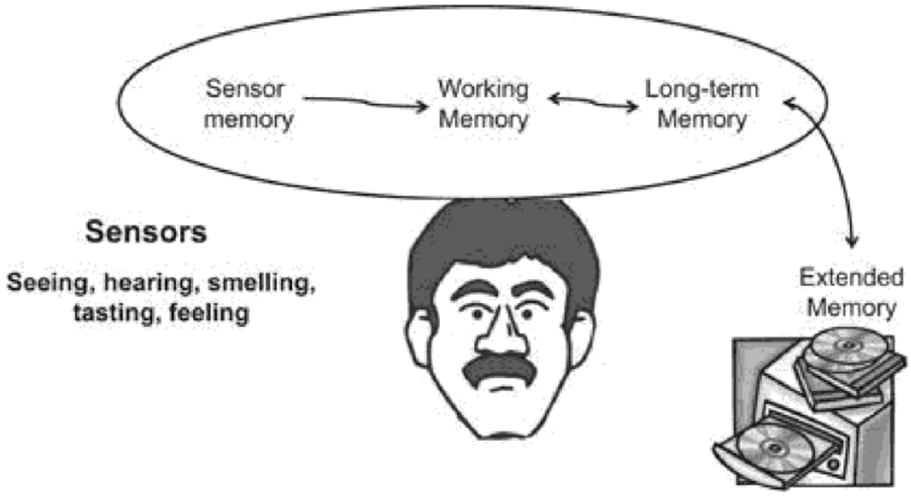

Figure 1.1 The extended human information system.

When we view the world, our brain uses a filter to separate the pertinent sensory input from the non-pertinent. This filter is known as a "cognitive filter" in the behavioural science literature (Wu and Yoshikawa 1998), and as a "decision frame" in the management literature (Russo and Schoemaker 1989). Cognitive filters and decision frames:

- Are filters through which we view the world.
- Include the political, organizational, cultural, and metaphorical, and they highlight relevant parts of the system and hide (abstract out) the non-relevant parts.
- Can also add material that hinders solving the problem.[1] Failure to abstract out the non-relevant issues can make things appear to be more complex and complicated than they are and gives rise to artificial complexity (Section 13.3.1.1).
- The brain connects concepts using a process called reasoning or thinking.

1.3 The Systems Approach

"The systems approach is a technique for the application of a scientific approach to complex problems. It concentrates on the analysis and design of the whole, as distinct from the components or the parts. It insists upon looking at a problem in its entirety, taking into account all the facets and all the variables, and relating the social to the technological aspects" (Ramo 1973), namely, the systems approach is the application of Systems Thinking (Section 1.4) and Critical Thinking (Chapter 3). Moreover, the advantages of the systems approach to problem-solving have been known for centuries. The literature contains many examples including:

- "When people know a number of things, and one of them understands how the things are systematically categorized and related, that person has an advantage over the others who don't have the same understanding." (Luzatto circa 1735)
- "People who learn to read situations from different (theoretical) points of view have an advantage over those committed to a fixed position. For they are better able to recognize the limitations of a given perspective. They can see how situations and problems can be framed and reframed in different ways, allowing new kinds of solutions to emerge." (Morgan 1997)

Yet the systems approach is rarely used when dealing with problems and issues. It seems that systems thinking which leads to the systems approach must be a learned skill because many people would say that human nature has a non-systems approach to thinking about issues. The non-system thinker views issues from a single viewpoint/perspective or when multiple viewpoints are used, they are individual non-standardized viewpoints in random order depending on the person. I often heard people saying, "Let's make sure we are on the same page," or engineers[2] saying "Let's make sure we are on the same wavelength" to try to ensure meeting participants were viewing something from the same perspective or viewpoint.

C. West Churchman introduced three standardized views in order to first think about the *purpose* and *function* of a system and then later think about *physical* structure in *The Systems Approach* (Churchman 1968). These views provided three anchor points or viewpoints for viewing and thinking about a system. Twenty-five years later, *The Seven Streams of Systems Thinking* (Richmond 1993) introduced seven standardized viewpoints. Richmond's seven streams were modified and adapted into nine Systems Thinking Perspectives (Kasser and Mackley 2008). The nine perspectives introduced nine standardized viewpoints which can be used in sequence or in a random order. The nine Systems Thinking Perspectives cover purpose, function, structure, and more and were later renamed as the Holistic Thinking Perspectives (HTP) (Section 10.1). The number of perspectives was limited to nine in accordance with Miller's Rule (Section 3.2.5). The nine perspectives and the Active Brainstorming tool (Section 7.1) improved the way students applied systems thinking in the classroom and seem to provide a good way of teaching applied systems thinking.

1.4 Systems Thinking

Books on systems thinking don't teach it very well. There are books such as *The Fifth Discipline* (Senge 1990) which focuses on Causal Loops (Section 6.1.1) and seems to imply that systems thinking is the use of Causal Loops. There are books on the history and the philosophy and on what constitutes systems thinking, but there really aren't any practical handbooks on applying systems thinking to deal with problems and issues. Similarly the books on problem-solving tend to describe the process. They don't describe how to do the process. And the few articles that do, describe how to use a specific tool published in domain literature and do not get a wide distribution, so few people hear about it and even fewer people actually use it.

I found that out the hard way when I started to teach systems thinking at the University of South Australia (UniSA). I could describe the benefits and history of systems thinking, but no one at the Systems Engineering and Evaluation Centre (SEEC) could teach how to use systems thinking very well. We could teach Causal Loops (Section 6.1.1) in the manner of *The Fifth Discipline* (Senge 1990), but that was all. There weren't any good textbooks that approached systems thinking in a practical manner. So I ended up moving halfway around the world to Cranfield University in the UK to develop the first version of a practical and pragmatic approach to teaching and applying systems thinking to systems engineering under a grant from the Leverhulme Foundation.

1.4.1 The Two Distinct Types of Systems Thinking

Subsequent research identified that one reason for the lack of good ways of teaching systems thinking might be because if you ask different people to define systems thinking, you will get different and sometimes conflicting definitions. However, these definitions can be sorted into two types, namely:

1. ***Systemic thinking***: thinking about a system as a whole.
2. ***Systematic thinking***: employing a methodical step-by-step manner to think about something.

Many proponents of systems thinking consider either systemic or systematic thinking to be systems thinking not realising that each type of thinking seems to be a partial view of a whole, in the manner of the fable of the blind men perceiving the elephant (Yen 2008). For example, Senge wrote, "Systems thinking is a discipline for seeing wholes" (Senge 1990); accordingly, his book only covers systemic thinking. However, both types of systems thinking are needed (Gharajedaghi 1999). Consider each of them:

- Systemic thinking has three steps (Ackoff 1991):
    1. A thing to be understood is conceptualized as a part of one or more larger wholes, not as a whole to be taken apart.
    2. An understanding of the larger system is sought.
    3. The system to be understood is explained in terms of its role or function in the containing system.
- Systemic thinking has two facets:
    1. ***Analysis***: breaking a complicated topic into several smaller topics and thinking about each of the smaller topics. Analysis can be considered as a top-down approach to thinking about something and is associated with René Descartes (Descartes 1637, 1965). It has been termed reductionism because it is often used to reduce a complex topic to a number of smaller and simpler topics.
    2. ***Synthesis***: combining two or more entities to form a more complex entity. Synthesis can be considered as a bottom-up approach to thinking about something.
- Proponents of systemic thinking tend to:
    - Equate Causal Loops (Section 6.1.1) or feedback loops with systems thinking because they are thinking about relationships within a system (e.g. Senge 1990, Sherwood 2002).
    - Define systems thinking as looking at relationships (rather than unrelated objects), connectedness, process (rather than structure), the whole (rather than its parts), the patterns (rather than the contents) of a system and context (Ackoff, Addison, and Andrew 2010: p. 6).
    - Systematic thinking is mostly discussed in the literature on problem-solving, systems thinking, Critical Thinking, and systems engineering. It is often taught as the "problem solving process."

1.4.2 Systems Thinking and Beyond

Systematic thinking provides the process for systemic thinking which helps you understand the problematic situation. The "beyond" part is where the problem definitions and solutions come from. This is what I call holistic thinking. It emerged from the research in 2008 and has been refined since then. It goes beyond the two traditional components of systems thinking and includes Critical Thinking as well as the internal, external, progressive, and other HTPs (Section 10.1).

1.5 Problem-Solving

The systems approach to problem-solving is based on:

1. Visualizing (Section 7.11) the problem-solving process as a Causal Loop (Section 6.1.1), as shown in Figure 11.1, in which solutions evolve instead of the non-systems approach of visualizing the problem-solving process as a linear process from problem to solution.
2. Examining the problematic situation from a Perspectives Perimeter (Chapter 10), usually the HTPs (Section 10.1) to gain an understanding of the problem.
3. Going beyond systems thinking (Section 1.4.2) to determine the root cause or causes of the undesirability and Visualizing (Section 7.11) the solution.
4. Using the *Continuum* HTP to differentiate between subjective complexity and objective complexity and then abstracting objective complexity out of the problem. Objective complexity is being managed in many domains (Section 13.3). Distinguishing between objective complexity and subjective complexity in English is difficult because there isn't a single word that uniquely defines either concept (Section 13.3.1). The words "complicated" and "complex" have been used in the literature as synonyms to describe both types complexity. This book uses the words according to the following definitions:
    - ***Complex***: objective complexity – made up of lots of things.
    - ***Complicated***: subjective complexity – difficult to understand.

1.6 Alphabetical List of Tools

The tools presented in this book are grouped in various ways. Accordingly, Table 1.2 contains an alphabetical list of the tools to assist in speedily locating the different tools.

TABLE 1.2 Alphabetical List of Tools

TOOL	SECTION
2x2 format generic framework	5.1
Active Brainstorming	7.1

Templates	14
Thank You	8.13
Theory of Inventive Problem-Solving (TRIZ)	11.7
Three Streams of Activities	8.14
Timelines	8.15
Traffic Light Charts	8.16.1
Trend Charts	2.15
Visualization	7.11
Waterfall Chart	14.9
Work Breakdown Structures (WBS)	8.18
Work Package (WP)	8.19
Working Backwards from the Solution	11.8
XY Charts	2.16
Zone of Ambiguity	13.5

1.7 Summary

Chapter 1 began with an overview of benefits provided by this book followed by a section on how to read and use this book. This chapter continued with a discussion on thinking and the systems approach, introducing systems thinking and the two distinct types of systems thinking: systemic thinking and systematic thinking, as well as the benefits of going beyond systems thinking into holistic thinking. This also contains a list of acronyms used in this book and a table listing the tools used in the book in alphabetical order to facilitate quickly locating each of the tools.

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1 . For example, the differences between the Catholics and Protestants in Northern Ireland are major to many of the inhabitants of that country, but are hardly noticeable to most of the rest of the world.

2 . This sentence is not meant to imply that engineers are not people.

2

Charts

Charts are tools that we use all the time when thinking and communicating. They range from simple sketches on the back of an envelope or napkin to complex graphics produced by computers. This chapter discusses the following charts in alphabetical order:

1. Bar Charts in Section 2.1.
2. Cause and Effect Charts in Section 2.2.
3. Compound Bar Charts in Section 2.3.
4. Compound Line and Bar Charts in Section 2.4.
5. Control Charts in Section 2.5.
6. Financial Charts in Section 2.6.
7. Flowcharts in Section 2.7.
8. Hierarchical Charts in Section 2.8.
9. Histograms in Section 2.9.
10. N^2 Charts in Section 2.10.
11. Pareto Charts in Section 2.11.
12. Pie Charts in Section 2.12.
13. Polar Charts in Section 2.13.
14. Product-Activity-Milestone (PAM) Charts in Section 2.14.
15. Trend Charts in Section 2.15.
16. XY Charts in Section 2.16.

This book also discusses:

- Categorized Requirements in Process (CRIP) Charts in Section 8.1.
- Causal Loops in Section 6.1.1.
- Gantt Charts in Section 8.4.
- Program Evaluation Review Technique (PERT) Charts in Section 8.10.
- Traffic Light and Enhanced Traffic Light (ETL) Charts in Section 8.16.
- Waterfall Charts in Section 14.9.

Each type of chart shows information in a different way. Select the chart that helps you think about the information or presents the information you want the viewer to see in a way that is familiar to the viewer.

2.1 Bar Charts

Bar Charts are tools for comparing the values of independent variables on a single chart. The length of the bar represents the size of the variable. Bar Charts come in various forms and may show a vertical bar per grouping or several bars as needed to present the appropriate information. Sometimes the bars are shown horizontally. Depending on the chart, the bars may represent different variables at the same point of time, or the same variable at different points of time. One example is shown in Figure 2.1. Fred has been to a shooting range and fired six shots at a target. He plotted the distance from the centre of the target for each shot in the form of the Bar Chart shown in Figure 2.1.

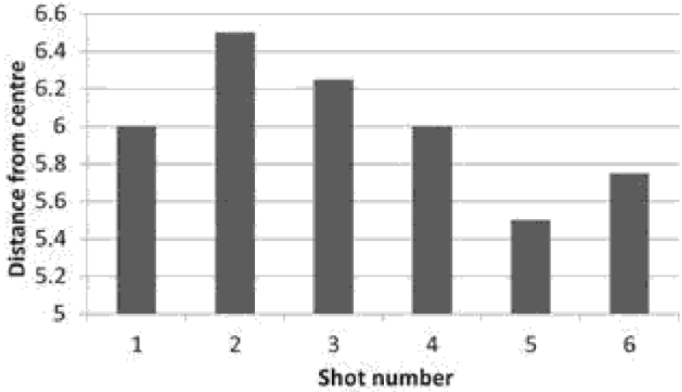

Figure 2.1 Bar Chart representation of the results of Fred's session.

2.2 Cause and Effect Charts

Cause and Effect Charts:

- Are specialized flow-charting tools used primarily in:
    - Tracking down the root cause (problem) of a specific symptom.
    - Identifying failure modes in failure analysis and risk management.
- Take the form shown in Figure 2.2.
- Are also known as:
    - ***Ishikawa diagrams***: because of (the association with) Kaoru Ishikawa, the person who developed them.
    - ***Fishbone Charts***: because of (the association with) the similarity in the shapes between the chart and the skeleton of a fish when there are a large number of items on the chart.
- Are often used in ideation sessions to examine factors that may influence a given situation.
- Facilitate:
    - Distinguishing between causes and effects or symptoms.

- Determining the relationships between causes and effects.
- Determining the parameters associated with causes.

- Consist of three parts:
  1. ***The effect***: a situation, condition or event produced by a cause. The effect:
     a. Is shown as a box with a horizontal arrow in the centre of the chart, pointing to, and joined to the box.
     b. May be desirable or undesirable.
  2. ***The primary causes***: drawn as sloping lines leading towards the effect box. The lines are labelled with "the cause".
  3. ***The secondary parameters of the cause***: drawn as horizontal lines leading to the cause lines.

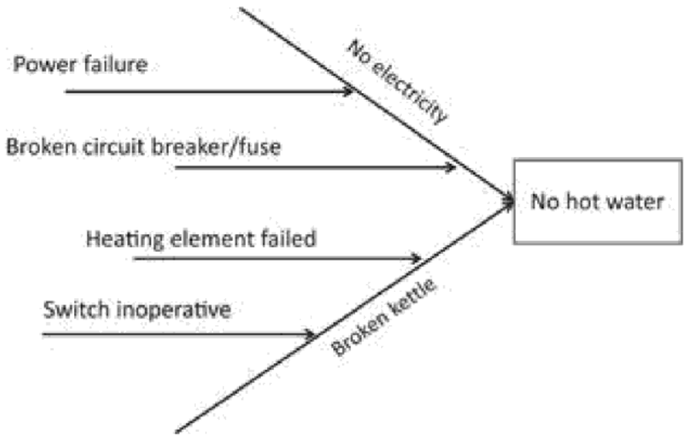

Figure 2.2 A Cause and Effect Chart.

2.2.1 Using a Cause and Effect Chart

The Cause and Effect Chart is:

- Generally used in a manner that thinks backwards from the effect to the cause; an instance of the generic working backwards from the solution process (Section 11.8).
- Very useful when using the Five Whys (Section 7.5) to determine the cause of a failure in a complex situation where there may be more than one potential cause.

When using the systems approach to thinking about a process, you should generally also think about things that might go wrong with the process (risk management), and the appropriate Concept Map to link these thoughts is a Cause and Effect Chart.[1] For example, when thinking about making a cup of instant coffee, one of the things that might go wrong is that the water does not get hot. Figure 2.2

shows a typical Cause and Effect Chart drawn when trying to determine the type of failure that could cause the water not to get hot when using an electric kettle. The symptom is shown in the box on the right side, and in this case, the symptom is "no hot water". After some thought, two possible causes are identified: "no electricity" and a "broken kettle". Further thought postulates that "no electricity" might be due to a power failure or a tripped circuit breaker or blown fuse, and the "broken kettle" might be due to a failed heating element or switch. These ideas are connected as shown in Figure 2.2.

2.2.2 Creating a Cause and Effect Chart

Create a Cause and Effect Chart by:

1. Creating the box containing the effect or symptom as shown in Figure 2.2. Label the box with the effect. In Figure 2.2, it is "no hot water".
2. Think about what could cause the effect and draw slanting lines into the box as shown in Figure 2.2. Label each of the lines with their cause.
3. Think about secondary causes for each slanted line and draw them as horizontal lines, as shown in Figure 2.2. Label each line with the cause.

2.3 Compound Bar Charts

A Compound Bar Chart is a tool that can be used to compare two sets of information about some attributes of something where the information is shown in the form of a Bar Chart (Section 2.1). In this example, the performance, speed, weight, length, width, height, payload, and flight duration of two different model airplanes (Series 1 and 2) have been evaluated. Each parameter has been evaluated on a scale of 0 to 5, and the resulting scores are shown in Figure 2.3. The chart shows that Series 1 is better in some respects, Series 2 is better in others, and the two model aircrafts received identical scores for speed. The same information is shown in Figure 2.4 but in the form of a Polar Chart (Section 2.14). When comparing a small number of parameters, either type of chart may be used, but when there are a large number of parameters to be compared, the Polar Chart is a better way of presenting the comparison results. Another example of a Compound Bar Chart is the performance evaluation Control Chart in Figure 2.5 which shows the performance evaluation for a candidate against the criteria E1 to E10 for two successive time periods. The figure is a Control Chart (Section 2.5) drawn as a Compound Bar Chart.

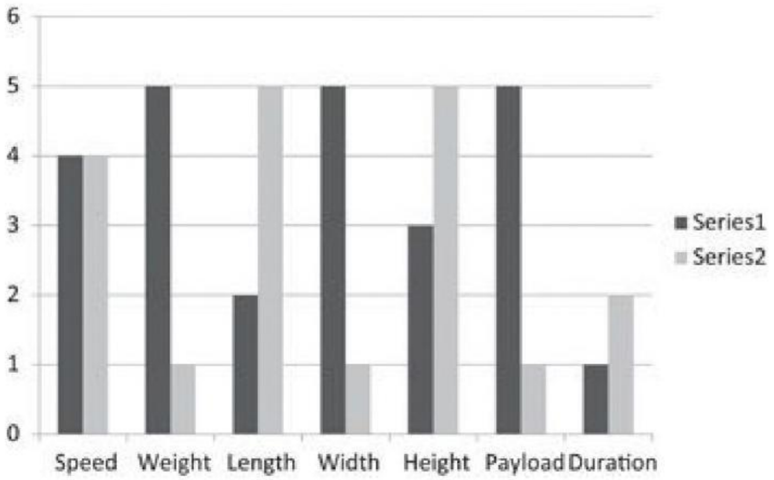

Figure 2.3 Compound Bar Chart for comparisons.

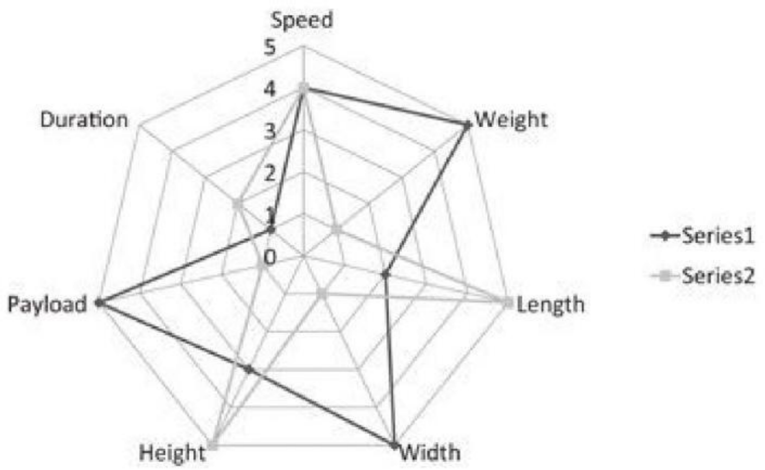

Figure 2.4 Kiviat Chart polar plot of model aircraft evaluations.

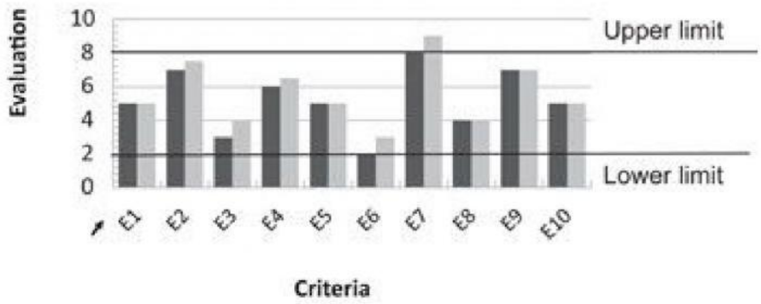

Figure 2.5 Performance evaluations over two periods.

2.4 Compound Line and Bar Charts

There are times when a chart containing a mixture of lines and bars is useful, such as when thinking about cumulative values and values in specific time periods. Each type of chart shows information in a different way. Select the chart that helps you think about the information or presents the information you want the viewer to see in a way that is familiar to the viewer. For example, Figure 2.6 is a Compound Line and Bar Chart (Section 2.4).

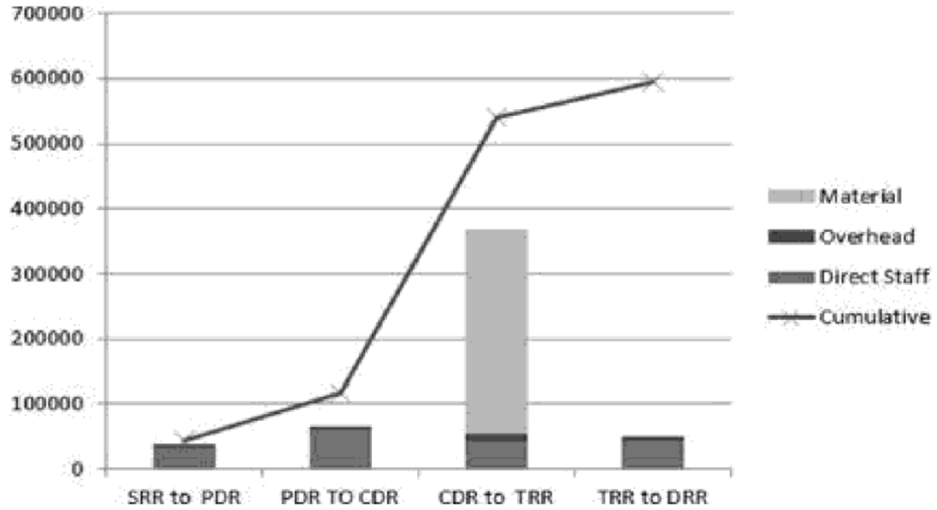

Figure 2.6 Compound Line and Bar Chart, NUS SDM5002, Session 7, 2014, Team Integral.

2.5 Control Charts

Control Charts are:

- Tools by used by management to monitor and control a process.
- Trend Charts (Section 2.15) with upper and lower limit levels as shown on the line graph in Figure 2.7.
- Used to identify when pre-determined upper and lower limits have been exceeded.
- Useable in other situations as well (*Generic* HTP). For example, one use is in personal performance evaluations. Figure 2.8 shows a Control Chart used in performance evaluation. The person has been evaluated on nine (E1–E9) criteria, and when the information is plotted in the chart, is seen to exceed the upper limit on one of them, superior performance which might be recognized. In this figure the evaluation is plotted as a Bar Chart, not as a line chart. When the subsequent evaluation is added to the chart (for a different person), as shown in Figure 2.5, improvements can be seen. On the other hand, should the performance have dropped, someone should determine the reason.

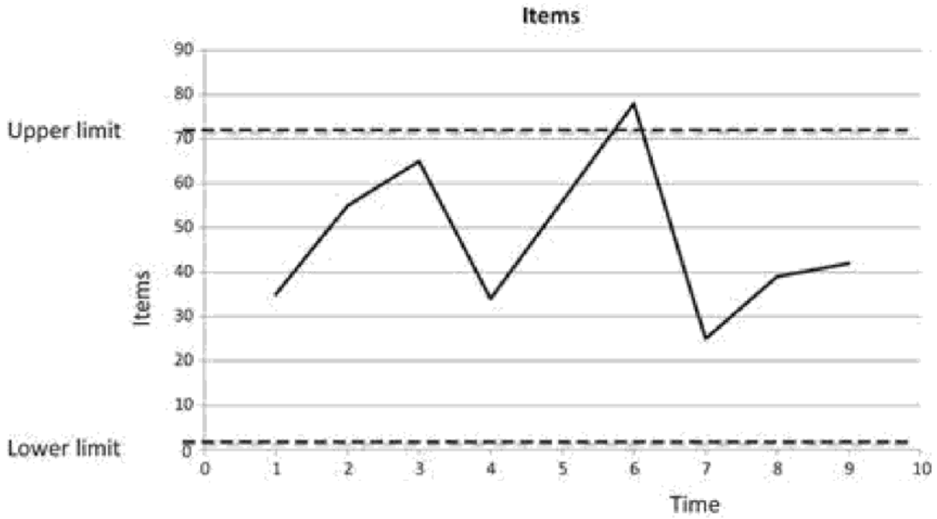

Figure 2.7 A typical Control Chart.

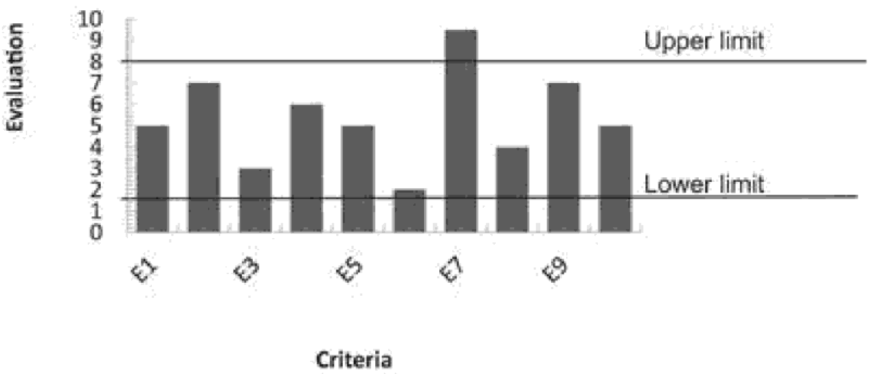

Figure 2.8 Control Chart for performance evaluation.

While Control Charts are usually shown as Trend Charts using lines, in the performance evaluation scenario, the information is more easily extracted from the Bar Chart view (Section 2.1).

2.6 Financial Charts

Financial Charts are tools for thinking about and communicating financial information. They include Graphs (Section 6.1.3), Bar Charts (Section 2.1) and Compound Line and Bar Charts (Section 2.4). When planning a Financial Budget (Section 8.3), a typical chart summarizing the information might be the one shown in Figure 2.9. It is a Trend Chart (Section 2.15) with two trend lines. The funds committed to the project trend line at $50,000 are not expected to change over the life of the project, so the line is drawn as a flat horizontal line. The budgeted line shows total planned budgeted expenditure over the 12 months of the project increasing each month by a planned value until it gets to about $45,000. Since the figure shows the planned budget before the project begins, nothing has been spent so the actual costs are zero.

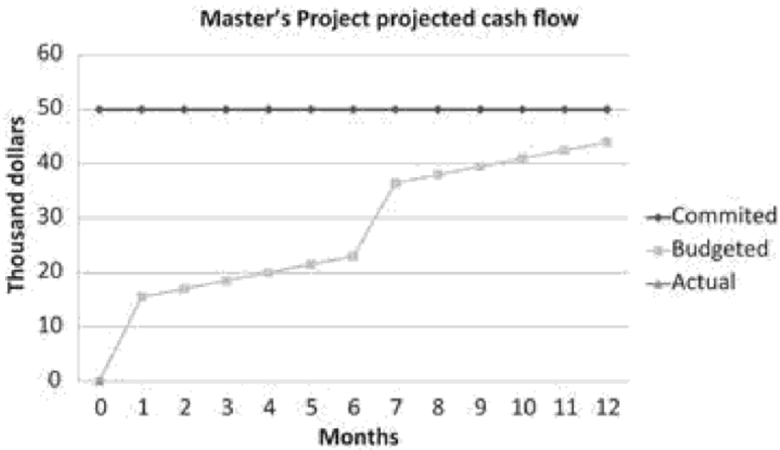

Figure 2.9 Project projected cash flows.

Figure 2.10 is another type of Trend Chart showing the project financial status after nine months. The actual amount of funds spent has varied slightly from the planned amount but the project is currently expected to finish within budget. This type of chart is used in Earned Value Analysis (EVA) (Section 8.2). Figure 2.6 is a Compound Line and Bar Chart (Section 2.4) containing both a Line Chart and a vertical Bar Chart. The figure is a Financial Chart for a different project. The Trend Chart shows the cumulative expenditure over the project by for the time between the major milestones (Section 14.9). The vertical Bar Chart shows the expenditure for each milestone period as a stacked bar broken out by a number of categories of costs.

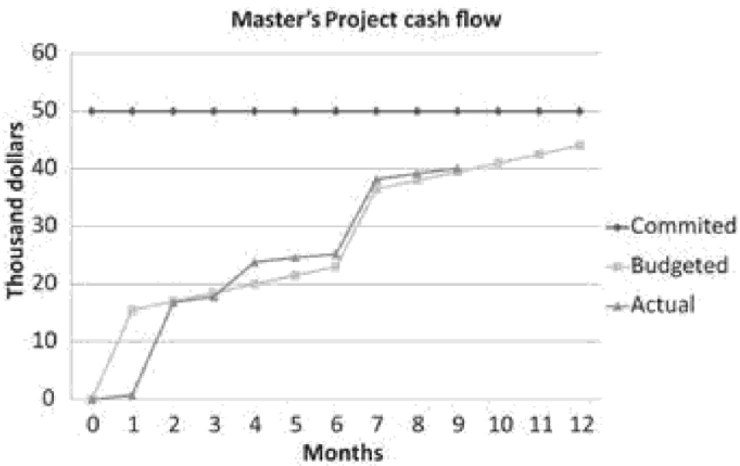

Figure 2.10 Project financial status after nine months.

2.7 Flowcharts

A Flowchart is:

- A tool for describing a conceptual or real process.
- A tool for describing a sequence of activities/events.
- A graphic representation of the procedural association between items. It is often used when thinking about or discussing:
    - The relationship among parts of a process.
    - A signal (data) flow through a data processing system.

Depending on the content in which it is used, the Flowchart maybe used to think about something that exists or to conceptualize about something that is desired.

2.7.1 Types of Flowcharts

Perceptions from the *Continuum* HTP indicate that there are two types of Flowcharts, namely:

1. A process Flowchart.
2. A functional Flowchart.

Where:

- ***A process*** Flowchart shows the elements of the process in a time-ordered manner sequentially from start to finish. Since time does not go backwards, a process Flowchart must not contain any backward arrows. If a block of activities is going to be repeated, it has to be shown as a second block, identical to the first, but taking place later in time.
- ***A functional*** Flowchart is a Relationship Chart (Section 6.1.2). Since it's not time-dependent, arrows can loop back when functions are repeated; the most common example is a Causal Loop (Section 6.1.2).

2.7.2 Flowchart Symbols

The symbols for the four most common elements in a Flowchart are shown in Figure 2.11 in the context of describing adding water to something until there is enough water. The elements are:

- ***Begin*** and ***end***, shown as ovals. These symbols show the entry point and the exit point of the Flowchart. They may be labelled "begin", "end", "start", or "stop" as appropriate.
- ***Process, task, action, or operation***, shown as a rectangle. The label inside the rectangle shall contain a verb.
- ***Decision***, shown as a diamond. A decision poses a question. The answer to

the question determines the exit path out of the decision shape. So in Figure 2.11, the "no" response path flows back to the "add water" process symbol, while the "yes" path flows forward to the "end" symbol.

- ***Connections***, shown as lines ending with an arrow in the direction of the flow.

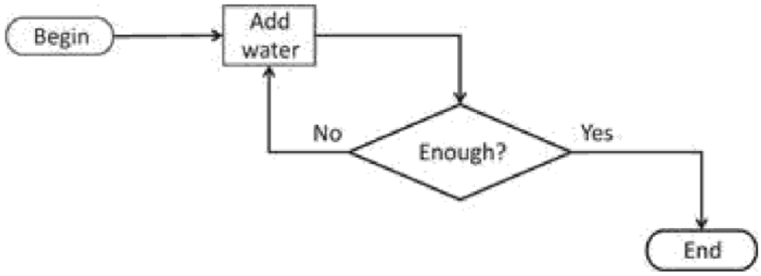

Figure 2.11 Flowchart for adding water showing the four most common flowchart symbols in use.

Flowcharts may be drawn in various ways such as by hand freestyle, by hand using templates, or using computer software. When using software, the connections can sometimes be shown as thick arrows as in a process for making a cup of instant coffee shown in Figure 2.12.

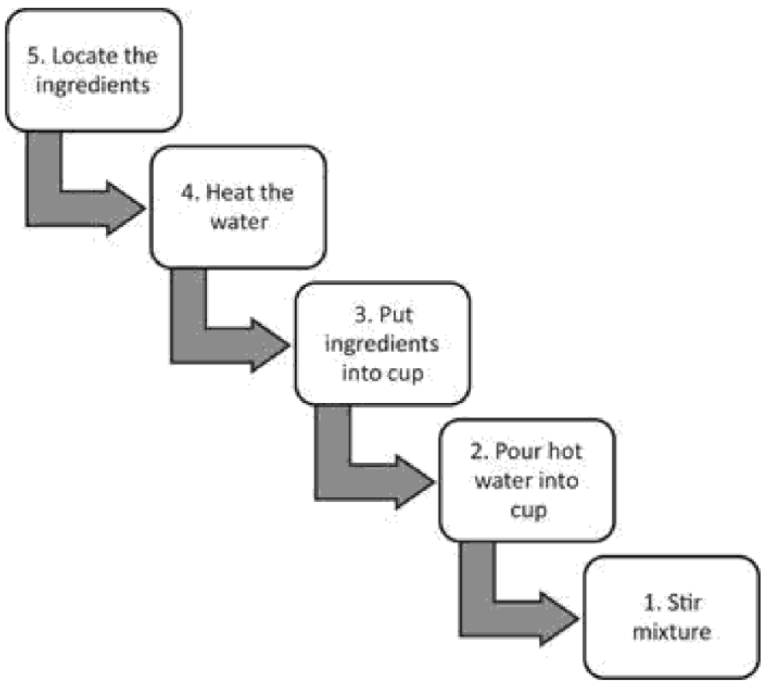

Figure 2.12 Process for making a cup of instant coffee.

2.7.3 Rules for Drawing a Flowchart

The rules for drawing a Flowchart are:

1. All information shall flow into process inputs.
2. All information shall flow out of process outputs.
3. The Flowchart shall show the sequential and concurrent nature of the activities.
4. The Flowchart shall show all the potential paths an activity can take. If those paths are not pertinent, they shall be deemphasized accordingly. One way of doing so is to colour the paths grey.
5. All of the decision points shall be shown accurately.
6. The Flowchart shall be drawn from top (start) to bottom (finish) or left (start) to right (finish).
7. There shall be no more than nine shapes in a Flowchart in accordance to Miller's Rule (Section 3.2.5).

2.7.4 Creating a Flowchart to Represent a Process

Creating a Flowchart requires thinking about the sequence of activities. For example, think about the process for making a cup of instant coffee. There are three ways to do this:

1. Starting from the ending and working backwards to the beginning, discussed in Section 2.7.4.1.
2. Starting from the beginning and working forwards to the ending, discussed in Section 2.7.4.2.
3. Starting in the middle and working backwards and forwards, discussed in Section 2.7.4.3.

2.7.4.1 Starting from the Ending Here you start with a completed product, namely the cup of instant coffee, and think about what you did to create it (Section 11.8). Working backwards from the completed stirred cup of instant coffee ready for drinking, you first thought of the last step you performed to realize the product and wrote it down. After writing down the step, you thought of the items you used when you performed the step. You then conceptually moved back to the previous set of activities that you used to make sure the items were ready when you needed them. So, you would end up with a list such as, you:

1. Stirred the mixture.
2. Added the ingredients to the hot water in the cup.
3. Poured the hot water into the cup.
4. Waited for the water to boil.
5. Started to heat the water.
6. Put the water into the kettle
7. Located the ingredients (coffee powder, creamer and sugar) and kitchen items

(cup, spoon and kettle).

Or you could have written that you:

1. Stirred the mixture.
2. Poured the hot water into the cup.
3. Put the ingredients into the cup.
4. Waited for the water to boil.
5. Started to heat the water.
6. Put the water into the kettle
7. Located the ingredients (coffee powder, creamer, and sugar) and kitchen items (cup, spoon, and kettle).

Or you could have written that you:

1. Stirred the mixture.
2. Poured the hot water into the cup.
3. Put the ingredients into the cup.
4. Heated the water.
5. Located the ingredients (coffee powder, creamer, and sugar) and kitchen items (cup, spoon, and kettle).

Or you could have written a similar list of sequential ideas using slightly different wording. The first process was completely sequential; the second process contained two parallel activities in that you put the ingredients into the cup while the water was heating which shortened the time to create the product. The third version of the process was also sequential. In all three versions of the process, the "1. Stirred the mixture" step contained three sub-steps, namely:

1.1. Picked up the spoon.
1.2. Stirred the mixture in the cup.
1.3. Put the spoon down.

Similarly, in the third example the "4. Heated the water" step contained three sub-steps, namely:

4.1. Waited for the water to boil.
4.2. Started to heat the water.
4.3. Put the water into the kettle.

All three versions are acceptable at this time because they are just the initial ideas for the process. Note that each step is numbered and when a step is broken out into sub-steps the numbering is adjusted accordingly. In these examples, Step 1 is broken out into sub-Steps 1.1, 1.2 and 1.3, while Step 4 is broken out into sub-Steps 4.1, 4.2, and 4.3. This numbering style makes it easy to locate a sub-step in the process.

When working backwards, you can have a vision of the product in your mind and working out how you got there minimizes the probability of forgetting an ingredient (part) or a step in the process. However, when you draw the process as a Flowchart, irrespective if drawn forwards from the start or backwards from the finish, the Flowchart always appears as if it had been drawn from start to finish, as shown in Figure 2.12. From the *Generic* HTP, Figure 2.12 may also be considered as a simple Design Structure Matrix (DSM) (Eppinger and Browning 2012).

2.7.4.2 Starting from the Beginning Starting from the beginning means that you have to think forwards and ask questions. Here you might have thought about:

1. Locating the ingredients.
2. Heating the water.
3. Putting the ingredients into the cup.
4. Adding the hot water into the cup.
5. Stirring the mixture.

When you thought about locating the ingredients, you had to ask, “What are the ingredients?” You thought for a while and came up with the hot water, coffee, sugar, and creamer. Then you thought about heating the water and associated putting water into a kettle. The sequential process slowly took shape in your mind and is the same sequence of ideas as you developed starting from the ending.

2.7.4.3 Starting in the Middle Here the ideas come in no particular sequence and you write them down as they come. You then arrange them in Lists (Section 9.4) and Relationship Diagrams (Section 6.1.2), then in hierarchies showing how the parts come together to make up the product.

2.7.5 The Most Common Mistakes Made When Drawing Flowcharts

The most common mistakes made when drawing Flowcharts are:

1. ***Too many objects in the Flowchart***: a violation of Rule 7 in Section 2.7.3.
2. ***Inconsistent flow direction***: a Flowchart should have a consistent flow direction. It should be top-to-bottom or left-to-right. Note, loops may violate this rule when the Flowchart contains a small number of elements.
3. ***Inconsistent hierarchical arrangement*** in which the elements are at different levels in the process hierarchy.

For example, Figure 2.13 describes the flow for a CQ function in an amateur radio contest which contains the following subfunctions:

1. ***Call CQ***: the radio amateur operator calls “CQ” on an unused frequency indicating that she is looking for someone to respond.
2. ***Reply?***: tests for a reply. If a reply is not received, the process advances to Step 3. If a reply is received, the process advances to Step 4.
3. ***Enough?***: tests to see if the operator has been calling for a predefined time period without a response. If the time period has not been exceeded, the process flows back to Step 1 for another CQ call.
4. ***Duplicate?***: tests to see if the station that responded to the CQ has already been contacted. If it has, the process flows to Step 5; if it has not, the process flows to Step 6.
5. ***Send worked B4***: transmits a message to the other station that contact has already been made; the station has been worked before (B4). The inference is that the other station will depart the frequency. The process then flows back to Step 1 and the first CQ call of the next sequence is transmitted.
6. ***Send message***: transmits the contest exchange information and the process advances to Step 7.
7. ***Receive message***: the operator receives a contest message exchange from the other station, and the process advances to Step 8.
8. ***Complete?***: tests to determine if the received message is complete. If the message is not complete, the process advances to Step 9; if complete, the process advances to Step 10.
9. ***Request repeat***: asks for a repeat of the message and returns to Step 7.
10. ***Store the data***: stores the received message and corresponding transmitted data and advances to Step 11.
11. ***Say “Bye”***: terminates the contact and the process flows back to Step 1.

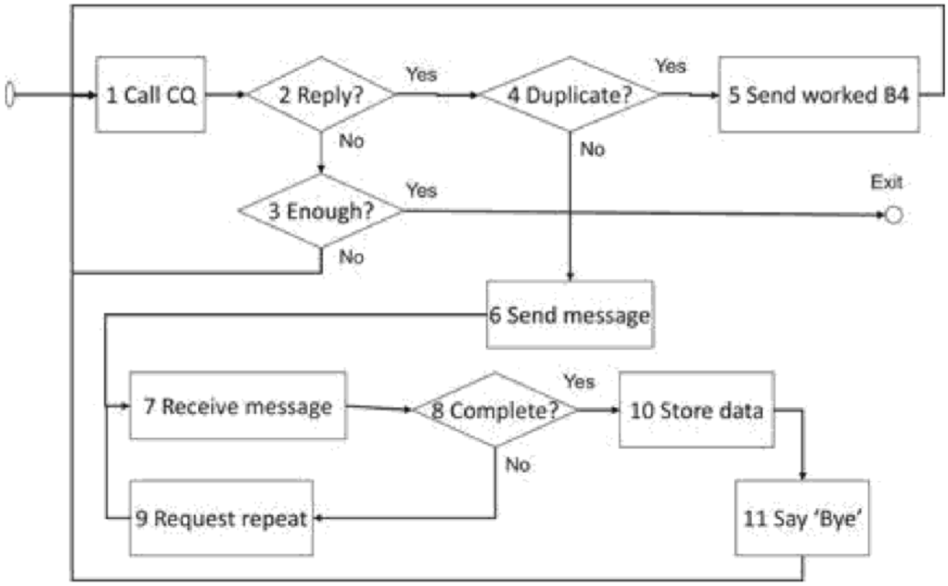

Figure 2.13 Initial call CQ function.

Note that the blocks in Figure 2.13 have been numbered to facilitate discussing their content. Figure 2.13 contains a number of errors including:

- ***Too many objects***: there are eleven which is a violation of Rule 7 in Section 2.7.3.
- ***Elements from two levels in the hierarchy***, and should accordingly corrected to Figure 2.14. This type of mistake tends to arise because Figure 2.13 is generated while thinking about the process and is not converted into Figure 2.14 by grouping Steps 6, 7, 8, and 9 into a new higher level Step 6. One might also, as an alternative, have included Steps 10 and 11 into Step 6 and renamed the Step as a QSO function.
- ***A potential indefinite loop*** in Steps 7, 8, and 9 because unlike in Steps 1, 2, and 3, there is no timeout specified.
- ***Inconsistent branch directions out of decision points*** which make it harder to follow the logic. This means that one decision point may have a "yes" branch out of the right side and another decision point may have a "no" branch out of the same side. One way of avoiding this mistake is to flow "yes" out of the bottom of the decision and "no" out of the side. Another way is to flow out of the left and right sides as shown in Figure 2.11. You should use either way and not mix them.
- ***Not showing directions (arrow heads) on the connections*** which makes it difficult for other people to figure out the flow sequence.
- ***Ambiguous branches*** such as the one shown in Figure 2.15 which represents an approach to dealing with situations. Consider what happens after the "understand the situation block" in Figure 2.15. The flow can go back to "observe", down to "formulate problem statement", or in both directions.

The implied decision is to return to "observe" until an understanding is achieved and then advance to "formulate the problem". Figure 2.15 should be redrawn as Figure 2.16 to remove the ambiguity by adding the decision point showing when each path is taken.

- ***Failure to the use standard symbols*** shown in Figure 2.11. Figure 2.15 also uses circles for the entry and exit points. The entry and exit points should be ovals as shown as in Figure 2.16.
- ***Looping back in process Flowcharts***. Time does not flow backwards, so when process Flowcharts take the form of Causal Loops (Section 6.1.1), people tend to forget that time passes during the subsequent iterations and the need for baselining each iteration.

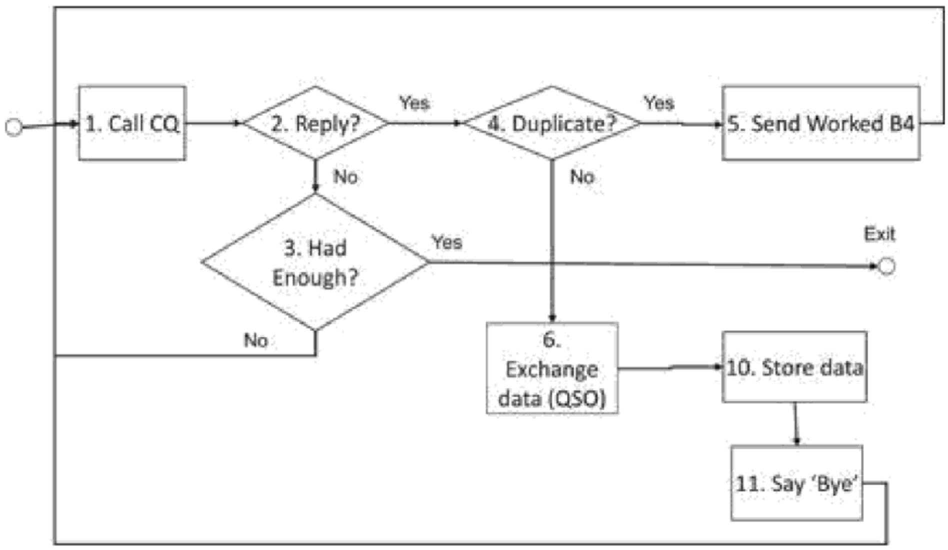

Figure 2.14 Adjusted call CQ function.

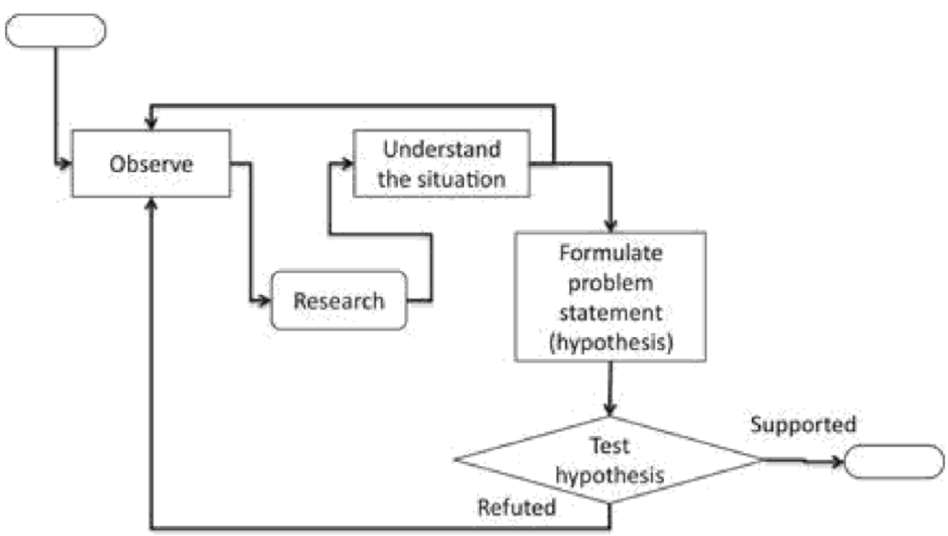

Figure 2.15 The scientific method (poor).

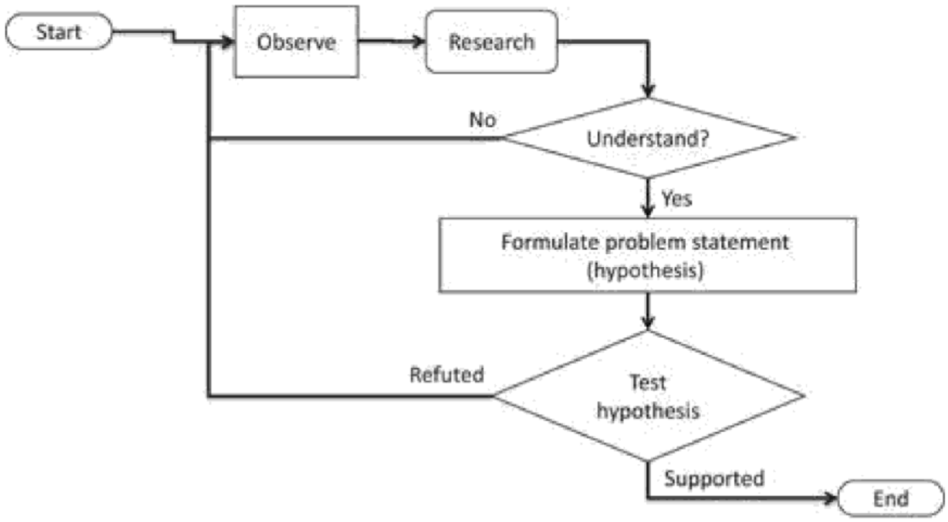

Figure 2.16 The scientific method.

These mistakes generally arise because the person drawing the chart is familiar with the context, does a brain dump, and does not take the time to fix the chart before distributing it.

2.7.5.1 Creating Flowcharts When Designing Software Flowcharts are often drawn when designing the logic in computer software. This section now provides an example of creating a number of Flowcharts in the context of designing the software for a game which simulates an amateur radio contest and shows how some of the most common mistakes in creating Flowcharts appear and how they can be corrected.

2.7.5.2 Perceptions of an Amateur Radio Contest From the *Big Picture* HTP, the purpose of an amateur radio contest is to simulate an emergency situation in which amateur radio operators are sending and receiving messages into and out of a disaster area and as such provide training in this type of operation.

From the *Operational* HTP, amateur radio operators perform a number of scenarios including:

- Searching for other amateur radio stations to contact.
- Calling CQ, a signal that the amateur radio station is waiting on a frequency for other amateur radio stations to contact them as shown in Figure 2.13.
- Exchanging messages with other amateur radio stations.

From the *Functional* HTP, functions can be thought of in a sequential manner, as shown in the top-level contest Flowchart in Figure 2.17 in which each item element is numbered to facilitate the discussion.

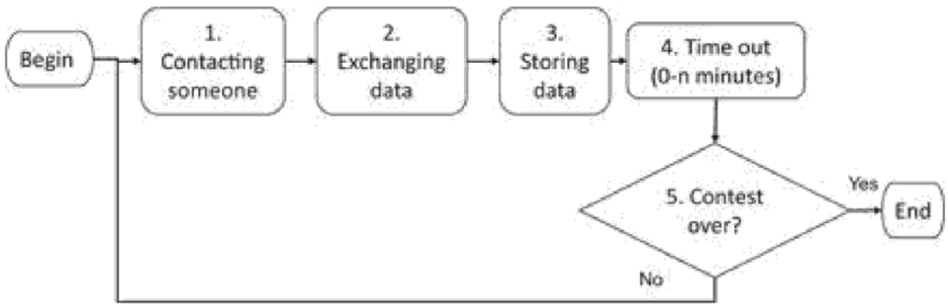

Figure 2.17 An amateur radio contest.

2.7.5.3 Creating the Flowcharts Consider each element in Figure 2.17:

1. ***Contacting someone*** which can be done in several ways including:
   a. Calling CQ.
   b. Tuning the radio to find someone calling CQ and then calling them.
   c. Tuning the radio to find someone else in a contact to QSO (exchanging messages), waiting for the QSO to end, and then calling them.
2. ***Exchanging data*** or messages, a function which can be done sequentially either by sending data first and then receiving data from the other station or vice versa.
3. ***Storing the data*** in the computer.
4. ***Taking a timeout*** for various reasons such as refreshment, comfort, equipment malfunctions and interference from members of the family.
5. ***An "is the contest over" check*** to terminate the software.

The Flowchart for the contacting someone or CQ scenario as developed by the software designer is shown in Figure 2.13. While it documents the functions, it contains several of the most common mistakes made when creating Flowcharts including:

- Non-standard entry and exit symbols (circles instead of ovals).
- The flow from item 6 to items 7 and 9 is backwards (saves space to draw it this way and the chart is still understandable, so this may be a valid exception).
- Items 6, 7, 8, and 9 are at a lower level in the system hierarchy than the remaining items.
- Too many items in the Flowchart.
- The "no" exits from the decision points are not labelled.

Figure 2.17 shows a partially adjusted Flowchart. Items 6, 7, 8, and 9 have been aggregated into a new higher-level exchange data function, item 6, and some of the other mistakes have been corrected. Two different versions of the exchange data function (item 6 in Figure 2.14) are shown in Figures 2.18 and 2.19 since participation in real contests[2] have shown that both ways of exchanging messages are used and so need to be implemented in the simulation. The items have been labelled a 6.1, 6.2, 6.3, etc. to show that they are subfunctions of item 6.

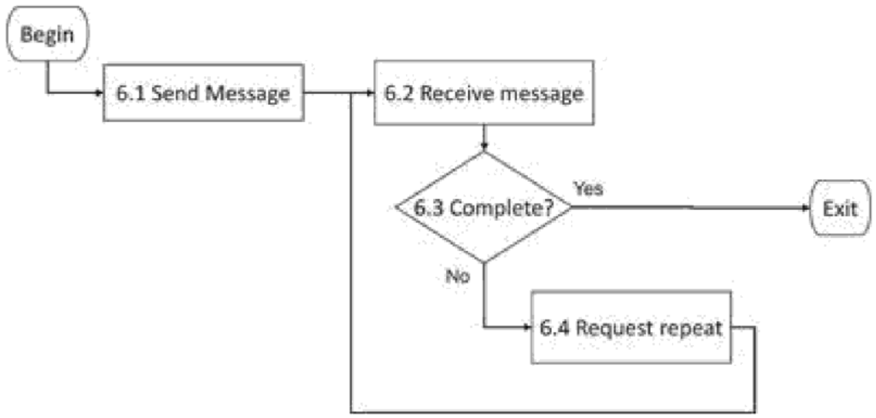

Figure 2.18 The exchange data function -1.

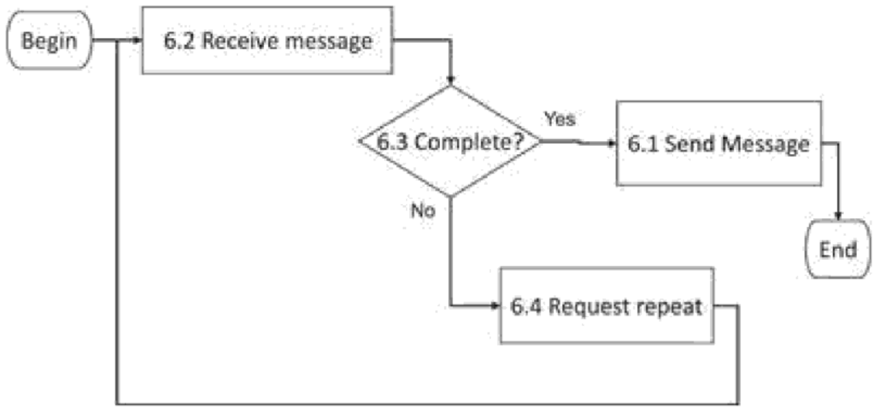

Figure 2.19 The exchange data function -2.

In addition, each of the functions in Figures 2.18 and 2.19 must be shown in lower-level functional Flowcharts of their own.

2.8 Hierarchical Charts

Hierarchical Charts are:

- Tools showing relationships from the *Structural* HTP.
- Often used to describe reporting relationships in organizations, hence they are often known as organization charts.

For examples of the use of Hierarchical Charts, consider the problem of making a cup of instant coffee with creamer and sugar. When faced with a complex problem, we break it up into smaller, less complex problems (analysis), then solve each of the smaller problems and hope that the combination of solutions to the smaller problems (synthesis) will provide a solution to the large complex problem. When faced with the problem of making a cup of instant coffee, we use analysis to identify and create a List (Section 9.4) of the components that make up the complete cup of instant coffee. So the coffee powder, cup, hot water, cream, and sugar spring to mind. We then use synthesis to create the cup of instant coffee from the ingredients. We use Concept Maps to think of the relationships between the ingredients. When we think of the process, we think of mixing the ingredients, and in drawing the process flow chart (Section 2.7) we think of a spoon; when we think of heating the water, we think of a kettle and gas or electricity as the fuel.

A typical initial set of the items or parts used in making a cup of instant coffee is shown in Figure 2.20. The spoon is drawn as an assistant to the cup of coffee because it is used during the process of creating the cup of instant coffee and then discarded. The kettle and gas/electricity are associated with heating the water and so are shown in a similar manner as assistants to the hot water. However, this arrangement mixes concepts at different levels of the hierarchy and a better arrangement of the ideas is shown in Figure 2.21. The insertion of an abstract or virtual "ingredients" concept into the chart clarifies the arrangement of ideas, showing which ideas constitute the ingredients and which ideas are associated with other aspects of the cup of instant coffee.

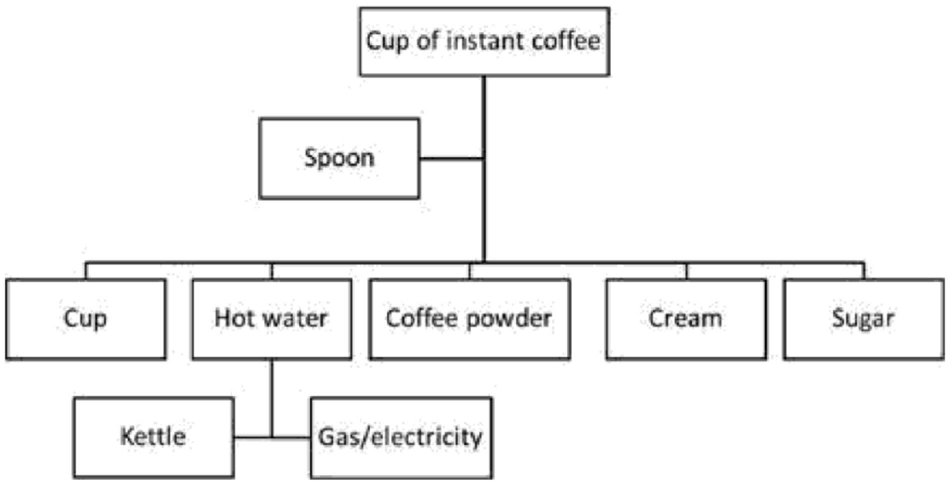

Figure 2.20 Initial set of ideas pertaining to a cup of instant coffee.

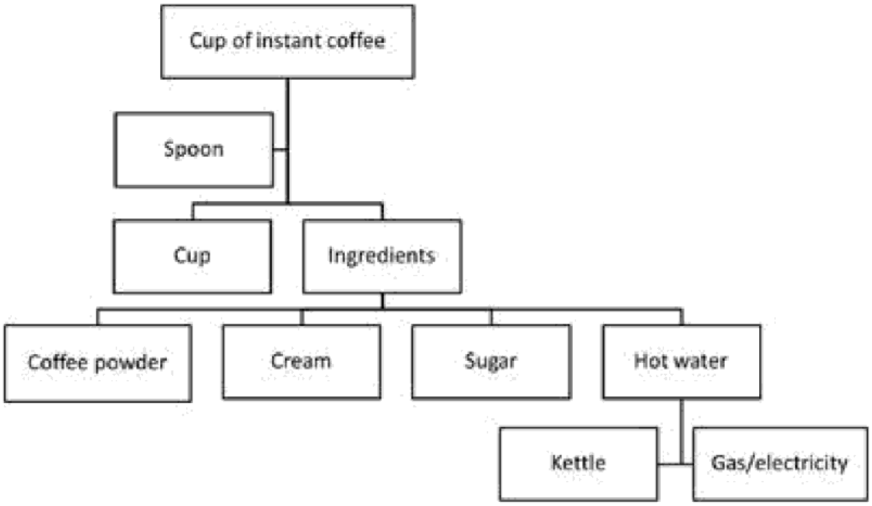

Figure 2.21 Hierarchical arrangement of items pertaining to a cup of instant coffee.

However, Figure 2.21 should only be considered as an interim or working drawing. A better (simpler) final drawing is shown in Figure 2.22 which clearly distinguishes between the items associated with the cup of instant coffee and the aggregation of the spoon and kettle into an abstract concept called "kitchen items", the constituents of which are used in the process of creating the cup of instant coffee.

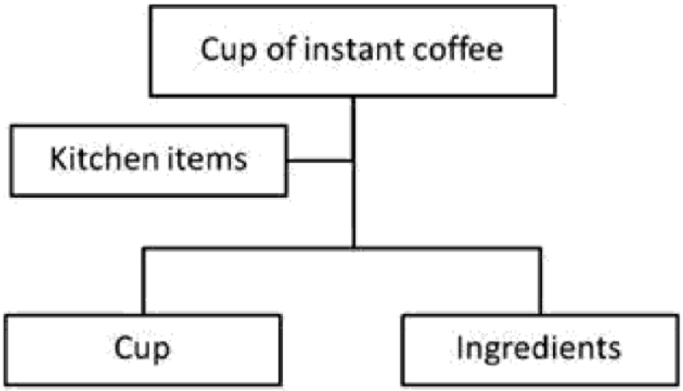

Figure 2.22 Top-level hierarchical chart for a cup of instant coffee.

A common mistake in drawing Hierarchical Charts is the general mistake made in drawing Concepts Maps (Section 6.1.2.2) in which a high-level chart such as Figure 2.22 is often extended to include the lower-level items such as in Figure 2.21 and Figure 2.23. The ideas or objects should have been sorted and aggregated prior to presentation and shown in the appropriate drawings. In this case, Figure 2.22 would show the entire system, Figure 2.24 would show the ingredients, and a third figure would show the kitchen items. Namely, the mistake is made up of the following two components:

1. We use a single chart for all the items instead of a set of charts, hence creating artificial complexity (Section 13.3.1.1).
2. We do not remove the clutter by grouping the items into a mixed hierarchy of less than nine items in accordance to Miller's Rule (Section 3.2.5).

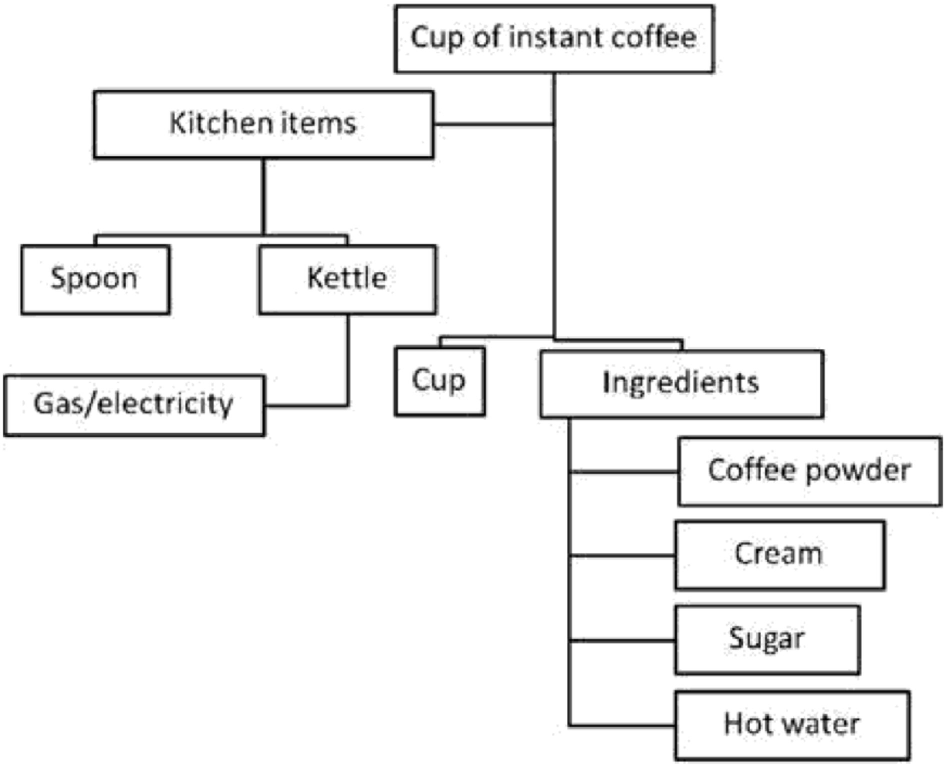

Figure 2.23 Sorted hierarchical arrangement of ideas pertaining to a cup of instant coffee.

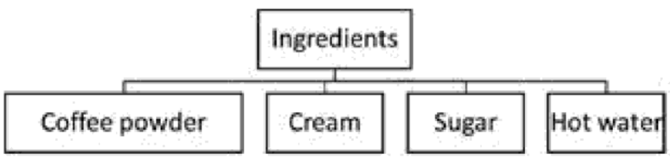

Figure 2.24 The ingredients.

2.9 Histograms

A Histogram:

- Is a specialized type of Bar Chart (Section 2.1) used in statistics to display a graphical summary of the distribution of data rather than the data (Pearson 1895). For example, Fred's hobby is shooting. After a session at the target range, Figure 2.36 shows the distance of Fred's shots from the centre of the target, as well as the angle. If Fred is interested in the number of shots hitting the target at specific range zones from the centre rather than the actual distances or angles, he could plot a Histogram to provide that information. Fred would create “buckets” for ranges of data, such as from 5.4 to 5.6 centimeters, 5.6 to 5.8 centimetres, etc., from the centre of the target at 0.2 centimetre intervals. He would then go through the data and increase the bucket count each time the value of a shot was inserted into a bucket. When he finishes the operation and displays the results, the Histogram would show up as depicted in Figure 2.25. As you can see, most of the shots were in the range 6.0–6.2 while none of the shots were in the range 5.8–6.0.

- Shows the relative distributions of items in a group. When the individual number of items is large, software can be used to calculate the data to be shown in the Histogram such as a chart summarizing the distribution of the final grades of students in a class at the end of a semester shown in Figure 2.26. The figure shows that five students achieved a grade of A; six achieved a grade of A-, and so on. If the instructor wanted to grade on a curve, he or she could reduce the limit for a B grade to increase the number of B- grades.

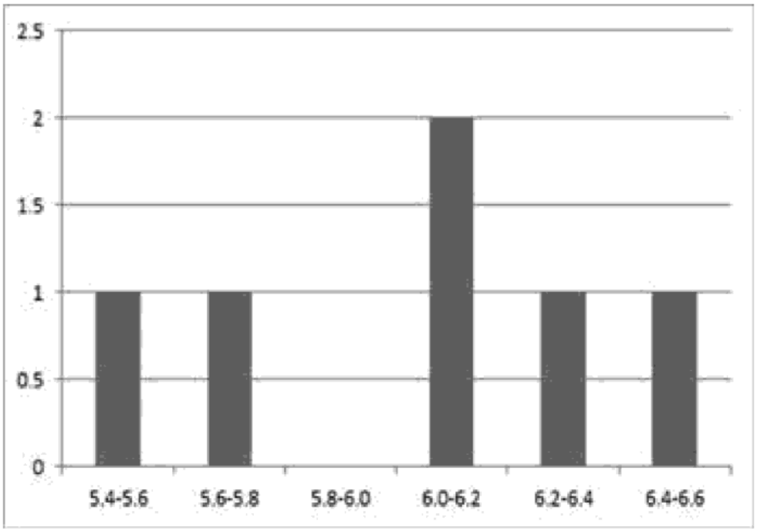

Figure 2.25 Histogram of Fred’s shots grouping distance from target.

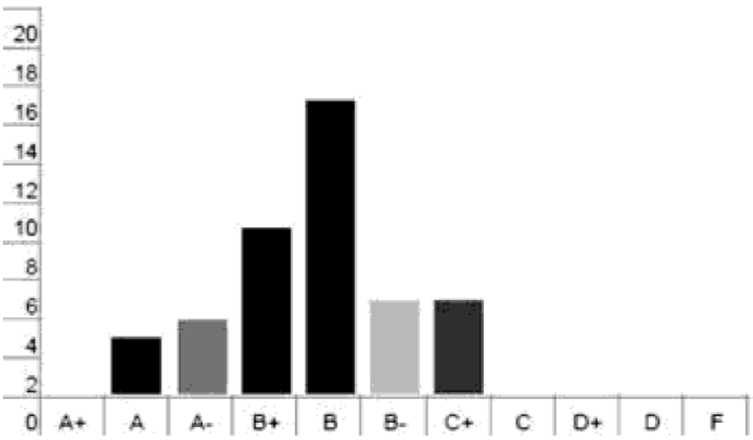

Figure 2.26 Histogram of student grades.

2.10 N^2 Charts

The N^2 chart (Table 2.1):

- Was invented by R.J. Lano (Lano 1977).
- Is a table tool that shows relationships between entities, functions, people, organizations, equipment, etc.
- Appears in many different guises, including the Waterfall Chart (Section 14.9) of the System Development Process (SDP).
- Performs the same function as the Design Structure Matrix (DSM) (Eppinger and Browning 2012) but which reverses the flows in the rows and columns as summarized in Table 2.1.

TABLE 2.1 N^2 Charts and DSM Inputs and Outputs

FUNCTION	N^2 CHART	DSM
Input	Column	Row
Output	Row	Column

2.10.1 The Basic N^2 Chart

The basic N^2 chart is based on a table in which the entities are listed across the columns and down the rows as shown in Figure 2.27. Since an entity does not connect to itself, the common cell in the table is blocked out. The N^2 chart is a modified version of Figure 2.27 in which the heading rows and columns have been removed and the common cell contains the row and column designator. Inputs between entities are shown as a connection in a column, outputs as a connection in a row. The output from an early column flows out and down; a typical example is a Waterfall Chart (Section 14.9). So, for example, if there was a connection between the output of entity A and the input of entity C in Figure 2.27, an indication of the connection would be inserted in the cell in row A column C. As well as containing a simple indicator that a connection exists, cells can be populated with information such as priorities in the event of conflict or concurrency, data pertaining to interface such as type of connectors, data types and rates, etc. From the *Generic* HTP, Figure 2.12 may be considered as a DSM with the rows and columns abstracted out since the outputs are in columns and the inputs are in rows.

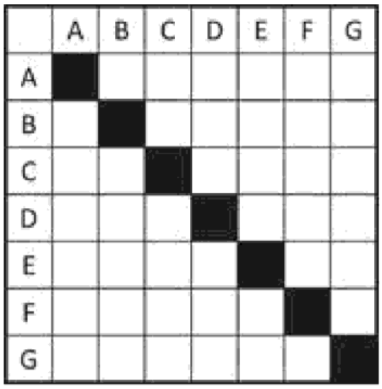

Figure 2.27 The table underlying an N^2 Chart.

2.10.2 The Aggregation Example

Consider the following example of using N^2 Charts for aggregating entities. The set of functions shown in Concept Map format in Figure 2.28 needs to be aggregated or combined into a smaller but more complex set of functions. The Concept Map view of the functions in Figure 2.28 is not very useful for this purpose since it is difficult to see any useful pattern in the interconnections between the entities. However, when the functions are drawn in the form of the N^2 Chart as shown in Figure 2.29, you can see patterns in the interfaces. For example, entities B, C, and D all have inputs and outputs from each other, so they could be combined into one higher-level BCD entity. Entities E, F, and G show a similar pattern of interconnections and could likewise be combined into a higher-level EFG entity. The resulting higher-level representation of Figure 2.28 and Figure 2.29 is shown in N^2 and Concept Map formats in Figure 2.30. The Concept Map in Figure 2.30 is simpler than Figure 2.28 and Figure 2.29, but BCD and EFG have become more complex due to their each containing three elements.

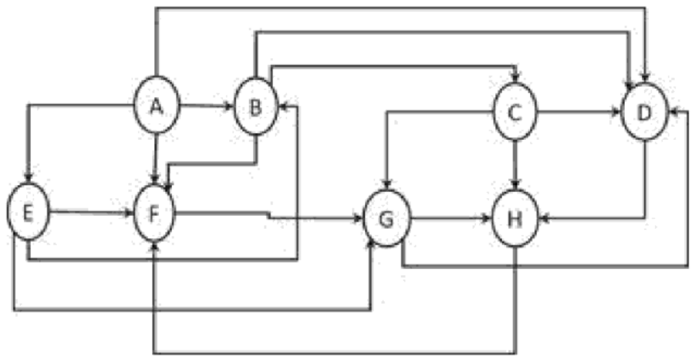

Figure 2.28 Complex Concept Map of relationships between functions.

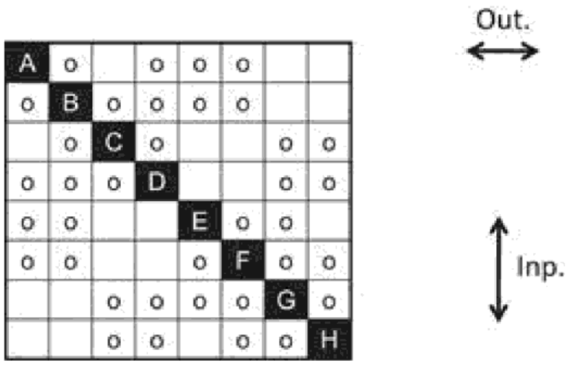

Figure 2.29 N^2 Chart of the relationships in Figure 2.28.

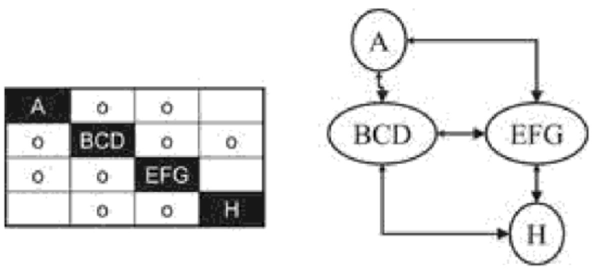

Figure 2.30 Higher level (more complex, less complicated) representations.

Note that while the N^2 chart shows patterns suitable for aggregation, it does not show you which pattern to choose. In this instance, there are a number of alternate groupings including:

- ABEF, CD, and GH as shown in Figure 2.31.
- ABD, CGH, and EF shown in Figure 2.32.
- ABEF and CDGH.

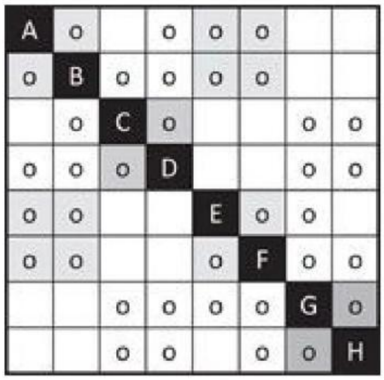

Figure 2.31 Alternate grouping -1.

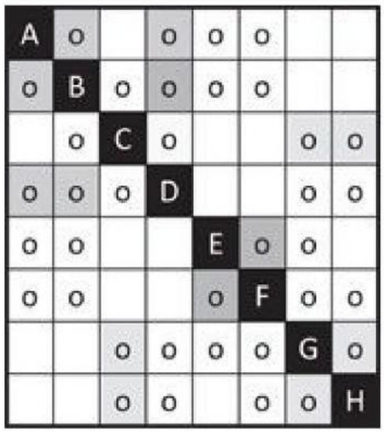

Figure 2.32 Alternate grouping -2.

The ease or difficulty of seeing the different arrangements depend on the initial sorting of the entities prior to drawing the chart in Step 3 of the process in Section 2.10.3.

2.10.3 Creating an N^2 Chart

Creating an N^2 Chart is a relatively simple process as follows:

1. Identify the entities in the area of interest often known as the system.
2. Make a List of the entities (Section 9.4).
3. Sort the entities into groups that seem connected without actually drawing any connections. This step facilitates seeing patterns in the chart once drawn.
4. Count the entities.
5. Create a table for the set of entities. Label the common cell in a meaningful manner.
6. Fill in the cells that contain the connections. Use an "x" or an "o" as in Figure 2.29 and Table 2.2 or provide the information as appropriate to the situation as in Table 2.3.

TABLE 2.2 Connections between Vivo City and Kent Vale

VIVO CITY	0	0	0	0		0									
0	Taxi								0					0	
0		10	0	0	0	0	0	0		0	0	0	0		
0		0	30	0	0	0	0	0	0			0	0		
0		0	0	143	0	0	0	0	0				0		
		0	0	0	51	0	0	0	0				0		
0		0	0	0	0	188	0	0						0	
		0	0	0	0	0	Haw Par villa					0			
		0	0	0	0	0		Clementi Rd				0			
			0	0	0				Back gate				0		0
		0								Kent Ridge Terminal	0		0		
		0								0	33			0	
		0	0	0	0	0	0	0				183		0	
		0	0	0	0				0	0			189	0	
						0							0	Front Gate	0
									0					0	Kent Vale

TABLE 2.3 N^2 Chart Linking Locations by Transportation Option

VIVO CITY	SUBWAY, 10, 30, 143, 188	10, 30, 143, 188	10	TAXI, 30, 143	TAXI, 188	
10, 30, 143, 188	Haw Pah Villa	10, 30, 51, 143, 188	10	30, 51, 143	188	
10, 30, 143, 188	10, 30, 51, 143, 188	Clementi Rd.	10	30, 51, 143	183, 188	
10	10	10	Kent Ridge Terminal	189	33	
Taxi, 30, 143	30, 51, 143	30, 51, 143	189	Back gate		0
Taxi, 188	188	183, 188	33		Front gate	0
				0	0	Kent Vale

2.10.4 Inserting Data in the N^2 Chart

The examples shown in this section so far only show that a link exists between the inputs and outputs of the system elements. There is no reason why the linking cells should not contain information about the way the connection is made such as in the following example. In solving the problem of determining the fastest route for travelling from Vivo City and Kent Vale, based on the information in the Rich Picture shown in Figure 2.33, the initial N^2 chart showing the travel connections between Vivo City and Kent Vale is shown in Table 2.2. The chart starts at Vivo City and ends at Kent Vale and shows the interconnections between the transport routes and locations.

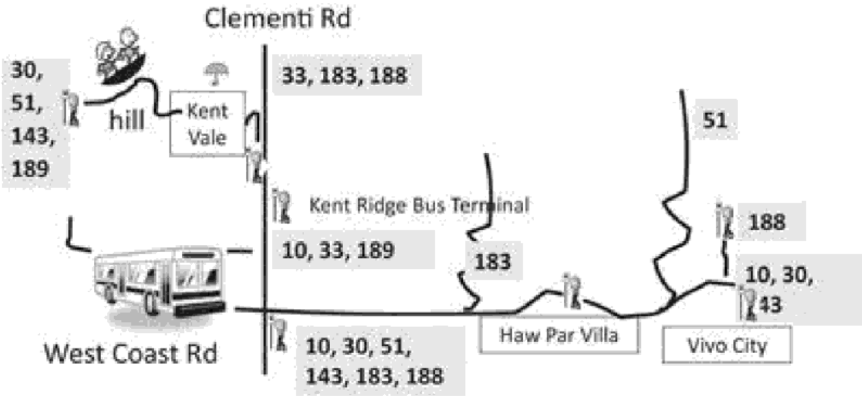

Figure 2.33 Rich Picture showing options for Vivo City to Kent Vale travel.

Now change the perspective and put the locations in the cells in the chart and link the locations by transportation option, namely using the *Continuum* HTP to perceive the bus, subway and taxis as signals travelling along the interfaces between the locations. This redesign shown in Table 2.3 shows clearly that the option to take the 10 and transfer at Kent Ridge Terminal provides fewer bus choices than all the others and reduces the number of options. Note how the N^2 chart in Table 2.3 provides information about the nature of the interface as well as the existence of an interface.

2.11 Pareto Charts

Pareto Charts:

- Were invented by Vilfredo Pareto (1848–1923).
- Are Histograms (Section 2.9) drawn with vertical bars showing the variables in order of increasing or decreasing length as shown in Figure 2.34. The figure shows the number and type of defects found when testing a requirement document in which the bars corresponding to the type of defect have been ranked according to the number of defects associated with the type. Consider the data shown in Table 2.4. Figure 2.34 graphically presents the information that poor wording and multiple requirements in a paragraph are the most common defects in the document. It is easier to see from the figure than the table that fixing those two types of defects alone will remove most of the defects in the requirement document.
- Are often used to display the degree that variables or parameters contribute to problems.
- Help to identify the few significant factors that contribute to a problem and separate them from the insignificant ones. The approach used to deal with the problem is to concentrate on the largest value first, then on the next

largest and so on, such as repairing the requirements with poor words.

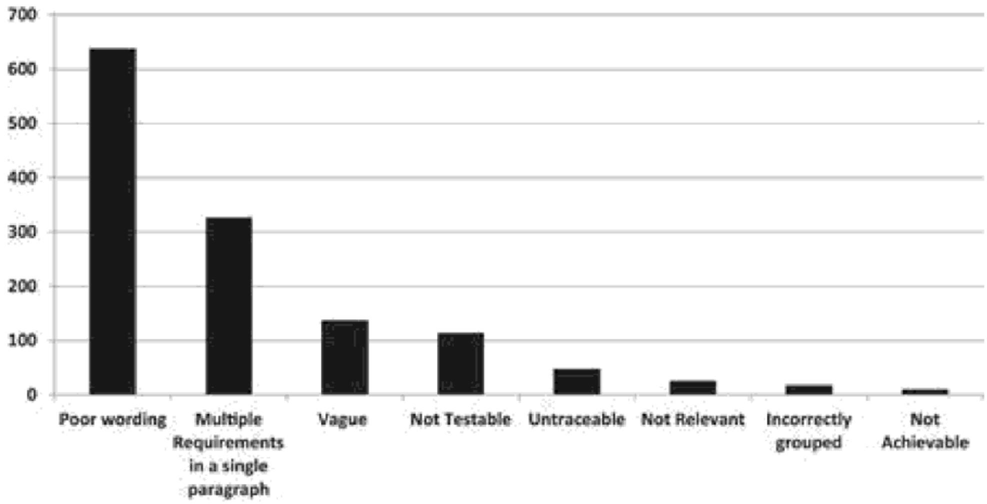

Figure 2.34 Number of defects in a requirements document shown as a Pareto Chart.

TABLE 2.4 Summary of the Defects Found in a Requirements Document

CATEGORY OF DEFECT	NUMBER OF DEFECTS
Poor wording	638
Multiple requirements in a single paragraph	327
Vague	137
Not testable	114
Untraceable	48
Not relevant	26
Incorrectly grouped	18
Not achievable	10
Total defects	1318
Total requirements	613

2.12 Pie Charts

A Pie Chart:

- Is shaped like a round pie, hence its name.
- Shows the relative values of each data item in a set as a percentage of the whole in the form of a circle or round pie. The value of each variable is represented by the size of the slice of the pie.
- Is best used to compare the size of a particular data item or slice with the whole rather than to make comparisons between different slices.
- Is often used instead of a Histogram (Section 2.9) to provide representations of summaries of data.

The same data as in the Pareto chart (Section 2.9) of Figure 2.34 is shown in

Figure 2.35. The Pie Chart makes it very clear that the "poor wording" category of defects constitutes about 50% of the defects.

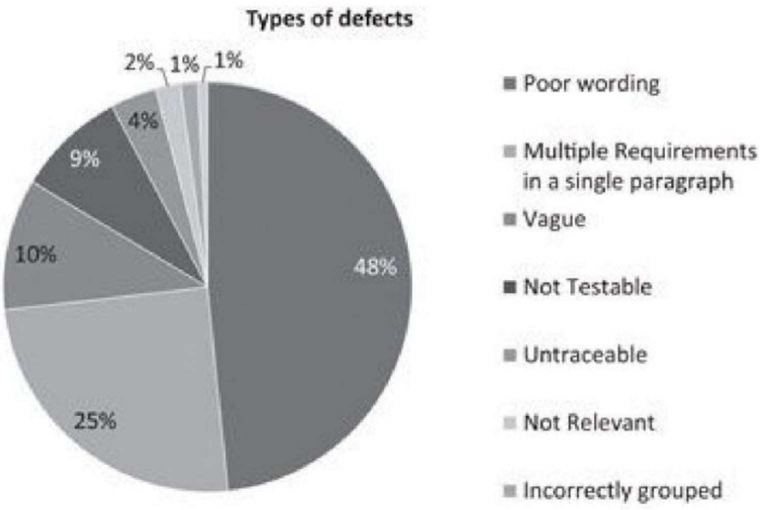

Figure 2.35 Number of defects in a requirements document shown as a Pie Chart.

2.13 Polar Charts

Polar Charts, sometimes called Kiviat Charts, Radar Charts, or Spider Charts, are used to show comparisons of a number of variables on a single chart where:

- Each spoke or axis on the chart represents a metric.
- The distance from the centre of the chart represents the metric's value plotted on that spoke.

For example, Fred's hobby is shooting. After a shooting session, he draws a Polar Chart shown in Figure 2.36 of the grouping of his shots in the target. The six-centimetre line is highlighted in the figure. Note the information shown in the figure; the distance and direction. Figure 2.36 shows the grouping of the shots, which suggests that Fred's shooting is pretty good, but he needs to adjust the sights on the weapon to move the centre of the grouping to the centre of the Polar Chart (target).

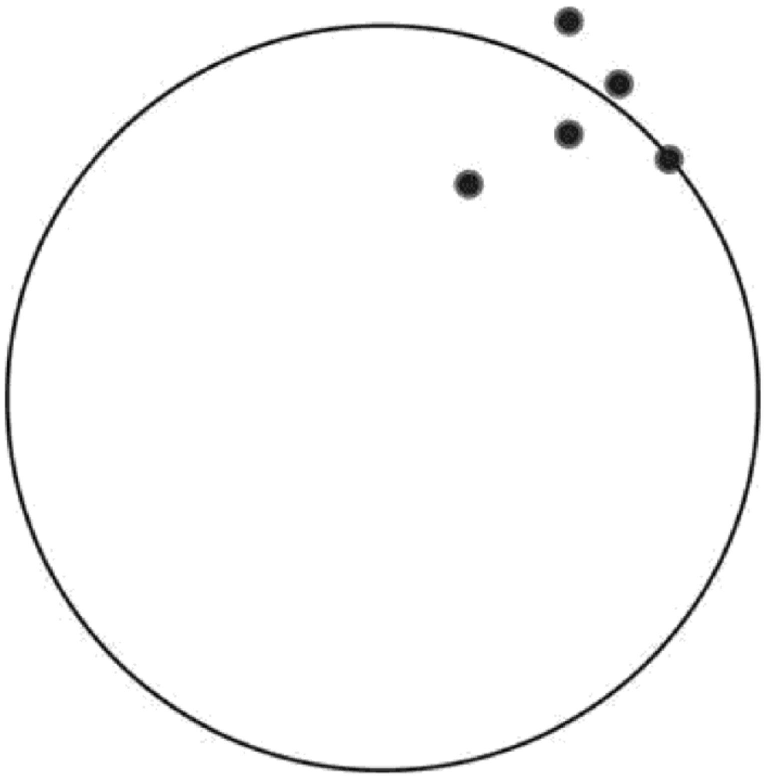

Figure 2.36 Polar plot of Fred's shots.

Polar Charts can be also used to compare two sets of information about some attributes of something, such as the performance the speed, weight, length, width, height, payload, and flight duration of two different model airplanes (Series 1 and 2). Each parameter has been evaluated on a scale of 0 to 5, and the resulting scores are shown in Figure 2.3. The chart shows that Series 1 is better in some respects, Series 2 is better in others, and the two model aircrafts received identical scores for speed.

2.14 Product-Activity-Milestone (PAM) Charts

The Product-Activity-Milestone (PAM) Chart (Kasser 1995):

- Is a tool to facilitate project planning by:
  - Defining a point in time (milestone).
  - Defining the product(s) or goals to be achieved by the milestone.
  - Determining the activities to produce the product(s).
  - Defining the resources needed to produce the product(s).
- Is designed to facilitate thinking backwards from the answer/solution to the problem (Section 11.8).
- Is shown in Figure 2.37.
- Has been found to be a very useful project-planning tool for thinking about

the relationships between the product, the activities that realize the product, and the milestone by which the product is to be completed.

- Is a Concept Map (Section 6.1.2) linking products, activities, and milestones.
- Can be used to think about the inputs to PERT Charts (Section 8.10). Note that the PAM Chart milestones are in triangles to relate them to Gantt Chart milestones (Section 8.4), while the PERT Chart milestones are in circles.
- Consists of four parts:
    1. ***The milestone***: shown as a triangle.
    2. ***The product(s) produced by or delivered at the milestone***: drawn as a sloping line(s) leading towards the milestone. Two products (A.1 and A.2) are shown in the Figure.
    3. ***The activities that produce the products***: drawn as horizontal lines leading to the product line. They are listed above the line. Labelling reflects the activities associated with the product, so activities A.1.1 and A.1.2 are associated with producing product A.1, and activity A.2 is associated with producing product A.2. All activities shall start and end at milestones.
    4. ***The resources associated with each activity***: shown as labels below the activity lines. They are listed below the line. Labelling reflects the resource associated with the activities, so resources for A.1.1 are listed below A.1.1, resources for A.2 are listed below A.2, etc.

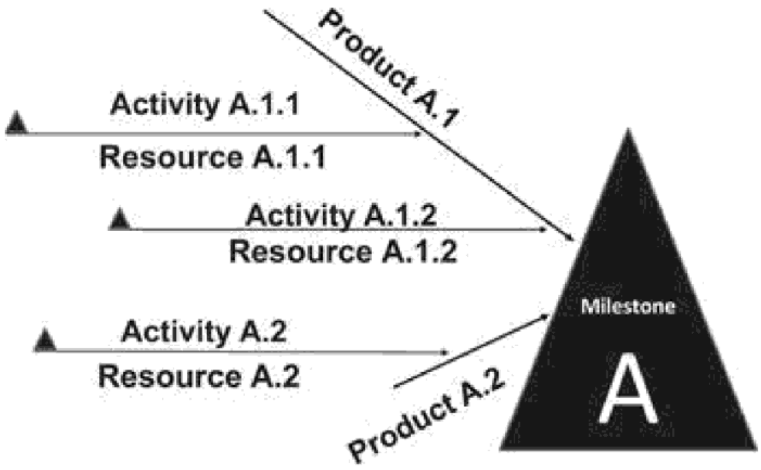

Figure 2.37 Product-Activity-Milestone (PAM) Chart.

2.14.1 Creating a PAM Chart

Use the following process to create a PAM Chart:

1. Start with a blank page.
2. Position a milestone at the right side of the paper.
3. Draw diagonal arrows for each product to be delivered at the milestone.

4. Draw horizontal activity lines that end at the product lines for each activity that creates the product. The starting point of each activity will be a previous (in time) milestone when the PAM Network Chart (Section 2.14.2) is completed.
5. Number the milestones, products, and activities where each milestone, product, and activity has an identical numeral component as shown Figure 2.37. The PAM triptych numbers at each milestone must match, which facilitates identifying missing products and activities. The letter “A” identifies activities, “P” identifies products, and “R” identifies resources. Thus product P1 is produced by activity A1 using resource R1, which may consist of R1-1, R1-2, R1-3, etc.

The PAM Chart is a node in a project network because there is more than one milestone within a project. For example, consider the partial PAM Network Chart linking the products, activities, resources, and milestones in making a cup of instant coffee, shown in Figure 2.38. Working back from the last milestone (4), the product is a stirred cup of instant coffee ready to drink. The activity between milestones 3 and 4 is “stir the mixture”, and the necessary resources are a spoon, the mixture, and a person to do the stirring. At milestone 3 the product is the “mixed ingredients”, and there are two activities, adding hot water (between milestones 1-3) and adding the ingredients (between milestones 2-3). The product produced at milestone 1 is the hot water, and the resources needed consist of water, the kettle, electricity, and a person to do the job. The product produced at milestone 2 is the set of ingredients (instant coffee, creamer, and sugar) purchased separately or as a 3-in-1 packet. Look at the figure; can you see what is missing? No? Then what are you thinking of putting the water and ingredients in before stirring the mixture? The answer is, of course, the cup.

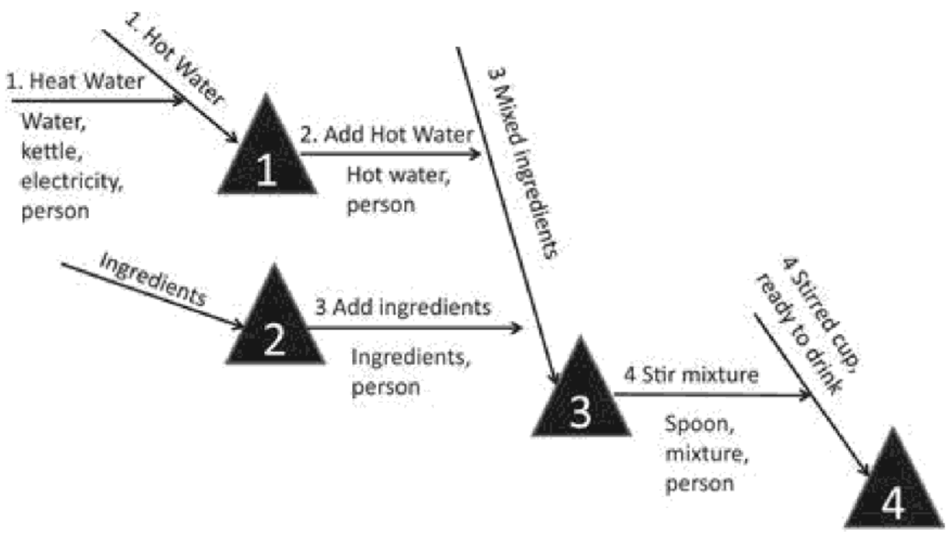

Figure 2.38 Partial PAM Network Chart for making a cup of instant coffee.

2.14.2 The PAM Network Chart

The PAM Chart can be considered as a node in a network of PAM Charts. A typical partial PAM Network Chart is shown in Figure 2.39. Information in the figure includes:

- The ending milestone is 8.
- Two products are produced at milestone 8, products P8-1 and P8-2.
- Activity 8-1 produced product P8-1, activity A8-2 produced product P8-2.
- Activity A8-1 begins at milestone 2.
- Activity A8-2 uses resource R-2.
- There are no resources allocated to activity A8-1.
- Activities A6-1 and A8-2 do not follow from a prior milestone.
- There are no activities subsequent to milestones 6 and 7.

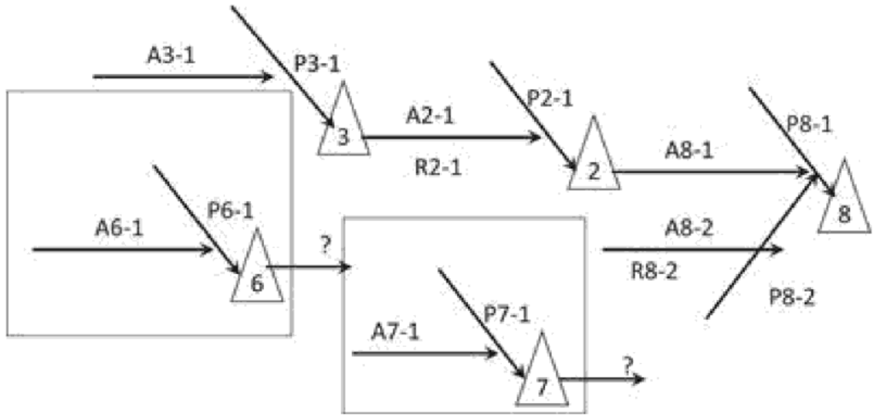

Figure 2.39 A Partial PAM Network Chart.

Accordingly, PAM Network Charts are not really useful as outputs from a project database because the PAM Network Chart can become complex and complicated very quickly when the number of milestones and products is more than nine, namely they are non-compliant with Miller's Rule (Section 3.2.5). The time taken by the activity and the milestone information should be presented in the corresponding PERT Chart (Section 8.10). The resources and other information should be stored in the Work Package (Section 8.19) and presented in the appropriate manner. For example, timelines and schedules would be presented in Gantt Charts (Section 8.4).

Partial PAM Network Charts are useful as input tools for checking that the PAM triptych numbers are complete at each milestone, all activities begin and end at milestones and all the appropriate information has been identified and either inserted into the Work Package (WP) (Section 8.19) or a "TBD" (To Be Determined) has been inserted into the WP for the corresponding activity as a placeholder.

2.15 Trend Charts

Trend Charts:

- Are sometimes called Run Charts and show how the value of something changes over time.
- Plot time along the X-axis, with the parameter being depicted along the Y-axis. The example in Figure 2.40 plots (shows) the increase in items from 0 to 4.5 over three time periods. The figure shows that there was a change in the rate of increase in the first time period which might need to be investigated.
- Are used to compare changes in a number of variables over time.
- Are widely used in finance to show how the value of a stock or commodity changes over time.

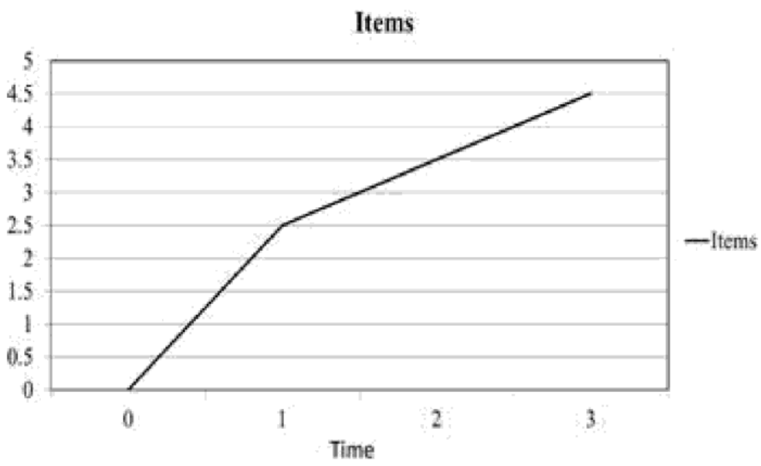

Figure 2.40 A Trend Chart.

2.16 XY Charts

XY Charts, sometimes known as Scatter Diagrams, are tools (graphs) plotted to examine the relationship (correlation) between two variables (X and Y). One variable is plotted on the X-axis, the second on the Y-axis. The difference between a Trend Chart and a XY Chart is that a Trend Chart is always a plot of one or more parameters (Y-axis) as a function of time (X-axis). Lines between the points on the graph are optional in XY Charts. For example, Fred's hobby is shooting. After a shooting session, he draws the graph shown in Figure 2.41 that shows the distance from the centre of the target for each of the six shots he fired. The chart plots the distance from the centre in centimetres on the Y-axis for each shot and the shot number on the X-axis. While Figure 2.41 shows the distance from the centre, Figure 2.36 shows the grouping, distance, and direction. The difference in the information