Australian National University

ENGN2226
Systems Engineering Analysis

Semester 1, 2016

Analysis Toolkit

Course Topics and Reading Guide

v2016 Release Candidate 2 - 15 August 2016

In this guide

This resource has been compiled to support learning in ENGN2226 Systems Engineering Analysis, and draws inspiration from a wide variety of sources. This document is supplemented by a detailed assessment guide and course outline.

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Note that ALL RESOURCES ARE IN THE RESOURCES DIRECTORY

Also see the online classroom for videos on certain topics

ADVICE TO THE STUDENT SYSTEMS ENGINEER

A large part of engineering practice is applying the rules of thumb that are learnt through experience. This is often because undertaking detailed analyses as a systems engineer can, at times, be tedious, especially when data is murky, or not available.

However, if you can wade through the murkiness, the results can be very rewarding. The Richard Feynman quotation comes to mind…

"I don't know anything, but I do know that everything is interesting
if you go into it deeply enough"

- Richard Feynman, Nobel Prize 1965

The ideas herein are to be nurtured and explored as you make your analysis interesting.

ENGN2226 ANALYSIS TOOLS

The topics covered in ENGN2226 can be undertaken in almost any order. Understanding which tools are required when is an important skill in the application of analysis.

The course topics are divided into three themes:

- rules of thumb - these are practical tips, trends and principles to base analyses
- research methods - these are approaches that will help you to conduct analysis in a research context
- system perspectives - these are ways to view, measure and analyse a system

Table 1: Analysis Tools

Part 1: Rules of thumb	Part 2: Research methods	Part 3: System perspectives
T01: Fermi estimation	R01: Research question	S01: Social & cultural
T02: Pareto principle	R02: Surveys and interviews	S02: Safety & risk
T03: Occam's razor	R03: Quantitative & qualitative	S03: Anthropometrics
T04: Hofstadter's law	R04: Data organisation	S04: Planning approaches
T05: Parkinson's law	R05: Research ethics	S05: Queue theory
T06: Jevon's paradox	R06: Coding research data	S06: Process control
T07: Moore's law	R07: Error types	S07: Control theory
T08: Correlation and causation	R08: Descriptive statistics	S08: Material impact
T09: Bathtub curve	R09: Hypothesis testing - populations	S09: Energy-mass balance
T10: Vicious & virtuous cycles	R10: Hypothesis testing - categories	S10: Energy efficiency
T11: I=PAT	R11: Simple linear regression	S11: Life-cycle cost
T12: Diminishing returns	R12: Confidence intervals	S12: Payback period

There is no set textbook in this class. Instead, this resource has been prepared to guide your thinking about systems engineering analysis. Most readings have been linked directly, or can be accessed through the course website with your university login.

If you are looking for resources to supplement your investigations, there are a number of good resources that partially cover the concepts in this course:

- Blanchard, B.S., W.J. Fabrycky, 2011, Systems Engineering and Analysis, Fifth ed. Pearson, NJ.
- Faulconbridge, I, Ryan, M., Introduction to Systems Engineering. (eBook for $11.99)
- Hitchens, D.K., 2007, 'Systems Engineering - A 21st Century Systems Methodology', Wiley, NJ.
- IDEO's human-centred design process (Online or download PDF
- The Systems Engineering Body of Knowledge (SEBoK): http://sebokwiki.org/
- Service Design Tools has great collection of activities and ideas for design: http://www.servicedesigntools.org/
- Stasinopoulos, P., Smith, M., Hargroves, K. and Desha, C., 2008. Whole System Design - An Integrated Approach to Sustainable Engineering, The Natural Edge Project, Earthscan, London.
- Systems Engineering Fundamentals, Department of Defence
- MIT's Opencourseware subject on systems engineering (check out the reading list too..)

TOPIC OVERVIEW

There are 36 topics covered in this course, divided into three themes. The topics, however, overlap between the themes, and many can be used interchangeably and for different purposes.

Another way to divide these topics is to consider the factors that might help you navigate analysis of engineering problems. A suggestion of these factors are below:

Quantitative Data

Information about your system is not always nicely collated. Sometimes you have access to information, sometimes you have access to 'proxy' indicators, and other times you have to make an informed estimation. The focus of this topic is to develop a good working understanding of how you can make good estimations in the absence of good data.

Qualitative Data

Qualitative methods can help you move past the numbers and develop a rich understanding of what's happening behind the data. The process for collecting qualitative data can be as rigorous as collecting numerical data, but usually has many more insights or conclusions.

Human Factors

Humans are a major factor in design. When seats don't fit, when signs don't point you in the right direction, when buildings aren't comfortable – it's as if the designer hasn't considered humans in the design. These factors extend to the workplace health and safety factors so that human safety is paramount in the analysis of systems.

Time Factors

Life can be seen one big queue. Everyone spends time waiting, whether we like it or not. In time analysis, we take a birds-eye view of our systems, and look at the application of Queue Theory to optimise our systems, Gantt charts to plan activities, and behaviour over time graphs to understand the temporal behaviour of systems.

Materials Factors

Materials and energy are inextricably linked, so this week may appear to overlap with the energy topic. Ultimately the goal of this topic is to understand the life-cycle of the materials in your design, system or product, and how statistical methods can be used to anticipate material qualities.

Energy Factors

Energy takes many forms, and could apply to any energy input and output into your system. Our key driver in analysing energy is to improve energy efficiency by looking for opportunities to make our system more effective. This often has many co-benefits, including cost savings and improving environmental outcomes.

Control Factors

In this topic we look at the control systems that are required to make smart systems. Feedback concepts are a fundamental part of systems today, and a key way to improve performance of a system. We'll also look at the behaviour of dynamic systems that are not control systems.

Cost Factors

At the end of the day, the most important analytical technique to get a project off the ground is likely to be the economic analysis. Can the system pay for itself? Can it be profitable? Once you've established the feasibility of the other aspects of your design, now turn your mind to paying for it!

PART I: RULES OF THUMB

T01: Fermi Estimation

A Fermi estimation should get you to an estimation within an order of magnitude

Back of the envelope estimation is an important skill - one that Manhattan Project physicist Enrico Fermi was fascinated by. Fermi estimation isn't just a case of guessing, you can use a structured approach to estimating numbers, and you're often able to get to your estimation using multiple logic paths as a check.

Example applications

Fermi estimation is a useful technique when we don't have much data about a problem. The classic Fermi estimation might include

Steps

- take what you know about a problem, and work in the order of magnitude
- make simple assumptions and justifications
- in our case, verify your estimation using data that you can access

Key concepts for the Online Classroom

When preparing your resource, you should consider covering:

- the situations when Fermi estimation might be useful, and an example
- the process for generating a rapid order-of-magnitude estimation
- alternative ways of triangulating or verifying your Fermi estimation
- advice for student engineers about considerations of the likely error in a Fermi estimation, such as over- or under-estimation

Core resources

- A Clever Way to Estimate Enormous Numbers (video)
- Maths & Modern Life (Direct Link to Audio ~17min)

Similar concepts…

Fermi estimation is a "back-of-the-envelope" or "rapid estimation" technique. There are many others that might be suitable.

Figure T01: Fermi estimation according to xkcd comics
https://what-if.xkcd.com/84/

T02: The Pareto Principle

The Pareto principle, or 80-20 rule, shows that the vital few often control the majority

The Pareto principle is a rule of thumb that tells us that in any given problem, the majority (80%) of a problem is caused by the minority (20%) of reasons. First observed by Wilfredo Pareto in 1896, he noticed that 80% of the land in Italy was owned by 20% of the population, and this observation has been translated to many different applications.

Example applications

There are many different applications in process engineering, economics, business, science, and the social sciences.

Steps

In order to investigate the Pareto principle, you need to gather data about the problem. For example, if you were investigating complaints about a company's product, you would need to know the number of complaints and the number of customers in order to establish a Pareto relationship.

Key concepts for the Online Classroom

- the background of the Pareto principle
- example applications of the Pareto principle
- a worked example using real data, including constructing a Pareto chart
- how a company would priorities its efforts, given an understanding of the Pareto principle
- some considerations about the flexibility of the 80-20 rule (e.g. it is not a strict 80-20)

Core resources

- Leavengood, S., and Reeb, J., 2002, Pareto Analysis and Check Sheets
- The Wikipedia page provides a nice overview: https://en.wikipedia.org/wiki/Pareto_principle

Similar concepts…

There are many similar tools that describe the relationship between the minority and majority. We are the 99% was the slogan of the Occupy movement.

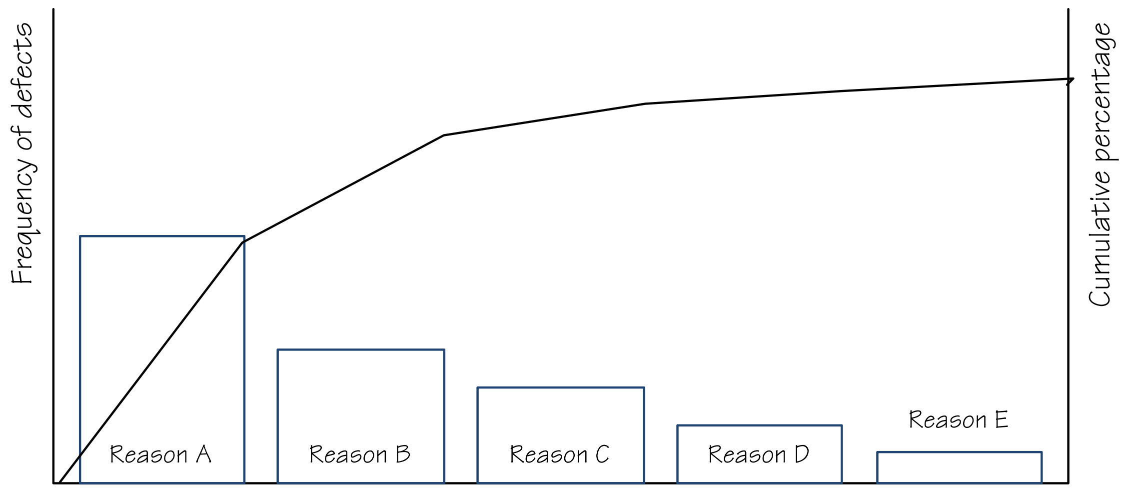

Figure T02: Example Pareto chart

T03: Occam's Razor

Among competing ideas, the simplest answer is probably correct

Occam's razor is a philosophical problem-solving technique that biases thinking towards selecting the simplest explanation. It does not state that we must create a simple explanation, rather it encourages one to preference simpler explanations.

Example applications

Occam's razor is commonly associated with the advancement of scientific theories. Occam's razor is only particularly useful if you don't know the answer already, as it is a method of evaluating competing hypotheses.

Steps

Take your competing hypotheses, and compare them in a non-biased way. Then, once you have examined the competing hypotheses, look more favourably at the explanations that have fewer assumptions.

Key concepts for the Online Classroom

- the background of Occam's razor
- an application of Occam's razor to a real-world engineering problem
- a discussion about the difference between simplicity and fewer assumptions (for example, Newtonian physics may be simpler than the General Theory of Relativity, but arguably has more assumptions, such as assuming we are in a vacuum).

Core resources

- Domingos, P., The Role of Occam's Razor in Knowledge Discovery provides a very academic approach to the concepts
- Adam Savage's TED talk on simplicity covers the concepts well

Similar concept…

Occam's razor is somewhat similar to the KISS (Keep It Simple, Stupid) principle in design.

Figure T03: Occam's Professor from Piled High and Deeper (PHD) comics

T04: Hofstadter's Law

It always takes longer than you expect, even when you take into account Hofstadter's Law.

Douglas Hofstadter's perspective of time can be seen everywhere, especially in project management. Hofstadter's law is self-referential, and explains the phenomenon that it is often difficult to estimate the time that it will take to achieve a goal.

Example applications

You might be familiar with the concept that assignments can often take longer than expected. As the complexity of the activity increases it becomes even more important to acknowledge Hofstadter's law in the planning of your activity.

Steps

Acknowledging Hofstadter's law doesn't necessarily help you produce a better estimate of time, but accounting for it in the planning stages of a project

Key concepts for the Online Classroom

- an overview of Hofstadter's law
- an example application of a project that has taken longer than expected. Examples of complex engineering project that are 'over-time and over-budget' would do this well
- advice for the student engineer about avoiding overruns through using Hofstadter's law

Core resources

- The Systems Engineering Body of Knowledge (SEBoK) is a good place to get started about project planning: http://sebokwiki.org/wiki/Planning
- The Wikipedia page has a brief introduction to the philosophical aspects of the law: https://en.wikipedia.org/wiki/Hofstadter%27s_law

Similar concept…

The classic project management rule-of-thumb that builds on Hofstadter's law is that you should estimate the time it will take to complete something, and then double it. The same often goes for estimating the cost of a project.

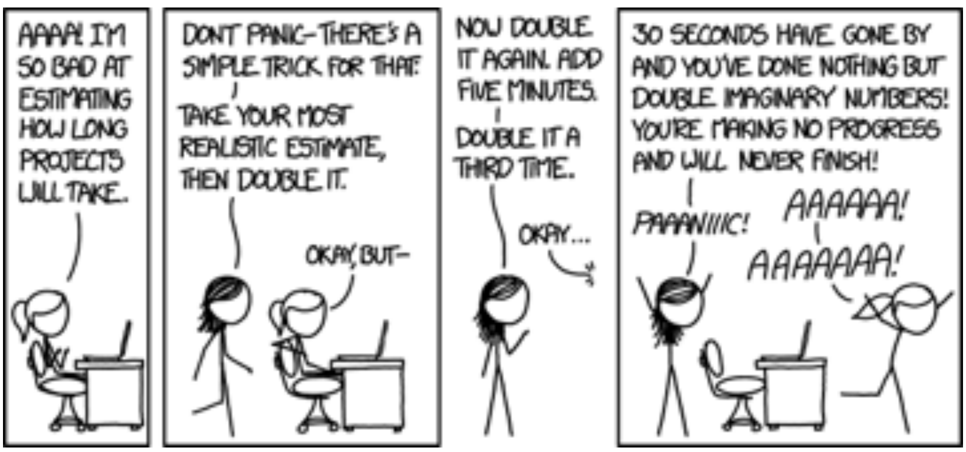

Figure T04: xkcd comics
hhttps://www.explainxkcd.com/wiki/index.php/1658:_Estimating_Time

T05: Parkinson's Law

Work expands to fill the time available for its completion

As almost a counter-example to Hofstadter's law, Parkinson's law describes the inflation of a project's scope to meet the time available for deadline.

Example applications

This law is probably, again, familiar to you as a student - if you are given three weeks to write an essay, it will take you three weeks; if you are given three hours, it will take you three hours. Cyril Northcote Parkinson famously observed this phenomena in relation to the British civil service, where the size of the bureaucracy continued to increase, and so did the scope of their duties (not the other way around).

Steps

Acknowledging Parkinson's law, again, doesn't necessarily help you to keep the project in check. In trying to examine Parkinson's law, you might find information about the timings of a project's planned and actual deliverables, or look for the growth of the workforce in a bureaucracy.

Key concepts for the Online Classroom

- an overview of Parkinson's law
- an example application of a project where the project scope has expanded, or the size of the workforce has increased without any perceivable gain
- advice for the student engineer about avoiding scope creep through referencing Parkinson's law

Core resources

- *The Economist,* Parkinson's Law [online]

Similar concept…

A similar concept to Parkinson's law is the idea of "shifting goalposts" or "scope creep", where the project shifts from its original intention and expands to fill the time before delivery.

Figure T05: Parkinson's Law by SYSADMINOTAUR
https://blog.devolutions.net/2014/02/sysadminotaur-27-parkinsons-law.html

T06: Jevon's Paradox

Technical efficiency reduces consumption, and in turn increases overall consumption

Jevon's paradox describes the frequently observed phenomena where the technical efficiency of system leads to an overall increased demand of the resource. Jevon's paradox is often referred to as the rebound effect.

Example applications

The classic example of Jevon's paradox was the use of coal in England after the creation of the steam engine. The coal-fired steam engine was far more efficient than other technologies at the time, and instead of reducing consumption of coal, the number of applications and volume consumed increased.

Today, there are many examples of technologies that improve the individual efficiency of a product, but lead to an overall increase in consumption. A good example is the continuous improvements in fuel consumption in cars, coupled with the average distance travelled increasing as with the total number of cars on the road.

Demonstrating Jevon's paradox

To demonstrate Jevon's paradox, data about consumption are required over a period of time. To demonstrate the paradox, efficiency improvement is also required.

Key concepts for the Online Classroom

- an overview of Jevon's paradox
- an example application of resource consumption over time, especially where there is a concurrent example demonstrating improved efficiency

Core resources

- Alcott, B, 2005, Jevon's Paradox, Ecological Economics

Similar tools…

Jevon's paradox can be related to the systems-thinking archetype fixes that fail.

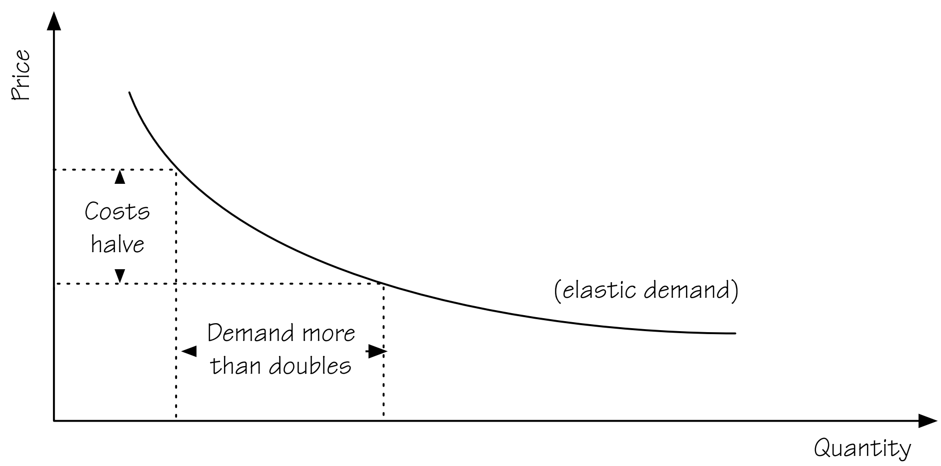

Figure T06: Jevon's paradox
As costs halve, demand more than doubles

T07: Moore's Law

The speed of progress doubles approximately every two years

George Moore's observation that the number of transistors on an integrated circuit roughly doubles every two years has held for approximately 40 years of technological progress. Nowadays, Moore's law is used more flexibly to describe that technological progress continues to grow exponentially.

Example applications

The classic example in Moore's law applies to transistors on an integrated circuit, but it has become both a target and self-fulfilling prophecy for a range of technology-related activities. Other examples include the affordability of IT equipment, hard disk drive capacity, pixels-per-dollar in digital cameras, and the cost of developing medicine.

Demonstrating Moore's Law

To demonstrate Moore's law, a 2-dimension scatter-plot is required, with the x-axis often describing time or money, and the y-axis as a log scale of the variable of interest.

Key concepts for the Online Classroom

- an overview of Moore's law, including the concept of unconstrained exponential growth or doubling over time
- an example approximately demonstrating Moore's law
- advice for the student engineer about how Moore's law can be used to forecast future demand or requirements.

Core resources

- Schaller, R., 1997, 'Moore's Law: Past, Present and Future', IEEE Spectrum, June,

Similar tools…

Moore's law has many variations that have been applied to different circumstances of technological advancement. The Wikipedia page has a good list of these: https://en.wikipedia.org/wiki/Moore%27s_law.

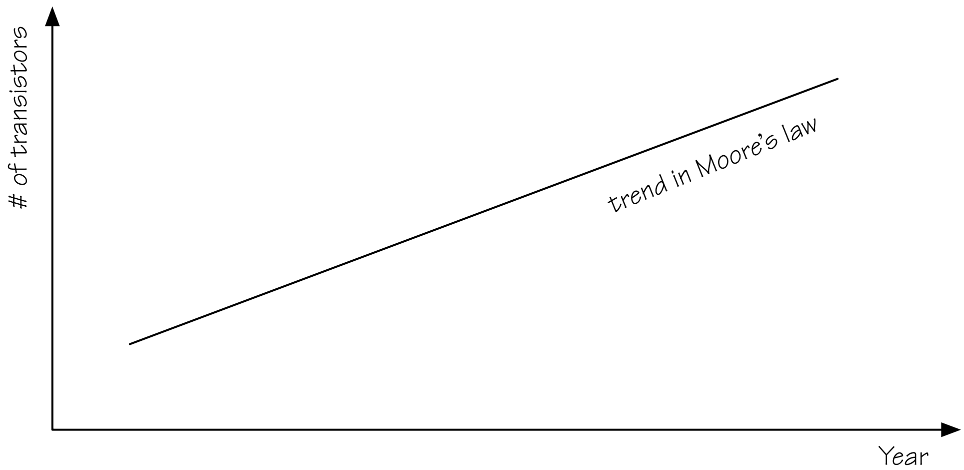

Figure T07: The trend in Moore's Law

T08: Correlation and Causation

Demonstrating correlation between two variables does not imply causation;

In this topic we examine the well-known rule of thumb that correlation does not imply causation. This is a cautionary rule of thumb that encourages the analyst to not jump to conclusions. Studies that take this form often prescribe that because of X, Y has happened. A more appropriate statement might be: when X happens, Y also happens, demonstrating correlation between the two events.

Example applications

Correlation is a common statistical tool that indicates how two or more variables change together, either in the same direction (positive correlation) or in opposite directions (negative correlation).

Demonstrating correlation and causation

This topic is a cautionary one, so it's about not jumping to conclusions. In order to discuss correlation and causation, you should be able to identify whether two variables show a linear correlation.

Key concepts for the Online Classroom

- an overview of what correlation is, and what causation is.
- an example of how correlation can lead to erroneous causation statements
- advice for the student engineer about how to be cautious around establishing cause and effect between two variables.

Core resources

- Velickovic, V, 'What everyone should know about statistical correlation' American Scientist.

Further information…

There are a number of 'spurious correlations' listed at TylerVigen.com, such as the number of people who drowned by falling into a pool, correlating with the number of firms Nicholas Cage appears in in a given year.

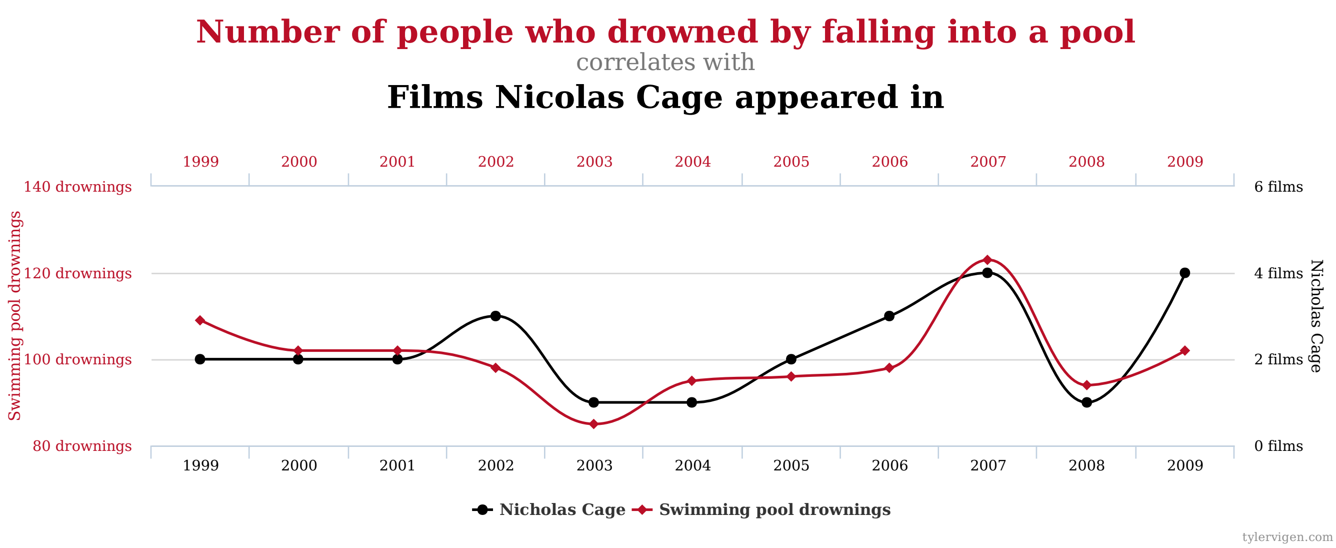

Figure T08: Correlation and causation
http://www.tylervigen.com/spurious-correlations

T09: The Bathtub Curve

The bathtub curve is a rule-of-thumb for understanding causes of product failure

The bathtub curve describes the shape of aggregated failure rates for a given product. Also known as a hazard function, it's a rule-of-thumb that generally states:

- random failure is likely to happen at all stages of a product's lifecycle
- early failure decreases over time as problems in a product are resolved. These are typically characterised as design flaws
- wear-out failure increases over time as components wear out. These typically occur after the warranty period of a product, and are either repaired or the product is replaced with the newer version.

Example applications

The bathtub curve is widely used in reliability engineering. It provides a way of thinking about the likelihood of failure during a product's lifecycle.

Building a bathtub curve

In order to replicate the bathtub curve, whole-of-system data is required. This is often difficult to find, so the practical value of understanding the bathtub curve in the context of this course is knowing that there are the three failure modes, and accounting for them in the planning about a design.

Key concepts for the Online Classroom

- an overview of the bathtub curve, and the three types of failure
- a practical example of the three types of failure (may be different examples)
- advice to the student engineer on how understanding the bathtub curve can lead to better engineering decisions

Core resources

- G. A. Klutke, P. C. Kiessler and M. A. Wortman, "A critical look at the bathtub curve," in IEEE Transactions on Reliability, vol. 52, no. 1, pp. 125-129, March 2003.

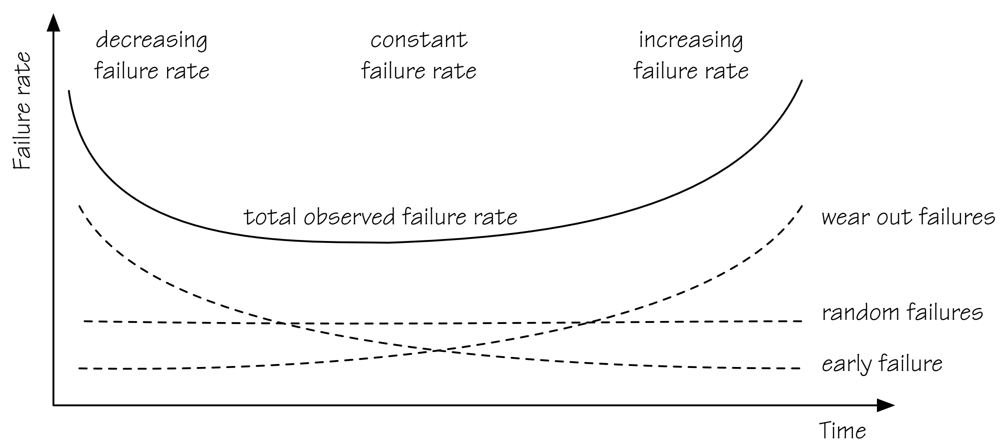

Figure T09: Bathtub curve

T10: Vicious and Virtuous Cycles

Vicious and virtuous cycles are feedback systems that push away from a steady state

Vicious and virtuous cycles are often caused by a chain of events that exhibit reinforcing behaviour. A virtuous cycle is established in a positive frame; for example, as a result of doing something good, you are rewarded, which enables you to do something better. A vicious cycle is the same feedback structure in a negative frame; for example, as a result of doing something bad, you are penalised, which encourages you to do something worse.

Example applications

Feedback structures are most-commonly seen in systems thinking examples, where causal links are made between variables. Commonly, a the two cycles are linked because of a finite resource; for example, the rich get richer and the poor get poorer. At the extreme, the feedback structure can lead to 'runaway' behaviour, such as runaway climate change.

Building a feedback cycle

A simple way of building a feedback cycle is using a Causal Loop Diagram. Note, that vicious and virtuous cycles are both 'reinforcing' feedback structures. A 'balancing' feedback structure is often referred to as 'goal-seeking'.

Key concepts for the Online Classroom

- an overview of the behaviour of vicious and virtuous cycles
- an example of the feedback structure using a causal loop diagram
- advice to the student engineer on how to promote and/or escape these cycles.

Core resources

- Systems Thinking on Coursera - Causal Loop Diagrams
- North, K., 2005, An Introduction to Systems Thinking.

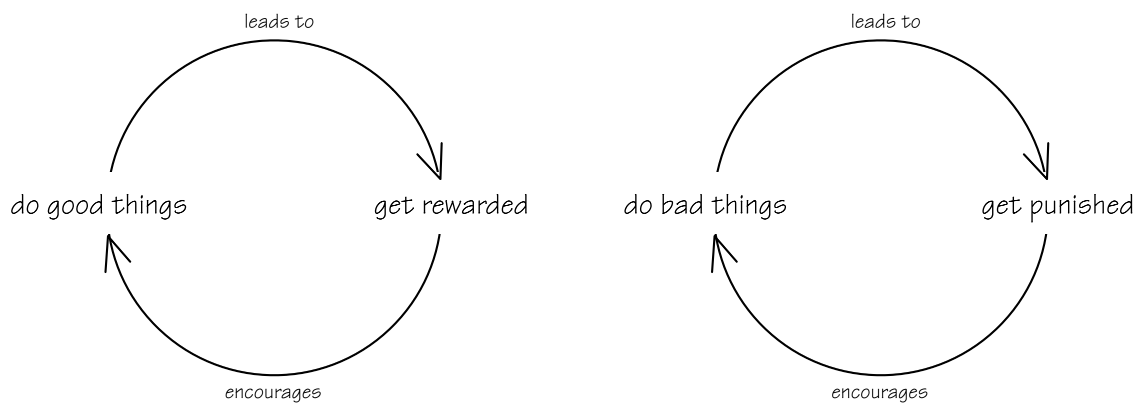

Figure T10: A virtuous cycle (left) and vicious cycle (right)

T11: I=PAT

The impact of a system can be measured by population, affluence and technology.

Impact = Population x Affluence x Technology is a rule-of-thumb designed to describe the key relationships of environmental impact. It is, obviously, a simplification, but it importantly describes that if population increases, affluence (consumption) or technology (efficiency) must balance out this change. In this way, the relationship clearly describes that unless these factors are kept in check, the environmental impact will increase.

Example applications

The argument around I=PAT in the 1970s between Commoner, Ehrlich and Holdren revolved around recognising the effect of a growing population on the environment. In recent decades, as material consumption has increased significantly, the focus has moved to a reliance on techno-fixes to solve the rapid growth of both ‘P’ and ‘A’.

Steps

In a given system or problem, identify the variables for P, A, and T. The units for these variables will determine the units for I.

Key concepts for the Online Classroom

- an overview of the I=PAT equation and the relationships between the variables
- an example comparing two similar scenarios, such as the impact between plastic or reusable shopping bags
- advice to the student engineer on how to use the IPAT framework to select options that reduce the impact of a system

Core resources

- Chertow, M.R., 2001, ’The IPAT Equation and its variants’, Journal of Industrial Ecology

Similar tools…

There are links in the IPAT equation to the behaviour in Jevon’s paradox.

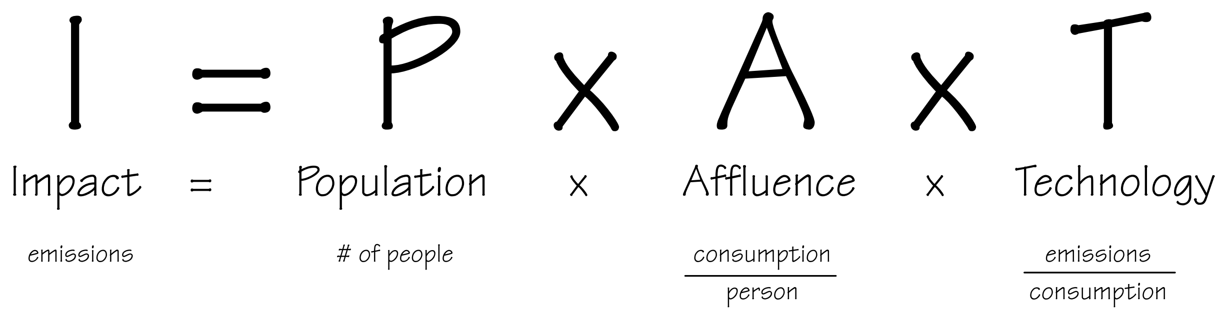

Figure T11: The I=PAT equation

T12: Diminishing Returns

There is a point where the return on resources given to a project do not yield improvement

The law of diminishing returns is a classic economic rule-of-thumb, often used in production theory. Similar to the Pareto principle, and exhibiting goal-seeking behaviour, the law of diminishing returns tells us that as you add more resources to a project, the per unit improvement of the additions becomes smaller and smaller, to the point where it could actually have a negative effect.

Example applications

Consider the number of workers in a production line. As you add more workers, performance will improve, up to a point. As more workers are added, the idle time increases, and the per-unit value of the worker goes down.

Similarly, you have probably experienced a situation where you have spent a small amount of time on an assignment, and have done OK, but in order to do better you might have to spend 3-4 times that amount of time.

Steps

To establish a graph that describes diminishing returns, you will need to establish two variables of interest, such as 'time spent on an assignment' and 'marks earned', or 'cost of wages' and 'production value'.

Key concepts for the Online Classroom

- an overview of the law of diminishing returns
- an example that demonstrates the law, preferably an engineering example
- advice to the student engineer on how to optimise performance, given an understanding of the law of diminishing returns.

Core resources

- Kossiakoff, A. Sweet, W., Seymour, S, and Biemer, S., 2011 *Systems engineering principles and practice* (particularly pages 28-30)

Similar concepts…

The law of diminishing returns exhibits goal-seeking behaviour; it is a balancing feedback system. There are also parallels to the Pareto principle, in that the majority of return is achieved with the critical few.

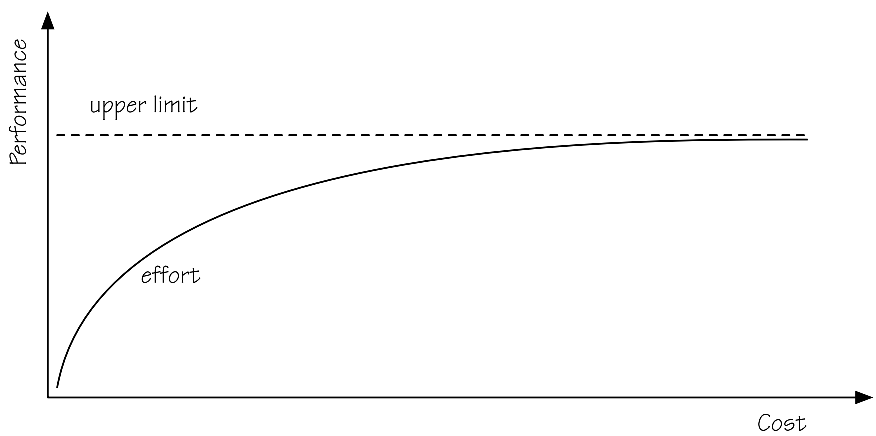

Figure T12: Graph of diminishing returns

PART II: RESEARCH METHODS

R01: Crafting a Research Question

Crafting a good question will set your research off in the right direction

Crafting a research question is an essential skill for engineers who want to understand how things work. Perhaps the most basic research question, as Emeritus Professor Bob Douglas would say, is “Why is it so?”. In this topic, we’re going to explore how to create a research question. Taking a research approach to your engineering will set you apart from technical engineers. A research approach requires you to look beyond the immediate problem, and understand it more completely.

Example applications

As ANU Engineering students, research will be a major component of your university degree. In ENGN2226, you’ll examine a problem in-depth in your research portfolio. Also, the best Online Classrooms will frame their investigation as a research problem.

Steps

Kirschner argues that good research questions:

- draw on background knowledge
- address a puzzle
- use ‘reporter’ questions (who, why, where, when, what)
- do not have a one-sentence answer or a single, factual answer
- do not contain a lot of proper nouns
- are within the scope of the project
- do not predict the future (these might be good questions for further work)

Key concepts for the Online Classroom

- an overview of what research is, and what a research question should do
- an example of how to craft a research question, including the difference between the theme, topic, focus and question.
- advice to the student engineer on how to craft a research question. Using the portfolio as a context might be useful.

Core resources

- Kirschner, S, Crafting good research questions, Allegheny College
- Thompson Writing Program, What makes a good research question, Duke University

More information

ANU’s Academic Skills & Learning Centre offer some great services around developing

Academic Skills, How to start researching your essay, ANU

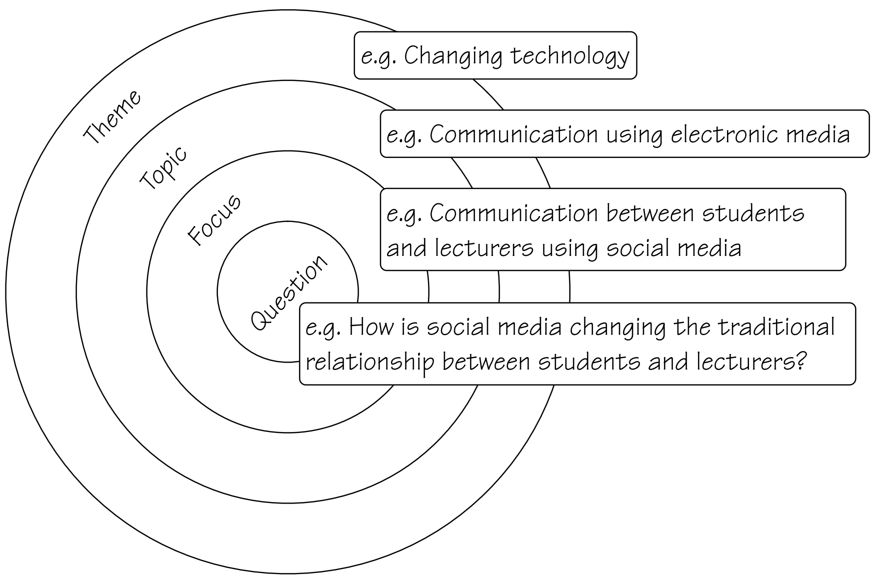

Figure R01: A research question should be focussed

R02: Conducting Surveys and Interviews

Surveys and interviews will help you understand more about the people you are engineering for

Conducting surveys and interviews is traditionally outside the scope of engineering, but more frequently (and for the better) engineers are talking to the humans that will use their designs. To find out what the user thinks, you're going to have to ask them some questions, and just like in the scientific method, your methodology needs to be sound and repeatable.

Example applications

Surveys and interviews are used extensively in requirements engineering and user evaluation. In ENGN2226, it is important to understand both how to design surveys and interviews, but also what some of the pitfalls might be in the design of these tools. Were the participants incentivised? Are there any sources of underlying bias or were leading questions used?

When to use them

Rowley (2012) suggests interviews are good to use when:

- the objectives centre on understanding experiences, opinions, attitudes, values, and processes
- there is insufficient known about the subject to be able to draft a questionnaire
- the interviewees might be more receptive to an interview than other data gathering approaches

Whereas Boynton and Greenhalgh (2006) note that surveys are useful when you can predict the possible range of answers.

Key concepts for the Online Classroom

- an overview of the key differences between interviews and a survey
- an example of how how a research project might generate data from an interview and a survey
- advice to the student engineer on how to conduct a quality survey or interview. Using the portfolio or the group project as a context might be useful.

Core resources

On interviews:

- Rowley, J., (2012) "Conducting research interviews", *Management research review,* Vol 03/2012 pp260-271. Online: http://www.emeraldinsight.com/doi/pdf/10.1108/01409171211210154 [access via ANU's reverse proxy]

On surveys:

- Boynton, P.M., and Greenhalgh, T., 2004, "Selecting, designing and developing your questionnaire", BMJ, 2004:328 pp1312-1315.

Similar tools…

If your approach involves talking to vulnerable people or groups, such as interviewing people in a development context, a great handbook that gives an overview of conducting field research is the Medecins Sans Frontiers guide:

- Quinn Patton, M and M Cochran, 2002, A Guide to Using Qualitative Research Methodology, Medecins Sans Frontieres

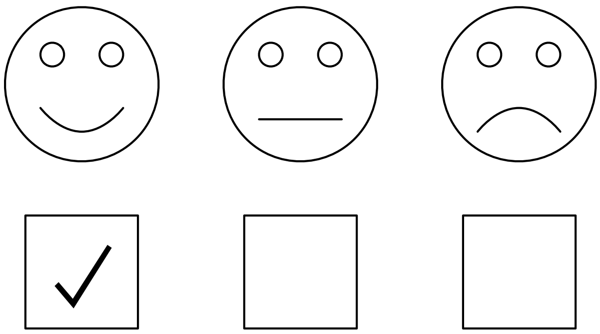

Figure R02: Simple survey design

R03: Quantitative and Qualitative methodologies

> Qualitative approaches encourage in-depth understanding of the issue in question; quantitative approaches can be used to generalise the outcomes.

Research methodologies can be broadly defined into three approaches: quantitative, qualitative and mixed methods (both). Traditionally, quantitative methodologies are the reserve of the sciences, where repeatable, controlled experiments are preferred. Conversely, qualitative methodologies have been associated with the social sciences, where research is a bit more nuanced. The reality is that both approaches are useful in different contexts, and understanding how and when to use them is important when gathering information about your system.

Example applications

Quantitative methodologies explore measurable trends, such as the data gathered in an experiment or in a survey. Quantitative approaches look for relationships between variables.

Qualitative methodologies explore phenomena that are harder to measure. Examples include narrative research, phenomenological research, grounded theory, ethnography and case studies.

Mixed methods explore a problem using both methodologies. For example, a survey might use mixed methods if it includes open-ended questions, or if observational data is quantified and generalised to a broader context.

Steps

To decide what approach your research might employ, you should have a clear idea of your research question (see R01), and what data might already be available. Creswell (2003, p19) suggests this rule of thumb:

- Quantitative approaches use closed-ended questions, predetermined approaches and numerical data
- Qualitative approaches use open-ended questions, emerging approaches, text or image data
- Mixed methods use open- and closed-ended questions, emerging and predetermined approaches, and both quantitative and qualitative data

Key concepts for the Online Classroom

- an overview of the key differences between the three research methodologies
- a practical example of each research methodology in the context of your DLab theme
- advice to the student engineer on how to select a research methodology given the data or approach that might be used

Core resources

- Creswell, J.W., 2003, Research Design: Qualitative, Quantitative and Mixed Methods Approaches, Sage Publishing (particularly p18-21) [PDF of Chapter 1]

Figure R03: A pragmatic approach to picking your methodology(?) by Tom Fishburne

R04: Data organisation

> The information you get out of an analysis will only be as good as the information you put in

Organising your data will make a big difference to the quality of your analysis and build confidence in the outcomes. It starts with accurate data entry in the first place, using systematic and established naming protocols.

Example applications

If you've conducted a survey on paper, you'll need to translate the data into a spreadsheet to manipulate it. To reduce the likelihood of error, it is convention to have two people input data, and resolve discrepancies line-by-line. Alternatively, as a student, a way to input data might be to use two different approaches, such as building a form to enter data, then entering data directly into a spreadsheet, then resolving any discrepancies.

Steps

The ANU's Statistical Consulting Unit suggests guidelines for organising data. In summary:

- in a spreadsheet, given an ID to each observation
- use one row per observation (e.g. survey response), and use one column per characteristic (e.g. sex, height)
- use brief, lowercase, consistent column names
- don't leave cells empty. NA is used to describe a definitive empty cell
- if the data includes calculations, each variable should be clearly listed

Key concepts for the Online Classroom

- an overview of the key reasons for organising data
- an example of how to record data, such as translating data from a survey into a spreadsheet
- advice to the student engineer on how to organise a dataset, including selecting appropriate variable names

Core resources

- The Statistical Consulting Unit has a set of guidelines for inputting data: https://services.anu.edu.au/research-support/tools-resources/data-organisation-guidelines

Extension

Although not required in this course, once you have your data organised, using a statistical package becomes very straightforward. The open source RStudio is a good place to start.

Figure R04: Garbage in, garbage out with Calvin and Hobbes

R05: Research ethics

Research is built on the foundation of trust

If your research portfolio involves people or animals, then it is likely that there are ethical considerations in your research design. As undergraduate coursework students, you are considered as trainee researchers, and aren't required to send your research proposals to an ethics committee unless you intend to take the research further, such as for publication to an academic journal. However, you should be aware of, and act within the framework of ethical research.

Example applications

The ANU has a number of ethics committees responsible to approving and investigating ethical conduct of research. For most research in the Research School of Engineering, ethics approval is not required as testing is done on inanimate objects. However, in biomedical engineering and user-centred design, there are ethical concerns about how people are used in research.

Steps

IDEO have a fantastic resource for Design Research Ethics. This is a must-read, and covers in easy-to-read terms three principles: respect, responsibility and honesty. It also includes an overview of ethical guidelines, such as the planning and preparation of a research project, concerns around gathering information, and using and sharing data.

For researchers applying for ethics approval at ANU, the key ethical concerns in human research involve: informed consent, confidentiality, privacy, security of the data, recruitment of participants, incentives, recruitment of vulnerable people, providing feedback to participants, and dealing with complaints.

Key concepts for the Online Classroom

- an overview of what the key issues are for research ethics
- examples of what ethical concerns might arise for conducting research in your DLab theme
- advice to the student engineer on how to approach a research project in an ethical way

Core resources

- IDEO's Little Book of Design Research Ethics (email sign-up required)
- ANU's Human Ethics - Key ethical concerns (website)

Further resources

- Engineers Australia's Code of Ethics provides guidance for the application of professional ethics as an engineer

Figure R05: xkcd.com Research Ethics

R06: Coding research data

Coding captures the essence of visual or textual data

Coding is a method to interpret qualitative data. After an interview, a giant corpus of text can be unwieldy. To manage this, it is common for researchers to 'code' their responses so that they can get an overview (or a meta-view) of the responses. This overview can often (with many caveats) be converted to quantitative data. For example, counting the number of positive responses. Coding requires interpretation, and can be quite subjective, so it is important to have a clear protocol for coding. Once these data has been coded, they can be categorised and converted into themes and theories.

Example applications

In my doctoral thesis, I asked about 1,000 university students to visually graph an integral, given a known rate of change. The case study used carbon in the atmosphere as the context. Students were given a graph of the greenhouse gas emissions per year, and were asked to graph the the corresponding accumulation, and write a written description. The graphical results were coded into five categories, using a stencil that showed the upper and lower bounds of a category (correct, decrease, stabilise, increase, other). This coding scheme allowed for me to quantify the frequency of different answers.

Steps

There are many reasons to engage with a coding process, but once you have collected the data, a general approach should include:

- pre-coding - getting a sense of the data by looking for codable opportunities
- preliminary coding - developing the schema
- code contrasting data - look for extreme cases (such as other researcher's data) to see if your coding scheme holds up. It's worthwhile discussing the schema
- decide on the lumping chunk-size - do you code everything, or just the key observations?
- finalise the code list - establish the rules for coding so that others can replicate your approach

Key concepts for the Online Classroom

- an overview of what coding is, in which situations it should be used, and the development of a coding scheme
- example of a coding activity, that develops into the categorisation of codes
- advice to the student engineer on how to approach an activity that requires coding (such as interpreting an open-ended survey question)

Core resources

For a comprehensive guide on what coding is, how to undertake coding, and things to watch out for, see Salda 2012:

- Salda, J., 2012, The Coding Manual for Qualitative Researchers, Sage Publications, Chapter 1.

Figure R06: Coding Research by Dedoose

R07: Error types

Acknowledging the key sources of error is essential to any research project

Error is inherent in all analyses. It is crucial to be aware of these errors, and to design your analysis in such a way that it minimises any bias in your data, or likelihood that your data is compromised because of methodological error. The Australian Bureau of Statistics website (ABS) describes two categories of error types when undertaking an analysis:

- sampling error - the sample does not represent the population
- non-sampling errors - systematic or random errors in the sample

There are many types of non-sampling errors, such as:

- coverage error - data is included or excluded in the sample
- non-response error - the failure to obtain a response
- response error - respondents intentionally or accidentally providing inaccurate responses
- interviewer error - incorrect recording of data at the point of collection
- processing error - error as a result of inputting or coding

Example applications

It is important to be careful in the selection of wording when asking people about an issue. The ABS notes that the wording of questions can lead to non-sampling errors, such as questions that rely on memory recall, ask for confirmation of a socially desirable behaviour, encourage under- or over-reporting, are leading, or are double-barrelled.

For example, and without generalising, having a parent ask an engineering student how much alcohol they can drink in a night could lead to under-reporting, whereas having a classmate ask the same question might lead to over-reporting. If you ask the same student how much time they volunteer per week, it might be artificially inflated, as volunteering is a socially desirable pursuit.

Tips and techniques

When designing your survey or approach, there are a few principles that can assist:

- keep your survey short and targeted
- use neutral language to avoid bias
- assure the interviewee of confidentiality in the process
- providing advance notice of the planned activity
- ensuring the sample size is large enough to account for non-responses
- triangulate your questions using multiple measures of similar things

Key concepts for the Online Classroom

- an overview of the error types
- an example of an incorrect or corrected survey, based on reducing the likelihood of error
- advice to the student engineer on how to approach the design of a survey to reduce error

Core resources

- Statistical Language, Types of Error, from the Australian Bureau of Statistics http://www.abs.gov.au/websitedbs/a3121120.nsf/home/statistical+language+-+types+of+error
- The National Statistical Service has a more comprehensive online resource on survey design: http://www.nss.gov.au/nss/home.nsf/NSS/4354A8928428F834CA2571AB002479CE?opendocument

R08: Descriptive statistics

Descriptive statistics summarise information about a sample

Descriptive statistics is a field of statistics that summarise information about a sample, as opposed to inferential statistics, which use the data to draw inferences about a population.
Descriptive statistics should be familiar to you from high school. The purpose of including this topic in ENGN2226 is that using descriptive statistics is usually the first step in understanding data about your population.

Example applications

Descriptive statistics are used widely in many disciplines. In engineering, statistics is often used in process control and reliability engineering, such as efforts to improve efficiency or reduce error. Using statistical models can allow for a more informed approach to improving reliability than if you were to react to each data point.

Fundamentals

Broadly, there are two types of descriptive statistics:

- measures of central tendency, such as the mean, mode, and median
- measures of spread, such as range, quartiles and standard deviation

For the purposes of ENGN2226, these values should be both described through calculation and contextualised graphically.

Key concepts for the Online Classroom

- an overview of key descriptive statistics concepts
- an example that walks through how to calculate the key descriptive statistics
- advice to the student engineer on how to use descriptive statistics to understand data in a system

Core resources

- Weiss, N.A., 2012, The Nature of Statistics, Chapter 1 (cover the relevant parts in chapter 1)
- Khan Academy - Series on Sampling Distribution (5 videos)

Further ideas…

Most descriptive statistics can be calculated very easily using a spreadsheet. Once you have established the basic descriptive statistics, you could extend your analysis by investigating other topics in the Research Methods theme.

R09: Hypothesis testing - populations

Hypothesis testing can be used to tell whether two populations are similar

Hypothesis testing is a fundamental statistical approach to determine the probability that an hypothesis is true. In ENGN2226, we will look at how to complete hypothesis testing on data about a population (R09) and on categorical data (R10). The broad principles of the approach for hypothesis testing between the two is, however, the same.

Example applications

Population data can be any sort of data that is sampled across a population (here, a population is not just 'people'). It must have a continuous quantitative variable of concern. Examples of quantitative data include: height, weight, salary, age, and so on, but could also include data like time, cost, speed, etc, sampled across a population of results.

Steps

In this instance, we are concerned with data that is approximately normally distributed. For our purposes, you can examine the plot visually. If the two data sets are from samples that are approximately normally distributed, you can then conduct a hypothesis test using the Student's T-test.

1. State the null and alternative hypothesis - typically the null hypothesis is that there is no difference between the samples
2. Calculate the test statistic - in this case, the Student's T-test
3. Determine the p-value associated with the test statistic
4. Determine whether the null hypothesis is accepted or rejected
5. Provide a conclusion on what that means

Key concepts for the Online Classroom

- an explanation of how the null and alternative hypotheses are formed
- an example that walks through how to conduct a t-test, and then the p-value
- advice on whether to reject or accept the null hypothesis
- advice to the student engineer on when to use hypothesis testing

Core resources

- Khan Academy have a series of videos on Hypothesis testing, and solve using a t-statistic (7 videos)
- RStudio has an active help community, R-Bloggers. See their example of conducting a t-test if you're planning on using RStudio: https://www.r-bloggers.com/two-sample-students-t-test-1/

Extra resources

Note, a T-test can be undertaken manually, or very easily using a spreadsheet. A T-test is built in to most spreadsheet packages - usually in the form `TTEST(Data1; Data2; Mode; Type)`[Libreoffice]. If you're looking for something more powerful, then using the open source statistical software RStudio could be useful.

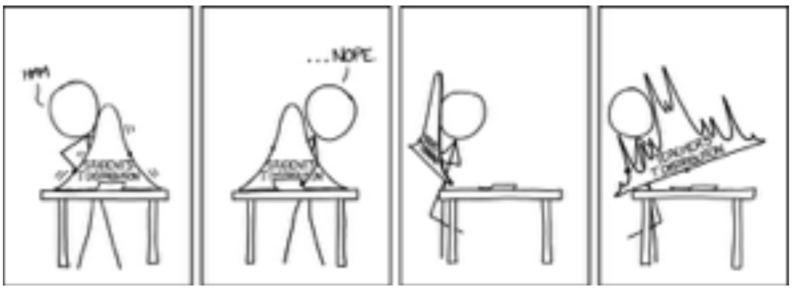

Figure R09: Student's T-Test distribution explainxkcd.com

R10: Hypothesis testing - categories

Hypothesis testing can also be used to tell whether two groups are similar

Building on R09, hypothesis testing can also be used to identify whether two categories or groups are similar. When comparing categorical data, a contingency table is used. In our case, we'll look at a 2x2 contingency table, with frequency reported in each cell of the grid.

Example applications

For example, if we were concerned with understanding whether engineering students had a gender representation similar to the rest of the university, we could created the following 2x2 contingency table :

	Male	**Female**	*Row Total*
Engineering	a	b	a + b
Other	c	d	c + d
Column Total	a + c	b + d	a + b + c + d

Steps

With a 2x2 table and small frequencies (as we might expect in a small survey for your portfolio), Fisher's Exact Test is a useful statistical approach. Using Fisher's Exact Test, you calculate the p-value directly, and so the process looks like:

1. State the null and alternative hypothesis - typically the null hypothesis is that there is no difference between the categories
2. Determine the p-value associated with the test statistic using Fisher's Exact Test
3. Determine whether the null hypothesis is accepted or rejected
4. Provide a conclusion on what that means

If you have a larger contingency table, calculating the test statistic χ^2 should be considered.

Key concepts for the Online Classroom

- an explanation of how the null and alternative hypotheses are formed using categorical data
- an example that walks through how to calculate Fisher's Exact Test to get the p-value
- advice on whether to reject or accept the null hypothesis
- advice to the student engineer on when to use hypothesis testing and what it means

Core resources

- John McDonald has authored an online textbook *Handbook of Biological Statistics*, which has a very clear entry on Fisher's Exact Test.
- RStudio has an active help community, R-Bloggers. See their example of conducting Fisher's Exact Test you're planning on using RStudio.

Similar tools…

There are many different statistical approaches for calculating significance in a contingency table. You could examine comparing the result in Fisher's Exact Test and using the test statistic χ^2 (chi-squared).

It's not straightforward to conduct Fisher's exact test in a spreadsheet, but using a statistical software package like the open source package RStudio allows you to easily conduct the test. There are many online packages too (though arguably are not as reliable).

R11: Simple linear regression

Simple linear regression summarises the relationship between two variables

Simple linear regression is a statistical method that examines the statistical relationship between the independent variable and a dependent variable. 'Simple' linear regression only concerns the relationship go one independent variable, whereas 'multiple' linear regression concerns two or more independent variables.

Example applications

Consider a situation where you have two variables of concern, and would like to understand whether there is a linear relationship between the two: that is, if one variable goes up or down, we can anticipate what the other variable will do. Examples include:

- height and weight - if height increases, we could expect that weight would increase
- time spent studying and marks - if you spend more time studying, we could expect that you earn a better mark (in reality, there is probably a low correlation here!)
- responsibility and income - if the responsibility in your job increases, we could expect that the amount of money you earn increases

Steps

When preparing your answer, you should:

- create a scatter plot of the data
- determine the line of best fit using the least squares method (using a statistical package such as RStudio or a spreadsheet application makes this very easy)
- report the regression equation, and the S and r values (whether it is positive or negative)
- provide a prediction of a value based on the regression equation

Key concepts for the Online Classroom

- an explanation of the type of data that can be using in simple linear regression
- an example that walks through how to build a scatter plot and solve the regression equation
- advice to the student engineer on how to interpret the results

Core resources

- John McDonald has authored an online textbook *Handbook of Biological Statistics*, which has a very clear entry on Linear Regression.
- RStudio has an active help community, R-Bloggers. See their example of conducting simple linear regression.

Similar tools…

There are many statistical approaches for examining the relationship between variables that can be more appropriate given the assumptions in a simple linear model. If your data exhibits non-linear behaviour when you draw your scatter plot, you should consider digging a little deeper to find a better statistical approach.

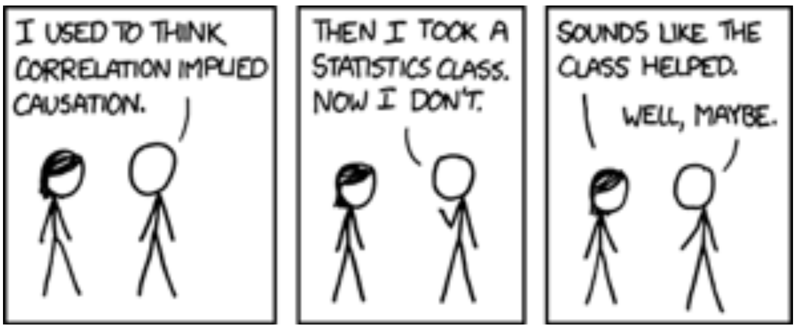

Figure R11: Correlation xkcd.com

R12: Confidence intervals

The range of values that are a good approximation for a population parameter

Confidence Intervals (CI) are calculated to show the range of likely values for a parameter. The CI can be set at any level, but is typically reported at the 95% confidence level. The confidence interval shows us that if we repeated the experiment on multiple samples, the true population parameter would be within the values of the CI, 95% of the time (not that 95% of the values are within the range).

Example applications

Confidence intervals are most commonly reported on bar charts, where the mean is reported in the bar chart, and the sample CI is reported using lines (error bars) that extend to the lower and upper bounds of the CI. Having a larger CI (e.g. 95%) means that the bars will be larger, but that we can be more confident of the difference and effect size if the bars do not overlap between samples. A CI should be reported if you report the average of a sample: such as the average height of students, or the average income of an engineer.

Steps

Assuming that you know the standard deviation (σ) is known, then:

- Identify the sample mean ($\bar{x}$)
- Identify the z^* to use as the critical value: for 95% CI, 1.96 is used
- Put the values into the formula on the right
- Plot and interpret the results

$$(\bar{x} - z^* \frac{\sigma}{\sqrt{n}}, \bar{x} + z^* \frac{\sigma}{\sqrt{n}})$$

As you can see, one easy way to reduce the confidence interval is to increase the number of samples in a population (n).

Key concepts for the Online Classroom

- an explanation of what a confidence interval is, and when it should be used
- an example that walks through how to establish the confidence interval
- advice to the student engineer on how to interpret the results

Core resources

- John McDonald has authored an online textbook *Handbook of Biological Statistics*, which has a very clear entry on Confidence Limits (limits are for our purposes the same as intervals).

Similar tools…

Confidence intervals are an alternative method to using p-values to establish the differences between two groups. If you're feeling inclined, you could explore the difference between the two.

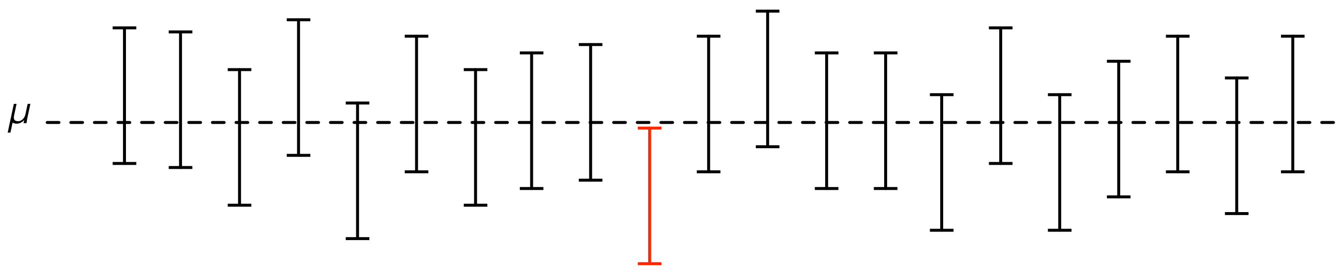

Figure R12: A 95% CI indicates that 19 out of 20 samples will produce CI that contain the population parameter

PART III: SYSTEM PERSPECTIVES

S01: Social & Cultural perspectives

Value the diversity of viewpoints from different cultures

The first, and most important, system perspective is the social and cultural perspective that an engineering project sits within. Engagement with minority cultures or groups within cultures can enrich a project through sharing the knowledge and social practices between cultures. As an engineer, you should recognise that we often frame our thinking about systems for the dominant culture, and by doing so we disenfranchise minority groups.

Example applications

Studying at ANU in 2016, there are two social and cultural perspectives that should be contextually at the forefront of your thinking - Aboriginal reconciliation and gender equality.

The term Aboriginal engineering is not commonplace, but it is a perspective that Leigh *et al* (2015) put forward in their approach for including Aboriginal perspectives into engineering education. Their steps for engagement are outlined below.

On gender equity, companies and organisations are developing frameworks for promoting equal opportunities. The ANU has taken a leading role in the *Science in Australia Gender Equity (*SAGE) framework, which upholds the Athena SWAN principles (see the Equity Challenge Unit's website).

It should be noted, though, on both of these perspectives, we have a long way to go.

Steps

Leigh *et al* (2015) suggests steps we should take for incorporating Aboriginal perspectives (which could easily be applied to other minority groups):

1. start with a new philosophy (focus on two-way learning)
2. explore engineering from three perspectives (dominant, Aboriginal, & engineering perspectives)
3. consider and validate 'an' Aboriginal perspective
4. consider the 5Rights by engaging with community
    - Right People, Right Place, Right Language, Right Time, Right Way
5. tailor the learning experience

Key concepts for the Online Classroom

- an explanation of what a social or cultural minority is, and how it is different to the dominant perspectives
- an engineering example of incorporating and valuing a different social or cultural perspective
- advice to the student engineer on how to incorporate social and cultural perspectives into their project

Core resources

- Leigh, E., Goldfinch, T., Dawes, L., Prpic, K., McCarthy, T., Kennedy, J., (2015) "Shifting the Focus. Incorporating knowledge about Aboriginal engineering into main stream content", Australian Association for Engineering Education Conference
- Athena SWAN principles on the Equity Challenge Unit's website

Similar tools…

Recognising the social and cultural context is a key part of professional practice - see the Engineers Australia Code of Ethics

S02: Safety & Risk perspectives

An approach for evaluating risk and human safety

When systems involve people, providing a safe environment to work or operate in is of utmost importance. A systematic approach to risk management should minimise the risk to an acceptable level, whilst still allowing for the activity to proceed.

Example applications

The most common place you will encounter this perspective is in the workplace health and safety regulations that a workplaces must comply with by law.

Steps

1. Identification of a hazard
2. Identification of the associated risk
3. Assessment of the risk - which includes: understanding the likelihood using a risk matrix, understanding the consequences of a risk, and assigning a priority for rectification
4. Control of the risk - using a hierarchy of control measures consisting of (in order of preference):
    A. Elimination - remove the risk altogether
    B. Substitution - achieve the same ends using different means
    C. Isolation - limit access to those who can operate the equipment or manage the risk
    D. Engineering Controls - put in place controls that improve the safety, such as sensors, guards or cut-off switches
    E. Administrative Controls - improve the procedures, training, or other planning around the risk
    F. Personal Protective Equipment (PPE) - wear personal safety gear, such as gloves or glasses
5. Documentation of the process
6. Monitoring and Review of the process.

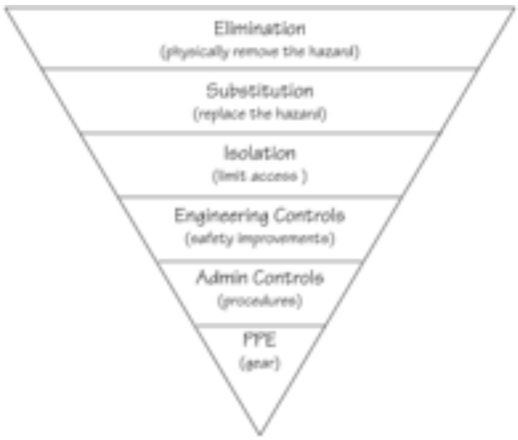

Figure S02: Hierarchy of controls

Key concepts for the Online Classroom

- an explanation of what risk is, and how to interpret a risk matrix
- an example that walks through an application of the hierarchy of controls
- advice to the student engineer on how to improve the safety of a project or system

Core resources

- Worksafe ACT have an overview of how to conduct a risk assessment on their webpage: http://www.worksafe.act.gov.au/page/view/1039

Similar tools…

Other factors of concern to workplace health and safety include:

- Richman, Requirements for lighting levels in workplaces from IESNA 9th Edition Handbook.
- Queensland Government, 2012, Office accommodation workplace fitout standards (see space allocation and lighting requirements)
- Worksafe Victoria, 2006, Officewise - a guide to health & safety in the office (see lighting, noise and thermal comfort, but lots of other great ideas too)

S03: Anthropometric perspectives

Designing for humans based on the measurement of humans

Anthropometrics (human measurements) are an important consideration when designing a system or analysing a workflow. Is your design a one-size-fits-all, or do you tailor it to a particular size? Anthropometric data can help you to understand human measurements that can give you informed understanding the size of the objects you design.

Example applications

The need to understand anthropometrics crosses many technology interfaces. Take a seat on public transport, for example. How heigh should it be to service the general population? How much adjustment should you allow? How high should a child's seat be? What sort of leg-room is required? All of these questions can be answered using anthropometric data for your target population.

Tips

- understand the characteristics of the target population, and whether or not the population anthropometrics are relevant. If needed, separate out the populations to get a better sense of the requirements, such as distinguishing between male and female populations
- investigate the ratios of body measurements. For example, knowing a population's average height should also allow you to extrapolate other measurement dimensions
- understand the cm range of the potential solution by considering the upper and lower bounds of the average data - two standard deviations is an adequate measure

Key concepts for the Online Classroom

- an explanation of what anthropometrics are, and where they could be used
- an example that walks through calculating the size of something based on available anthropometric data
- advice to the student engineer on how to incorporate anthropometrics in design

Core resources

- NASA Man-systems integration standards (see §3 for Anthropometric and Biomechanics)
- CDC, Anthropometric Reference Data for Children and Adults: United States, 2007–2010
- Anthropometric data and Australian populations - do they fit? this is a critique of how generic anthropometric data fits Australians
- Jain, A et al, 1996, Introduction to Biometrics, in Biometrics p1-41

Similar tools…

An ergonomic design will not only make your users happier, but can make big differences to the bottom line of any enterprise. Better ergonomics can lead to fewer chronic workplace injuries and a happier user.

- ANU, Ergonomic computer workstation design
- Apple Computer's Human Interface Principles
- ABS's Work-Related Injuries survey - details the cost of work-related injuries on industry

S04: Planning approaches

Planning your project will make you aware of the consequences if a project runs over time

Gantt charts can be used to plan a project, including deliberatively accounting for timing, sequencing and dependency. Gantt charts are a fundamental planning perspective in project management. Modern Gantt charts allow for complicated sequencing, multiple dependencies, and strategic planning as the dynamics of a live project change.

Example applications

A classic engineering project management example is seen in building projects. Sequencing the project correctly will save large amounts of money, and produce a faster build. For example, if the plasterers install the walls before the electricians have installed cabling, then the amount of time taken to install power will increase, and probably require the plasterers to re-work and will delay the painters. Planning this out beforehand allows the project manager to plan logistics around jobs correctly, and prioritise activity when the schedule changes.

Steps

- list all the activities required to complete the project
- estimate time that will be required for each activity
- look for dependencies, and activities that can run in parallel
- estimate the time and the critical path for the project
- plan for how you might 'crash' the project if the critical path gets extended

Key concepts for the Online Classroom

- an explanation of what a Gantt chart is, and how it is constructed, including how to find the critical path
- an example that walks through building and interpreting the Gantt chart
- advice to the student engineer on how to plan a project using a Gantt chart

Core resources

- Reid, R.D., and Sanders, N.R., Operations Management: An Integrated Approach, Wiley [Scheduling (Gantt Charts)]
- Couture, E., *Bridging the Gantt*, SANS Institute [PDF Online] is a good discussion about the pros and cons of using Gantt charts

Similar tools…

- PERT charts are a similar tool that allows you to explore a process flow in a graphical way
- Just-in-Time manufacturing is an example of how scheduling well can improve process flow and reduce inventory costs
- Reid, R.D., and Sanders, N.R., Operations Management: An Integrated Approach, Wiley [Network Analysis (PERT charts)]

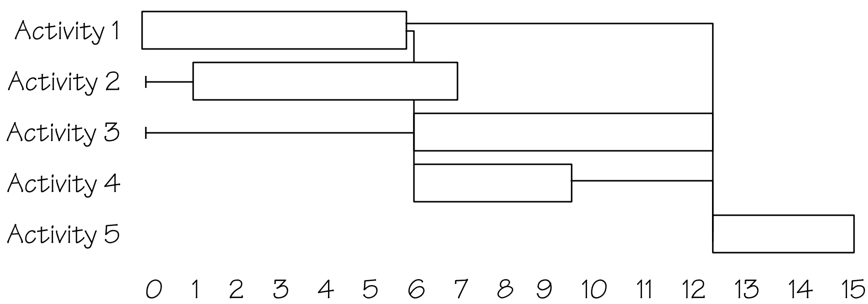

Figure S04: An example Gantt chart

S05: Queueing perspectives

Queue theory can help you optimise a given process, and improve the user’s experience too

Queues are an unfortunate part of life everywhere, and we often only notice them when they’re not working. Understanding the theory of queues can help us to improve the human experience in a system. In this topic, we are concerned with how understanding queues can be used to better inform your thinking about the design of a process or application area.

Basics

When considering a queue, there are some basic structures:

- Queues can be single channel (one line, one server) or multiple channel (one line, multiple servers).
- Queues can have single phases (ordering a coffee) or multiple phases (going through checkpoints in an airport
- Arrivals should be discrete units (e.g. people in a line, jobs to be processed, emails to be read)
- Population can be finite (e.g. the number of people getting of a bus) or infinite (at least for the purposes of the activity - e.g. number of phones to a call centre)

You should think of your system in terms of:

- the arrival mechanism (is it random or known) the service mechanism (the time it takes), the associated cost (the 'cost' of employing service)

The mathematics of queue theory should inform our design. You should be able to calculate:

- the mean number of units in the system, the average length of the line, the mean waiting time

Key concepts for the Online Classroom

- an explanation of Queue(ing) theory, and the different types of queues
- an example that walks through analysing and improving a real-world queue
- advice to the student engineer on how to design better processes using queue theory

Core resources

- Queuing Theory and Practice: A Source of Competitive Advantage

Further resources

- Chris' (traditional) lecture slides from 2012
- Blanchard & Fabrycky, Chapter 10 for the maths
- Queue theory calculator (use M/M/C for most familiar applications)

Queues in Practice

Experts in the dark art of queuing theory can use lavender smells, TVs, sight barriers, and music to warp your perception of time. When they get it wrong, queuing rage can result-with deadly consequences

- Fenella Kernebone hosts a discussion on ABC's 'By Design' (Direct link to audio) <<< great discussion

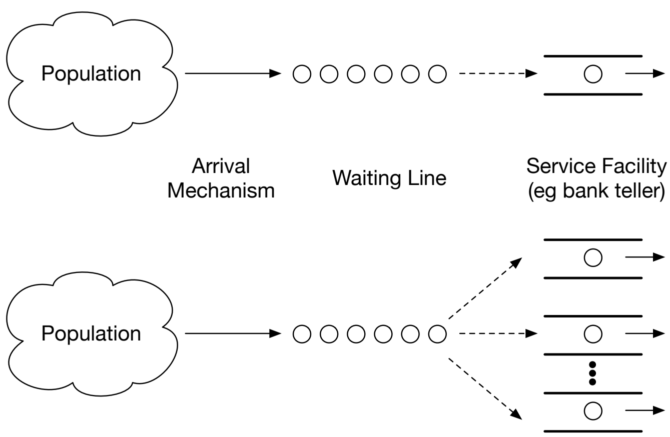

Figure S05: Single (top) and Multiple (bottom) channel queues. Which line would you want to be in?

S06: Process control perspectives

Improve the quality of your process using statistical measures

A time-series graph can help you to understand the past, present and future of your system. A time-series graph is essentially any graph that has time, or a proxy for time, as the x-axis. No matter what your system or product, aspects of the performance will change over time as components or workers wear and tire. In this topic, we'll explore control charts. In manufacturing, process and systems engineering, statistical bounds are placed on a variable of interest, and understanding any deviation outside of those statistical bounds can indicate that there's a problem in your system.

Example applications

Consider that you are running a process that filled a bottle of expensive hand lotion. The advertised volume is 250ml, with a tolerance of ±5ml. This tolerance, due to the machinery, has been established over many thousands of runs and is acceptable to the client. The bottle is weighed before and after it is filled, and then recorded. When a sample comes back that is outside of the bounds (below 245ml or above 255ml), it is removed. If the behaviour is repeated, this is a sign that there is a problem with your process.

Steps

- establish the mean value. This is probably the desired value - in the example above, 250ml
- determine the upper and lower bounds. This in probably an agreed tolerance, but could be determined statistically at first at a value that covers the majority of samples (e.g. 2 standard deviations from the mean)
- set up a repeatable and recordable experiment to measure the variable of interest (e.g. measuring weight as a proxy for volume)

Key concepts for the Online Classroom

- an explanation of statistical process control, and advice on setting up the upper and lower critical limits
- an example that walks through a relevant situation using statistical process control
- advice to the student engineer on how to interpret the results of a statistical process control analysis

Core resources

- Control charts take a statistical approach to looking for variation in a process over time - see Statistical Quality Control, Chapter 6

Similar tools…

Another similar approach could be to examine other time-series graphs. For example, the charging and discharging of a battery.

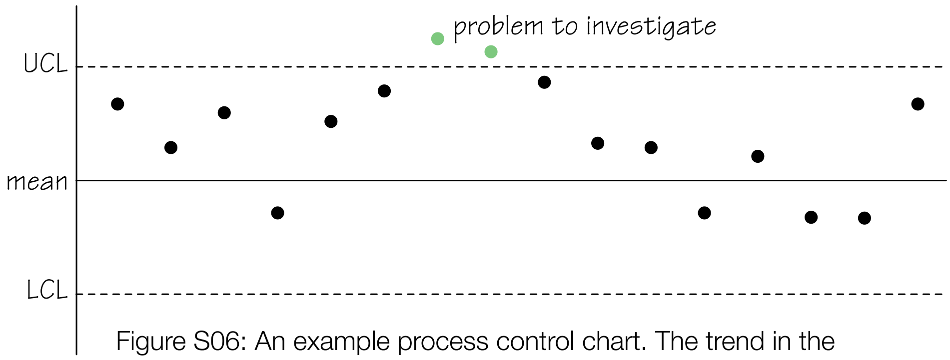

Figure S06: An example process control chart. The trend in the middle samples might indicate a process problem

S07: Control perspectives

Designing an effective control system in your design will improve performance

In control perspectives, we'll take the typical engineering approach to feedback structures, where there are three basic components of a feedback system: a sensing mechanism (something that senses a change), an actuation mechanism (something that is triggered), and a computation (something that compares the output to the input and determines the controls).

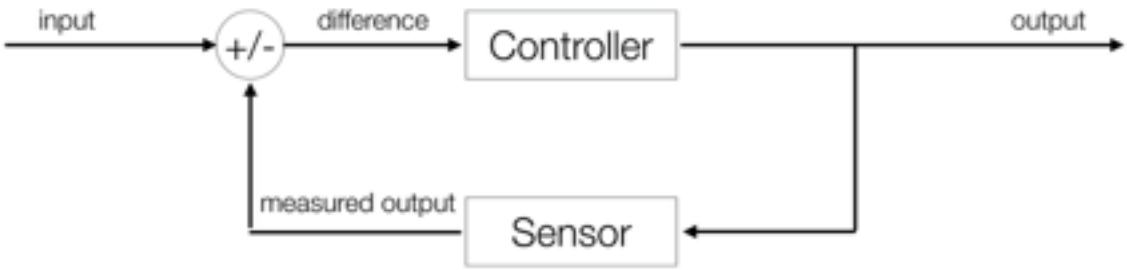

Figure S07: A basic control system

Example applications

Engineers typically use feedback structures to read the input and 'control' the output, such as in amplifiers, robots controlled by servos, thermostats that control air conditioners or cruise control that adjusts the throttle in your car. Most systems could be improved by improving the sensing mechanism in a feedback structure. A good example of this is a washing machine cycle - modern machines will weigh the load to estimate how long the wash cycle will take. Note that they are probably measuring the wrong thing, and a better feedback structure might look at how dirty the clothes actually are!

Basics

Identify the input and output signals, what the control mechanism is, and how the signals are measured in the sensor mechanism. A key way to improve the output of the system (other than changing the structure) is to increase the sampling rate, but this often comes at the expense of processing power.

Key concepts for the Online Classroom

- an explanation of a control system, and the key elements within it
- an example that conceptually walks through a relevant control system and identifies the key mechanisms
- advice to the student engineer on how to optimise one aspect of the control system

Core resources

A great overview of engineering control systems is in:

- Astrom, KJ and RM Murray (2009) Feedback Systems: An Introduction for Scientists and Engineers, Princeton University Press. See Chapter 1 (PDF)

There are also some great examples of engineering control systems in Chapter 3.

Similar tools…

Control systems can even be seen in social systems. System Dynamics modelling, the basis of ENGN3410 Engineering Sustainable Systems, explores this approach.

S08: Material impact perspectives

A material audit is a way to measure (and improve) the environmental impact of a system

Understanding the material life-cycle of your design, system or product is the goal of this topic. We'll use a technique called Life-Cycle Analysis (LCA), detailed in ISO standard 14040. Conducting an LCA is a large undertaking, which requires access to a lot of information. For the purposes of ENGN2226, we'll examine only one part of the LCA process - conducting a material audit. An LCA can be undertaken on any process, such as a manufacturing or construction process, or an entire business or enterprise.

Steps

To conduct a material audit, you will need to be able to:

- construct a table of all of the the materials involved in the process or design
- measure or approximate the mass or volume of each material
- apply an impact metric to understand the material impact of the process or design

PART	MAT.	QTY	EMBODIED ENERGY
SHAFT	OAK	400 g	x 2.0 MJ/KG = 0.8 MJ
HEAD	STEEL	600 g	x 20.1 MJ/KG = 12.6 MJ
			TOTAL: 13.4 MJ

Table S08: A simple material audit table

Once an audit has been conducted, you can explore opportunities to reduce the material impact of your design, such as material substitution or reduction.

Key concepts for the Online Classroom

- an explanation of the steps to conduct a material audit of a system
- an example that walks through a material audit, and measures the impact using an appropriate metric
- advice to the student engineer on how to reduce the material impact of a design, process or system

Core resources

- US Life-Cycle Inventory Database, a list of processes and flows of certain materials
- Weidama, B.P., 2000, Editorial: Increasing Credibility of LCA, International Journal of LCA
- Guidelines for Social Life-Cycle Assessment of Products by the UNEP (excellent resource!)

Impact metrics

There are alternative metrics to embodied energy that can be explored once you have conducted a material audit. Such measures include:

- *Embodied energy:* see the YourHome guide. Also explore the whole YourHome.gov.au website.
- *Carbon footprint:* see the Inventory of Carbon & Energy at the Circular Ecology site
- *Water footprint:* National geographic's water footprint calculator (see the methodology)

End-of-life issues

Once a product moves beyond its useful life-span, there is often a lot of waste material. Understanding how you can improve your design to either reduce the waste materials, or improve the reusability of products will become more and more important in a resource-constrained world.

- Lovins, A., Natural Capitalism. Ch 3 Waste Not
- Nowosielski, R., et al, 2010, 'Recycling as an important element of engineering design' in Journal of Achievements in Materials and Manufacturing Engineering

S09: Energy-Mass Balance

An Energy-Mass balance examines the flows of material and energy through a system

In this topic we will explore an energy and material flow perspective. Energy and mass takes many forms, and could apply to any energy input and output into your system. Our key driver in analysing energy is to improve energy efficiency by looking for opportunities to make our system more effective. This often has many co-benefits, including cost savings and improving environmental outcomes.

Example applications

An energy-mass balance is a practical application of the First Law of Thermodynamics and Conservation of Mass principles. Two case studies are provided in the core resources, conducting an EMB of a commercial building and of a transport system. In an EMB, the flows in must be accounted for in the flows out, or must accumulate in the system, such as material stored in inventory or heat energy stored in a building. The goal of conducting an EMB is to then identify opportunities for reducing costs through minimising flows or waste.

Steps

There are five iterative steps of constructing an EMB: develop a plan, collect data, map the system, analyse the EMB, and consider improvements for the next version. For the purposes of the course, we will only explore the *collect data* and *map the system* steps. This involves:

- identifying mass or energy inputs and outputs
- collecting metering data, using a simulation or modelling software, or estimate using engineering calculations (for our purposes, these can be rough estimates)
- mapping the flows into an energy-mass balance map

Key concepts for the Online Classroom

- an explanation of a the key aspects of an energy-mass balance audit
- an example that conceptually walks through the process of constructing an EMB map
- advice to the student engineer on how to improve the system after the EMB map is constructed

Core resources

There are two particular examples of Energy Mass-Balance audits relevant to your projects:

- Commercial Buildings (heaps of great examples)
- Transport (a good example of an EMB process, but doesn't include an EMB map).
- (All Energy Efficiency Opportunities resources)

Similar tools…

Once you have built an EMB map, explore the opportunities to improve the energy or material efficiency of the system.

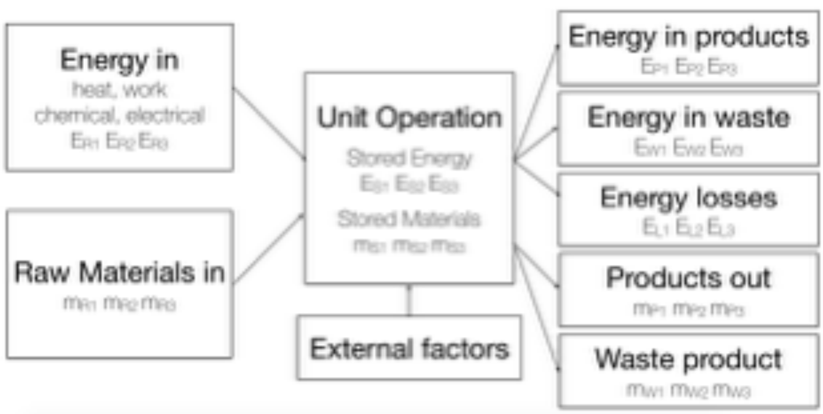

Figure S09: An example EMB map, with E representing different energy flows and M representing different mass flows.

S10: Sankey Diagrams (energy efficiency)

Sankey diagrams are used to visualise flows between process

A Sankey diagram is a tool to demonstrate the size of flows through a system or process. A Sankey diagram is a useful display approach, as the width of the flow 'arrow' directly maps to the size of the flows, thus highlighting larger flows. You should be able to complete a Sankey diagram for your entire system (such as energy flow/loss in a building), or at least an aspect of your system (such as energy flow/loss in a light globe).

Example applications

Although we are looking at Sankey diagrams in the context of energy, they can be used in many applications (such as data, time, probabilities, material or cost transfers between processes).

Steps

To create a Sankey diagram, you need to:

- establish the inputs and outputs of the process or system
- measure the flows and losses through the process or system
- create a Sankey diagram using these data
- calculate the energy efficiency (useful energy / total energy)
- look for opportunities to improve the efficiency of the process or system (note a Pareto approach would have us looking at the larger flows first)

Key concepts for the Online Classroom

- an explanation of the purpose behind using a Sankey diagram
- an example that conceptually walks through the construction of a Sankey diagram
- advice to the student engineer on how to interpret a Sankey diagram

Core resources

- See Page 26 of the Transport guide for an example Sankey diagram
- the Wikipedia page on Sankey diagrams provides a range of software tools that can be used to easily create Sankey diagrams
- The International Energy Agency has a great resource that balances the world's energy mix: http://www.iea.org/Sankey/

Further energy efficiency resources

If you're looking to investigate energy efficiency further, you might also want to investigate:

- Energy Freedom is part of the Beyond Zero Emissions movement explaining how to transform Australian houses into net energy producers.
- Beyond Zero Emissions is a movement dedicated to demonstrating how Australia can transform its energy needs to zero emission options – TODAY! Download the plan

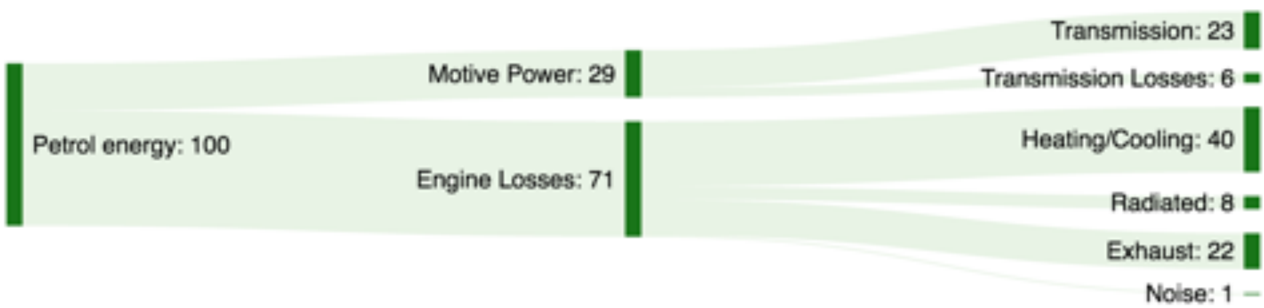

Figure S10: An example Sankey Diagram of energy losses in an internal combustion engine (percentage). Generated using http://sankeymatic.com/build/

S11: Life-cycle costing

Accounting for the costs of the entire life-cycle of a project

At the end of the day, the most important analytical technique to get a project off the ground is likely to be the economic analysis. Can the system pay for itself? Can it be profitable? Once you've established the feasibility of the other aspects of your design, now turn your mind to making the financial case for it!

Life-cycle costing can be applied to any project. Australian Standard AS/NZS 4536:1999 defines life-cycle cost as the sum of acquisition cost and ownership cost of an asset over its life cycle from design stage, manufacturing, usage, maintenance and disposal.

Advice on the project life-cycle

It is important to consider the entire life-cycle of the project - from project conception, build, use and finally decommission - in the life-cycle cost analysis. When projects span a long period of time, it is useful to factor in adjustments in costs. For example, the running cost of electricity will likely change over a period of time.

Steps

Key costs to consider in Life-Cycle Costing are (from Blanchard & Fabrycky, p583):

- Acquisition - research, design, construction
- Operations - personnel, facilities, utilities
- Software - operation and maintenance cost
- Product distribution - transport, traffic, handling
- Maintenance - customer service, factory cost
- Test and support equipment cost
- Training - operator and maintenance cost
- Technical data cost
- Refinement and disposal cost
- Supply support cost - spares, inventory, support

For the purpose of your analysis, if you're not including all these factors, it's worthwhile establishing which of these costs lie within and outside of the boundaries of your analysis.

Key concepts for the Online Classroom

- an explanation of what considerations are included in life-cycle costing
- an example that calculates the life-cycle costing of a project
- advice to the student engineer on how to interpret a life-cycle costing

Core resources

The NSW Government has prepared a management standard (clearly written for bureaucrats, be selective in your reading) for life-cycle costing. It includes the principles and a worked example.

- Transport for NSW, Life-Cycle Costing Management Standard (PDF, 18 pages)

Similar tools…

When it comes to accounting for your project, consider alternative costing mechanisms, such as:

- Cash flow concepts, see: Watts, J.M., and Chapman, R.E., Engineering Economics
- The Triple-Bottom Line is an accounting framework with many critics, but aims to balance out the requirements of people, profit and planet.

S12: Payback period

A payback period analysis will forecast the time taken to pay back a capital cost or break even

The payback period of a system is of concern when making decisions. Usually a decision involves a trade-off, where purchasing new equipment might have a higher upfront cost but allows for a lower ongoing cost, compared to the existing option that might have a higher ongoing cost. The payback period can be calculated as the time it takes for the new option to become cheaper than the existing solution.

Example applications

There are several classic examples to make economic arguments for one system over another, especially when weighing up options at the acquisition stage. Some everyday examples include:

- purchase a phone outright with lower monthly fee, or receive a phone as part of a contract arrangement with higher monthly fee
- purchase solar panels for your home (high up-front cost, ongoing cost offset by production) or continue to pay a higher ongoing cost for electricity

Steps

- identify a situation of interest, such as comparing the purchase of new equipment to the running costs of existing equipment
- conduct a life-cycle costing (S11) of the options, and establish which are the upfront and which are the ongoing costs, including when the ongoing costs are payable
- plot the costs over time (or other unit of interest, such as pages printed) for the options
- when plotted on an axis over time, there will be a point at which the two options cross - this is the payback period

Note that a payback period approach might also be used to discover the break-even point if the system is generating income.

Key concepts for the Online Classroom

- an explanation of when to use a payback period calculation
- an example that calculates the payback period
- advice to the student engineer on how to interpret a payback period calculation

A word to the wise

If you are conducting a payback period calculation extending out several years, you must take into consideration the range of likely values. For example, if electricity prices are a key part of your ongoing costs, you must consider the likely trends that might occur over that period of time (your variables are not constants!)

Core resources

A good guide for calculating the payback period is in the Victorian Government's EREP Toolkit: Calculating payback periods

Similar tools…

High costs aren't necessarily a problem, as long as the benefit can be clearly articulated as having value. A cost-benefit analysis could be useful to make the case about an investment. The Business Council of Australia' guide describes when, why and how to use a cost-benefit analysis.

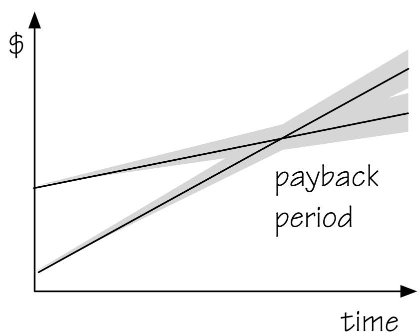

Figure S12: A simple pay-back period plot

FURTHER RESOURCES

The rules of thumb, methods and perspectives discussed in this toolkit are a selection of the available tools for undertaking an analysis of a system, design or process.

Chris actively encourages you to read wider, and incorporate other perspectives into your portfolio, such as developing models (physical and simulation) or choosing alternative tools. If you're in any doubt, please use it as an opportunity to have a discussion with Chris or your tutor.

A great place to start further reading are the Systems Engineering textbooks listed on page 2.