engineering
new zealand
te ao rangahau

RECOGNISING, DEFINING AND SOLVING COMPLEX PROBLEMS

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We expect Chartered Professional Engineers to be able to solve complex problems. But what makes a problem complex? How do you define it, how do you know you can solve it, and what steps are involved?

Introduction

Professional engineers are often faced with the challenge of solving complex problems that require not only technical expertise but also a strategic approach.

This article provides a framework for engineers to recognise, define, and solve complex problems by differentiating between determinate and complex issues. It emphasises strategic approaches and technical expertise, including identifying issues, consulting stakeholders, understanding knowns and unknowns, analysing system states, defining problems, evaluating solutions, and monitoring outcomes.

Key concepts highlight system interconnectedness, managing multiple variables and conflicting goals, and addressing uncertainties. Practical examples from various engineering fields illustrate these principles, emphasising the importance of balancing functional, economic, social, and environmental benefits while meeting diverse stakeholder needs.

This document will introduce you to:

- **Clear definitions:** Understand key terms and concepts essential for addressing complex engineering issues.
- **Problem differentiation:** Learn to distinguish between determinate and complex problems, enabling more effective problem-solving strategies.
- **Structured approach:** A step-by-step methodology for identifying issues, consulting stakeholders, and defining both current and ideal states of systems.
- **Practical examples:** Explore real-world case studies that illustrate the application of these principles in various engineering contexts.
- **Benefit analysis:** Gain insights into evaluating the functional, economic, social, and environmental benefits of potential solutions.
- **Stakeholder management:** Enhance your ability to balance diverse stakeholder needs and integrate their input into optimal solutions.

Definitions

Benefit: A positive outcome or advantage gained from implementing a particular solution. Benefits can be tangible (eg cost savings, increased efficiency, improved product quality) or intangible (eg enhanced customer satisfaction, better team morale, reduced risk). You must also discover whether the benefit is a need or a want. The final design must accommodate a need, whereas a want can be changed or eliminated.

Complex problem: A problem with multiple interacting issues with conflicting goals.

Determinate problem: A problem with a limited number of solutions.

Ideality: The best-case future state.

Issue: A situation or event causing a problem. Consider issues as symptoms of a problem.

Needs: Requirements that are essential for the solution's core functionality. Without these, the project objectives would not be met.

Problem: The root cause of the issues.

Sub-system: A component or parts of the problem or system. Alterations of the components will affect the system. Those effects must be identified as part of the problem-solving process.

Super-system: The high-level external environment with which the problem or system interacts or may interact. The regulatory environment can be a good example of a super-system.

System: A system comprises at least two parts (or components) that work together to form a whole. You cannot alter one part without influencing the other parts.

Typically, the level at which the problem resides sits above the component level and below the super-system level. It could be the current project being worked on or the environment (eg a company) within which the problem is occurring.

Wants: Desired features or specifications that would be nice but are lower priority. The solution can still be viable without these.

Determinate versus complex

Determinate problems

Determinate problems can be challenging to solve but are easy to define. For example:

- We need to rebuild this engine.
- We need to replace this piece of equipment as part of the maintenance cycle.
- We need to determine the capacity of this beam.

Rebuilding an engine or replacing a piece of equipment may be difficult, but it's easy to define the problem and its boundaries. A technician (rebuild the engine) or technologist (how do we replace this piece of equipment) can work on these problems because the problem and its boundaries are already defined.

It's normally easy to predict the outcome when facing a determinate problem. You can predict with some certainty what will happen. When rebuilding an engine, it will start and run provided you have put it together following a defined process. For instance, you can watch a video or read a book to learn how to do it if you haven't done it before.

Likewise, we can predict the results when replacing a piece of equipment because the system is well-known, and the problem and boundaries are defined. It may be physically difficult to replace the equipment, but it is unlikely to be a complex issue unless it meets the attributes of a complex problem.

Complex problems

Complex problems have multiple interacting issues with conflicting goals. There is uncertainty and you must make judgements based on the information available. Solving complex problems is a skill. Learners need to be coached on how to make judgements and evaluate the benefits versus risks.

A complex problem involves a system. A system comprises at least two parts that work together to form a whole. You cannot alter one part without influencing the other parts.

For a problem to be complex it must possess the following attributes:

- be a system
- have multiple possible solutions
- not have a linear solution
- have multiple, potentially conflicting, stakeholder requirements, priorities, and constraints.

Attributes of a complex problem

A problem does not need to be large to be complex, but it must contain some or all the attributes below:

1. The number of involved variables. A complex system will likely contain at least three variables, and their relationship is not linear.
2. Connectivity of the system – how the parts are connected and work together, impacting each other when the engineer makes changes.
3. The role of time and developments within a system. How will changes impact other parts of the system with time, and what is required to deal with those impacts.
4. There is a lack of transparency (in part or full) about the involved variables and their current values. There will be unknown unknowns.
5. Conflicting goals – there are likely to be goal conflicts, where altering one part of the system negatively impacts another. Additionally, a system may have unclear boundaries, whereby a change to one part has a knock-on effect in ways not not immediately apparent, such that each system is part of a wider, complex system.

Example of a complex problem

Putting a man on the moon in 1969 is an example of a problem containing multiple complexities. President Kennedy defined the goal, and then NASA had to solve numerous complex problems to reach that goal. Additionally, some problems existed that no one could see or know about. The examples below show how the engineers had to define problems and then break them into parts to solve them.

Some of the issues NASA faced were:

- How could they reduce the rocket's weight. One part of the problem was the weight of the batteries. How could they reduce power consumption? The answer was to reduce the weight of the insulation. Part of that solution led to the invention of mylar blankets.
- Keeping the astronauts healthy. They broke the problem down. They needed to ensure the astronauts were healthy getting onto the flight and had sufficient life support on the spaceship. Besides heat, light and oxygen, what about existing illnesses, and why would they get sick in space? NASA answered it with isolation before the flights and food safety. They then invented new ways of controlling the manufacture of food products to ensure they were free of microbes.
- How to reduce the chances of crashing the landing module. The system needed to minimise the opportunity for pilot error and improve precision. The existing technology used cables and rods to connect the pilot to the control surfaces physically, so they invented computer systems to help the pilot, the first example of fly-by-wire. To make the system possible, they also needed to hugely reduce the size of existing computers.

After the first launches, we could argue that putting a man on the moon again in 1972 was challenging but not complex. They knew the issues, and the boundaries were clearer. There were processes in place, and the results were more predictable and replicable.

Eleven steps to solving complex problems

1. What are the issues identified?

A stakeholder will normally come to the engineer with an issue (or issues). An issue is different from a problem. An issue arises from an underlying problem. It is the role of the engineer to determine the issue(s) and discover how the stakeholders are impacted.

2. Who have the stakeholders consulted and are any other issues identified?

Other stakeholders may identify related issues. Those issues can clarify the current situation and help with future gap analysis and problem definition.

3. Known knowns, known unknowns, unknown unknowns

Detail your assumptions and understand the limits of your knowledge. Look to other stakeholders for their knowledge of the issue to identify and understand the unknowns and the assumptions you're making. Identify the uncertainties surrounding the issues.

4. What is the past state of the super-system, system, and sub-system?

Set a timeframe and examine the different system levels. Typically, the current situation has arisen for several reasons. By identifying the reasons for the problem, the current state is more easily understood.

5. What is the defined current state for the super-system, system, and sub-system?

What is happening now at each of the different levels?

6. What is the ideality for the super-system, system, and sub-system?

- **Clarity and specificity:** Objectives should be clear and specific. Instead of broad goals, aim for detailed targets that specify what success looks like.
- **Measurable outcomes:** Ensure objectives are measurable. This could include quantitative targets (eg reduce downtime by 20%) or qualitative goals (eg improve user satisfaction to a specific level).
- **Time-bound goals:** Define a timeline for achieving the objectives. This helps in tracking progress and ensures that the goals are realistic and attainable within a specific period.
- **Alignment with stakeholder needs:** Objectives should align with the needs and expectations of key stakeholders. Engage with stakeholders to ensure their priorities are considered.
- **Flexibility:** Allow for flexibility to adapt objectives as new information or challenges arise during the project.

7. Define the benefits

Evaluating the benefits of different solutions is a crucial step in the decision-making process, as it helps to determine the most effective and valuable approach to addressing the problem at hand. To understand whether potential solutions are fit for purpose, you need to evaluate the key benefits a solution aims to provide. Common categories can include:

- **Functional benefits:** What are the benefits of any functions the project has? For example, reducing travel time, reducing illness, and increasing safety.
- **Economic benefits:** What are the expected economic benefits? Consider costs saved, revenue/profit enabled, and payback period.
- **Social/ethical benefits:** Does the solution provide value to society? Does it align with ethical principles?
- **Environmental benefits:** What are the environmental benefits of the project? For example, increasing biodiversity, enabling the overland flow of stormwater, or reducing energy consumption for an activity (eg transportation).

Needs versus wants

Determining needs versus wants is important when scoping engineering projects and defining project requirements. Here are some guidelines and examples:

Determining needs

- Analyse the core problem to solve. What must the solution do, at a minimum, to address this problem?
- Engage with the key stakeholders. Ask them what functionalities are critical. It is often worthwhile asking them if there are any other critical stakeholders that you haven't identified.
- Identify binding constraints that drive certain performance thresholds (eg time, cost, regulation).

Examples of needs:

- Bridge support cables must withstand wind shear forces up to 72m/s without failure.
- The rocket navigation system must guide the craft to the ISS with precision docking alignment.
- Prosthetic knee joint must support patient weight up to 150kg without buckling.

Determining wants

- Nice to have features that customers ask for but are lower priority for viability.
- Elements that would improve user experience but aren't essential.
- Capabilities that would be cutting edge or differentiate from competitors but aren't mandatory.

Examples of wants:

- Bridge lighting colour sequence harmonised with sunrise and sunset.
- Rocket cameras live stream astronaut perspectives during flight.
- Prosthetic knee comes in custom cosmetic skin tones.

Carefully prioritising needs versus wants focuses engineering resources on what truly matters most to solving the problem. It also avoids over-engineering something unnecessary.

Measuring benefits

Determine appropriate metrics and methods to measure how the solution provides each benefit claimed. These can be qualitative assessments or quantitative performance measures. Ensure the approach is realistic and rigorous. Some options for mea suring the benefits include:

Define success metrics: Clearly outline the metrics used to evaluate success. These could include financial metrics, performance metrics, customer feedback, or environmental impact.

Develop a scoring system: Create a scoring system to objectively compare different options. This could involve assigning weights to different criteria based on their importance.

Incorporate stakeholder feedback: Ensure that the evaluation criteria reflect the priorities and concerns of all relevant stakeholders.

Include risk assessment: Factor in potential risks and their impact on the project. Evaluation criteria should consider not only the potential benefits but also the associated risks.

Document the criteria: Document the evaluation criteria and make them available to all team members and stakeholders to ensure transparency and consistency.

Benefits prioritisation

Prioritise and rank benefits based on stakeholders' needs to guide optimisation trade-offs. The most critical benefits for stakeholders should typically receive top priority.

8. Define the problem

"If I had an hour to solve a problem, I'd spend 55 minutes thinking about the problem and five minutes thinking about solutions." – Albert Einstein

The problem is the result of the gap analysis between the current state and the future state. You must identify and define the problem to ensure that the potential solutions are fit for purpose. The more clearly the problem is described, the easier it will be solved.

"A problem well stated is a problem half-solved." – Charles Kettering

9. How are you getting the diversity of thought into your solution to check the optimal potential solution?

You need to balance the solution to meet the needs of the various stakeholders. You may need to reach out to a broader group of stakeholders. You may decide that not all stakeholders need to be consulted further. You need to be able to show your decision-making process.

10. Describe and evaluate the solution options

A complex problem will have more than one way of being solved. Identify the options available and investigate how they balance the needs of the stakeholders by testing the proposed solutions against their benefits.

Identify the positives and negatives of each situation and show how the negative points can be eliminated or mitigated.

The solution that best balances the stakeholders' needs can be chosen.

Now, the problem has been defined, and a solution has been found. The problem has been simplified. It may be complicated, but it is no longer complex. It can be solved with known techniques and resources.

11. Monitor and evaluate the solution

Were the objectives met? It's uncommon for a project to be entirely successful and meet or exceed all the performance criteria without any issues. How are you defining success and incorporating the lessons learnt into your next project?

Case study

A simplified example of a complex problem and how it was resolved is presented here.

Bracing in specifically engineered structures project

A senior engineer approached from a Building Consent Authority (BCA) approach Engineering New Zealand with concerns about submitted designs that appeared to use P21-tested bracing systems outside their scope.

The reviewing engineers from the BCA were under considerable pressure from engineers, architects, and developers to accept the designs. They approached Engineering New Zealand to work together to solve their perceived problem.

At this stage, the BCA had an issue. We still needed to identify the problem.

1. What are the issues identified?

- Engineers produced designs without a clear compliance pathway to meet the Building Code. They weren't ensuring compatibility between P21-tested bracing systems for use within an Acceptable Solution, and specific designs derived through Verification Methods.
- There was a lack of information available to engineers, architects, and Building Consent Officers (BCOs) about acceptable mixed design parameters.
- There was no design methodology guidance.
- There was a lack of understanding of the limitations of bracing design to NZS3604.
- There was very little training for engineers in residential bracing design.

2. Who are the stakeholders consulted?

We identified stakeholders in the area. Those are:

- Developers
- Architects and architectural designers
- BCAs
- Technical societies
- BRANZ (a testing agency for the P21 system)
- Major suppliers of elements used in these bracing systems
- Consulting engineers
- Ministry of Business, Innovation and Employment.

We discussed the issue that the BCA had brought to us and uncovered other related issues. Those issues were:

- Engineers were using P21-tested systems in non-residential buildings such as warehouses.
- Engineers peer-reviewing buildings struggled to push back on issues where P21 bracing systems were being used outside of NZS3604:2011 (Timber-framed buildings).
- Architects, architectural designers, and BCOs didn't understand the limitations of P21 systems.
- Engineers who tried to use specifically designed (SED) elements (like specifically designed ply shear walls) where they believed the structure was outside the scope of NZS3604:2011 were priced out of the market and stopped taking that type of work.
- It wasn't commonly understood that a P21 tested system was designed as a system, and individual elements of that system could not be replaced without invalidating the test results.

3. What are the benefits?

Needs	Wants
Provide guidance for engineers to produce robust designs	Concurrent training seminars
Agreement between major stakeholders	Worked examples
Document to have sufficient status for regulators to push back on less robust designs	
Increase design consistency and reduce Building Code non-compliant designs	
Publication within a twelve-month time frame	

4. Known knowns, known unknowns, unknown unknowns.

Known knowns	• P21 systems and their testing methodology • Examples of what engineers are providing to BCAs for consent. • The differences between P21-tested systems and capacity-designed systems.
Known unknowns	• Whether engineers understood the limitations of the P21 systems. • Why BCAs were accepting designs using bracing units outside of NZS3604 designs. • Whether the update to NZS3604 would cover this issue and when the update would be released.
Unknown unknowns	• We gathered as many stakeholders as possible and stayed flexible in bringing others into the project to fill any knowledge gaps. • Whether any of our current assumptions were false.

5. What is the past state of the super-system, system and sub-system?

This is where we start to build and populate a knowledge grid.

	Past – 1980s onwards
Super-system	• Regulatory system. • NZS3604. • 1980s and 1990s housing typology changing. • The introduction of mixed bracing systems. • High damage to mixed bracing systems in 2011 Christchurch earthquake.
System	• Engineers used to using force-based design principles are working with architects to produce different housing types using P21 and SED bracing systems. • Less attention paid to residential design versus commercial due to lower perceived risk. • Lack of specific training available
Sub-system	• Lack of design guidance for mixed bracing. • Engineers are typically trained for low-rise and commercial, not residential. • Often a lack of in-depth knowledge about the engineering basis of NZS3604.

6. What is the defined current state for the super-system, system and sub-system?

What is happening now at each of the different levels?

	Post 1980’s onward	Present
Super-system	• Regulatory system. • NZS3604. • 1980s and 1990s housing typology changing. • High damage to mixed bracing systems in 2011 Christchurch earthquake.	• Regulatory system. • NZS3604 is being reviewed and updated. The release date is currently unknown. • Guidelines about SED residential design is being released by agencies such as BRANZ and Engineering New Zealand. • Larger, more complex houses than built in the 1970s are now the norm. • Two and three-storey townhouses are becoming more common due to regulation changes.
System	• Engineers used to using force-based design principles are working with architects to produce different housing types using P21 and SED bracing systems. • Less attention paid to residential design vs commercial due to lower perceived risk. • Lack of training from technical societies or Engineering New Zealand. • Engineering companies starting to use P21-tested bracing systems in townhouses, warehouses, and apartment blocks.	• Engineering companies are becoming used to displacement-based design. • Less attention is paid to residential design versus commercial due to lower perceived risk. • Training and seminars for engineers have been improving recently. The General Practitioners Group, the Timber Design Society (TDS) and BRANZ have produced seminars and guidelines. Engineering New Zealand has been active in this space. • Engineers are producing designs with P21-tested bracing systems more suited to material standards (eg timber).
Sub-system	• Lack of design guidance for mixed bracing. • Engineers are typically trained for low-rise and commercial, not residential. • Often a lack of in-depth knowledge about the engineering basis of NZS3604.	• Data from P21 testing and system designs are being taken out of context and applied without a full awareness of the potential consequences. • There’s no consistent or collated guidance for townhouse designs using New Zealand bracing elements.

7. What is the ideality for the super-system, system and sub-system?

Set a timeframe. What are the ideal results you're looking to achieve in that timeframe?

Timeframe = 24 months, end of 2024, to see results.

	Past – 1980s onwards	Current	Ideality – December 2024
Super-system	• Regulatory system. • NZS3604. • 1980s and 1990s housing typology changing. • High damage to mixed bracing systems in the 2011 Christchurch earthquake.	• Regulatory system. • NZS3604 is being reviewed and updated. Release unknown. • Guidelines about SED residential design is being released by agencies such as BRANZ and Engineering New Zealand. • Larger, more complex houses than those built in the 1970s are common. • Two and three-storey townhouses are becoming more common due to regulation changes.	• Updated NZS3604 released. • Townhouse/multistorey designs submitted to regulators are designed using accepted good practice. • Guidance documents are consistent and kept up to date.
System	• Engineers used to using force-based design principles are working with architects to produce different housing types using P21 and SED bracing systems. • Less attention paid to residential design versus commercial due to lower perceived risk. • Lack of training from technical societies or Engineering New Zealand. • Engineers starting to use P21-tested bracing systems in townhouses, warehouses, and apartment blocks	• Engineering companies are becoming used to displacement-based design. • Less attention paid to residential design versus commercial due to lower perceived risk. • Training and seminars for engineers have been improving recently. The General Practitioners Group, the TDS and BRANZ have produced seminars and guidelines. Engineering New Zealand has been active in the space. • Engineers are producing designs with P21-tested bracing systems more suited to material standards (eg timber).	• Regulatory authorities understand good practice designs and are consistent in their approach to issuing building consents for these building types. • Engineers issue designs that consider the limitations of P21 bracing systems. • Companies invest in training engineers for residential design. • Architects and architectural designers understand the limitations of P21 systems. • There is a collaboration between Engineering New Zealand, regulators, and the technical societies to identify common design flaws and produce solutions to rectify those issues.
Sub-system	• Lack of design guidance for mixed bracing. • Engineers are typically trained for low-rise and commercial, but not residential. • Often a lack of in-depth knowledge about the engineering basis of NZS3604.	• Data from P21 testing and system designs are being taken out of context and applied without a full awareness of the potential consequences. • There's no consistent or collated guidance for townhouse designs using New Zealand bracing elements.	• There is consistent training for engineers in residential design. There is consistent education on design concepts, methodology and worked examples. • The current guidance is freely available for engineers, BCOs and architects. • Engineers understand the difference between P21-tested systems and designing using the material standards. • The Engineering Basis of NZS3604 has been updated and is widely distributed to, and read by, engineers.

8. Define the problem.

The problem results from the gap analysis between the current and ideal states. You must identify and define the problem to ensure that the potential solutions are fit for purpose.

The problem is a lack of emphasis on training engineers about residential building design and Standards becoming outdated as society progresses.

The lack of education emphasis likely occurred due to the traditionally high resilience of lightweight timber-framed buildings in New Zealand. As a result, Engineering New Zealand, technical societies, and universities have largely focused their training and research on commercial buildings.

The lack of training has led to a poor understanding of the implications of using P21-tested elements outside the bounds of NZS3604. This lack of knowledge has led to poor designs being submitted to BCAs across New Zealand, and increasing demand for medium-density housing has also helped bring the problem to light.

9. How are you getting a diversity of thought into your solution to check the potential solution is optimal?

You need to balance the solution for the needs of the various stakeholders. You may need to reach out to a wider group of stakeholders. You may decide that not all stakeholders need to be consulted further. You need to be able to show your decision-making process.

a. formal stakeholder group

The formal stakeholder group started with representatives from a regulator, major supplier Winstone Wallboards, and two technical societies: SESOC and TDS.

b. other stakeholders consulted

We consulted informally with other regulatory bodies, architects, and architectural designers to discover whether the issues we saw were spread across their jurisdictions and professions. We learned that the more complex bracing designs were passed to engineers. As a result, we decided not to include them in the full process but asked for their input periodically.

c. stakeholders bought in later

As the project progressed, it became apparent representatives from small design companies should be involved. We also decided to include representatives from the NZS3604 committee. Ideally, we would have considered these as key stakeholders earlier in the process.

10. Describe and evaluate the solution options.

A complex problem will have more than one way of solving it. Identify the options available and investigate how they balance the needs of the stakeholders by testing the proposed solutions against the requirements. Identify the positives and negatives of each situation and show how the negative points can be eliminated or mitigated. At that point, the engineer can choose a solution that best balances the needs of the stakeholders.

We considered several options to solve the problem. Each had positives and negatives. Examples are shown in the following table.

Option 1	Positives	Negatives
Inform the NZS3604 Standards Committee of the issues we saw and ask them to address them in the revised Standard.	• The issues would be addressed at a regulatory level. • We wouldn't need to dedicate resources to solving the problem.	• There's no clear release date for the updated NZS3604. • We may not be able to influence the Standards Committee heavily enough to alter ongoing work. • Simply having an updated Standard is unlikely to resolve the lack of understanding surrounding design limitations.
Option 2	**Positives**	**Negatives**
Release individual papers and webinars addressing the known issues.	• There are recognised distribution channels for these papers and webinars. • We can discuss the technical issues and show and provide solutions.	• Volunteer projects normally have a very long timeframe due to limited resources. • A stream of technical engineering articles won't address all stakeholders or design engineers. • There's a limited collaboration between the stakeholders. • The solutions proposed by the technical authors might not be acceptable to all stakeholders. • There's no central repository or owner for all the information, which means it may quickly go out of date or be inaccessible to stakeholders (eg behind a paywall).
Option 3	**Positives**	**Negatives**
Release a full guideline with case studies and worked examples. Provide training based on the document.	• The document will have sufficient authority for all stakeholders and provide a quasi-standard. • Engineering New Zealand would own the document and could update it as required. • Engineering New Zealand is in continuous contact with all stakeholders and will uncover issues quickly. • The worked examples provide sufficient information to educate engineers about designs they may not be familiar with. • The case studies provide non-technical information easily understood by other stakeholders like BCOs and architects. • We can use the document to conduct training in person and via webinars. • The document can be promoted by the technical societies, Engineering New Zealand, BCAs, and architects. • Most of the writing and production of the document will be handled by Engineering New Zealand, which has the required resources in-house.	• The worked examples will likely take months to produce unless funding is provided, delaying the project. • A new timber Standard is being released, which could outdate the worked examples before the document is released.

Option 4	Positives	Negatives
Release a guideline with case studies. Worked examples to be individually produced by the technical societies later.	• The document will have sufficient standing for all stakeholders and provide a quasi-standard. • Engineering New Zealand would own the document and can update it as required. • Engineering New Zealand is in continuous contact with all stakeholders and will uncover issues quickly. • The case studies provide non-technical information easily understood by other stakeholders like consenting officers and architects. • We can use the document to conduct training in person and via webinars. • The document can be promoted by the technical societies, Engineering New Zealand, regulators, and architects. • Most of the writing and production of the document will be handled by Engineering New Zealand, which has the required resources in-house. • Without worked examples, we can get the document into the public space reasonably quickly, where it can start to have immediate effect.	• There will be a knowledge gap for some engineers with some design aspects until resources are produced.

11. Present the solution and describe why it was chosen.

Benefits analysis

The underlying problem was a traditional lack of emphasis on residential building design. Engineering New Zealand, technical societies and universities have largely focused their training and research on commercial buildings.

To resolve the problem, we collaborated with the main stakeholders and released a guideline without worked examples. We decided that by providing a written document supplemented by case studies with multiple images, we could solve most of the problem.

By regularly showing the draft document to non-engineers, we could ensure that it was fit for purpose for a wider audience than engineers.

Although we would have preferred to provide worked examples with the document, we decided that information was available where engineers needed to fill knowledge gaps. The technical societies would continue collaborating to provide worked examples and future seminars.

By gathering enough expert engineers and representatives from the NZS3604 committee, we agreed on circumstances where the P21 bracing systems can and can't be used. We were able to provide informative design philosophies for engineers to follow.

The guideline gave us a reference document that we published within six months.

More attention was paid to this type of building by publicising the issues we found, which led to an increased awareness of the need for education. Engineering New Zealand has been working with organisations like the Building Officials Institute of Zealand (BOINZ) and individual regulatory bodies to train and educate continually.

12. Monitoring and evaluation.

Results to June 2024

We have received positive feedback from engineers, architects, and regulatory bodies. Stakeholders have welcomed a known method for designing these buildings.

We received feedback that we did not sufficiently describe the thinking behind the presented methodologies. Work is underway on an updated version. We want the updated version to contain examples for timber shear wall, floor/ceiling diaphragm, and portal frame connection detailing as we have discovered that these are areas where there are weaknesses in design.

We have seen one worked example released by a technical society so far and are encouraging further work.

Other examples

Mechanical engineering

1. **The number of involved variables. A complex system will likely contain at least three variables, and their relationship is usually not linear.**

   Arriving at a compatible value for each may involve experimentation, testing, iteration and/or deriving mathematical relationships.

Example: Design of a household wind turbine. Variables include wind direction, wind intensity, site space, planning restrictions on height, property boundaries and noise, plus aesthetics.

2. **Connectivity of the system - how the parts are connected and work together, impacting each other when the engineer makes changes.**

   Connections in a complex system are typically not 1:1, which means changes to one component will affect the connection to multiple other components. A similar approach to point 1 is often required when one part is modified.

Example: A heating and air conditioning system. This consists of a heat exchanger, blower, combustion chamber/heater, condenser coil/compressor and thermostat. All components must be connected and sized so they work cohesively and efficiently.

3. **The role of time and developments within a system. How will changes impact other parts of the system with time, and what is required to deal with those impacts.**

   In a mechanical system, one time-variant aspect is wear. There may be a hierarchy of wear, where the engineer designs cheaper or more accessible components to wear out first, in preference to more expensive or difficult to access components. In that example, the design would need to provide ways to identify the magnitude of the wear and replace the worn components.

Example: A vehicle's braking system. How do you ensure consistent and repeatable breaking despite wear on disks, pads and actuation systems? You will need to identify wear components and mechanisms (eg designing some components to wear out deliberately).

4. **The lack of transparency (in part or full) about the involved variables and their current values. There will be unknown unknowns.**

   A complex system may require a preliminary design (prototype) to identify some of the unknown unknowns and reclassify them as known unknowns. The engineer may not initially know the significance of some of the variables.

Example: Designing a consumer product. An engineer will know how the product should be used but won't know how it might be misused. Without full knowledge, how do you ensure the product is safe and reliable?

5. **Conflicting goals. There are likely to be goal conflicts, where altering one part of the system negatively impacts another.**

   One example is performance trade-offs, which may require a compromise between cost, size, mass, and force parameters. In other words, you cannot meet all the original requirements simultaneously, so you must resolve the conflicts to a point where the resultant specification is mutually acceptable.

Example: Designing a flying drone. There is a constant trade-off between payload, performance, endurance, safety, and control.

Engineering management

1. **The number of involved variables.**

   A complex engineering organisation will contain multiple variables in the areas of:

   - Product or service delivery
   - Marketing and sales
   - The needed people skills
   - Areas that provide funding and control over the business operations.

   Relationships between these areas are usually not linear.

   Business operation needs to balance variables such as intellectual property, product development, manufacturing or service delivery through a coherent business model with demand via marketing and sales, while also providing the cash flow and controls to keep a record of transactions.

   Eg commercialising a novel wind turbine design. The variables could include:

   - Market size and demand for the system
   - Attractiveness to investors, available finance, and cash on hand
   - Intellectual property protection as well as freedom to operate
   - Readiness of the technology
   - Having a viable product
   - Ramping up production capability
   - A successful business model that connects demand with capacity
   - Capable team leadership, team members and mentors/governance
   - Business control systems.

2. **Connectivity of the management process – how the elements are connected and work together, impacting each other when the engineer makes changes.**

   In a complex system, a change to one component typically affects the connection to multiple other components. A similar approach to considering variables is often required when one aspect of the commercialisation is modified.

   Examples include:

   - Market demand
   - Manufacturing capacity and available operating capital are intrinsically linked – higher demand requires increased capital and manufacturing capacity – possibly involving outsourcing
   - The capability of the personnel to manage and control a growing and more complex demand situation
   - Managing resources across competing demands and client requirements – how do you get the right balance of technical input on complex projects, providing people with developmental opportunities, and ensuring senior oversight to grow capability while not overloading your people?

3. **The role of time and developments within a system. How will changes impact other parts of the operation with time, and what is required to deal with those impacts?**

   As an operation or business grows, different demands are placed on the leadership of the operation. This ranges from:

   - A small simple team environment that grows to requiring more structured leadership, delegation and coordination of tasks until complex quality, procurement, diverse policy frameworks and communication systems are required.
   - Over time the nature and role of financing will also change from self-funding, "angel funding" to eventual large scale venture equity or debt funding to maintain cashflow over the growth period.
   - The demand for capital equipment and tooling will also change, impacting the need for cash and balance with market demand.
   - External demands on a team may change the nature of services offered and the skill sets needed. Understanding these and adapting.

4. **The lack of transparency (in part or full) about the involved variables in the operation and their current values. There will be unknown unknowns.**

   Examples include:

   - The reaction of competitors in the marketplace to the new product design may not be predictable.
   - Competitor strategies to usurp the new business and gain more market share may not be evident.
   - New emergent technologies making the new design rapidly obsolete may not be known.
   - Some risks like exchange rates, discount rates and inflation, and their timing or impact may not be readily forecast.
   - Unforeseen scope changes through clients, stakeholders or others may put additional pressures on your project teams and programmes and require agility and good client management.
   - Different parts of an organisation may have competing needs for the same resources with different client sets and priorities.
   - Identifying risks on projects and whether to do the work to minimise the impact or carry the risk and to what level.

5. **Conflicting goals – there are likely to be goal conflicts, where altering one part of the system negatively impacts another.**

   Examples include:

   - Optimising a design or adding product features may delay a launch into the market, giving a competitor a window to be a first mover.
   - Market growth will again impact on production rates, cash flow and affect supplier credit, so that a successful product that is in high demand could bankrupt the business if cashflow, inventories, production rates, and suppliers are not carefully managed.
   - Providing opportunities for staff development on projects versus ensuring the client gets the right technical resources.

Fire engineering

1. **The number of involved variables. A complex system will likely contain at least three variables, and their relationship is usually not linear.**

   An atrium smoke control system is often a complex fire engineering problem. It requires consideration of many variables, including but not limited to:

   - Spatial geometry
   - Risks within the space
   - The usage of the space
   - Human behaviour and capacity to move away from the risk
   - Achieving life safety objectives
   - Possibly meeting property protection and insurance expectations
   - Meeting budget
   - Meeting aesthetics
   - Providing a buildable and maintainable solution.

2. **The system's connectivity – how the parts are connected and work together, impacting each other when the engineer makes changes.**

   The design of fire stopping solutions requires understanding how each element contributes to the final compliance of the entire system. Altering any of the parts will alter the system and potentially the fire performance. The solution needs to include at least:

   a. the construction details for the substrate (eg a wall or floor)
   b. the orientation of the substrate
   c. the characteristics of the item(s) passing through the substrate.

   The fire stopping system will also likely be composed of several interacting elements.

3. **The role of time and developments within a system. How will changes impact other parts of the system with time, and what is required to deal with those impacts.**

   It is usually easiest to solve a key problem at the beginning of the project. However, you must first identify what those problems are. Design tolerances and flexibility typically reduce as the project progresses. For instance, the number and placement of stairs in a building have many flow-on implications, which are typically very hard and expensive to reverse later in a project.

4. **Lack of transparency (in part or full) about the involved variables and their current values. There will be unknown unknowns.**

   Failing to fully investigate the complexities and weaknesses of existing building systems early during a project can lead to greater challenges to solve later in a project or missed opportunities to take a different design path. See point 3.

5. **Conflicting goals. There are likely to be goal conflicts, where altering one part of the system negatively impacts another.**

   The number of occupants and how they use the spaces directly impact the building's fire safety features. A balance needs to be found, especially for large public buildings, between maximising the building owners' ability to use the building freely now and in the future and the complexity, cost and spatial impacts this has on the fire design.

Bridge engineering

1. **The number of variables involved.**

   A complex system will likely contain forces in at least two directions, often three, and time can be added as a fourth. How long will this bridge last, and what will change during that time?

2. **Connectivity – how the parts are connected and work together, thereby impacting each other when changes are made.**

   - Are forces at deck level applied directly into the deck?
   - How is the deck connected to the beams and cross members?
   - How do the forces (moments and shear) move into the abutments and then into the foundations?

3. **The role of time and developments within a system.**

   Eg unexpected but predictable loads. Earthquakes and wind are most common, but flooding can present huge forces on a bridge. The rafting of debris can quite literally push a bridge over when combined with water depth and pressure. Traffic impact is also a significant factor in bridge design. Slowing traffic gives more capacity and a lot less damage.

4. **Lack of transparency (in part or full) about the involved variables and their current values. There will be unknown unknowns.**

   Eg the materials used and their performance over time. The common use of concrete for modern bridges can still lead to hidden problems.

   - Cracking under loads and exposure to salt-laden air, will eventually cause an expansion in the steel reinforcement. Do we need extra cover or concrete additives?
   - Timber can rot from the outside in softwoods, but hardwoods often rot from the inside out. What you cannot see can be a hidden problem.
   - Steel needs a protective coating of some form, a sacrificial layer (weathering steel) or an applied coating (paints and/or wax). How long will it last, when do we renew it, and what happens if we don't?

   Another example is with foundation system.

   - Have we correctly interpreted the ground and what's underneath it at depth?
   - How will the ground be affected by other forces?
   - The Darfield earthquake caused liquefaction issues in deep gravels (with water at depth) that were simply never envisaged in that area.

5. **Conflicting goals.**

   There are likely to be goal conflicts where altering one part of the system negatively impacts another part. Eg increasing the loading on an existing bridge. Perhaps the original bridges were designed for a traction engine with trailers (1933), then a combined cab and trailer (1943), then an additional trailer (1961) and finally (for now) a combination of a UDL and point loads plus opposing traffic. Who knows what future (or accidental) loads on your bridge may actually be?

Water engineering

1. **The number of variables involved.**

   Finding the optimised solution may require assessment of a number of competing criteria and balancing the needs of each of these.

   For example, when identifying a new discharge location for a wastewater treatment plant, a number of factors would need to be assessed and re-assessed as the project developed. Assessment criteria includes, but is not limited to, resilience, growth demand, environmental impacts, social and community impacts, cost, and constructability, while giving effect to te mana o te wai.

2. **Connectivity of the system - how the parts are connected and work together, impacting each other when the engineer makes changes.**

   Eg a faraway site with a discharge location with fewer environmental impacts and better allowance for growth may have considerably larger operational costs, carbon impacts, and a higher risk from natural disasters. A closer site may require increased quality of treated wastewater with higher operational costs but with increased resilience against natural disasters.

3. **The role of time and developments within a system.**

   Eg what growth allowance do you allow for? What potential changes in legislation do you build into the design, how adaptable do you make a scheme? How do you allow for changes in land use and industry with flexibility in a scheme?

4. **The lack of transparency (in part or full) about the involved variables and their current values.**

   We know what legislative changes are coming in the near future but we don't know how the social and political landscape will change in ten years. Is what is acceptable now not going to be acceptable later?

   Recent events have shown how much of an effect there can be on materials and construction costs – what might have been viable at one stage of a project may change considerably. How is this adaptability built in?

5. **Conflicting goals.**

   As with point one, how do you balance the competing environmental needs with social impacts, cost, allowance for growth, and so forth? If you allow for future demand now, will the system operate as it is supposed to and is the community over-capitalising? And how does it align with giving effect to te mana o te wai?

Civil engineering

1. **The number of involved variables.**

   A complex system will likely contain at least three variables, and their relationship is not linear.

   Civil engineering projects often involve infrastructure that the society interacts with. These require consideration of a range of factors in projects past the technical design that need to be taken into account in understanding the problem and developing a solution.

   For example, an upgrade of a pipe network, or pipes within a network, contains many factors that will need to be considered. This may include, but is not limited to, stakeholder impacts, environmental considerations, other infrastructure projects that are underway in the area by that party or another, constructability and a number of other factors. Sometimes these factors are visible at the outset of a project and other times they become apparent as a solution is developed.

2. **Connectivity of the system – how the parts are connected and work together, impacting each other when the engineer makes changes.**

   It is necessary to understand what the problem is to be able to work towards a preferred solution.

   For example, a pipe might be identified to be replaced as there is surcharge from a utility hole. Several factors may need to be understood to ensure that a replacement pipe will not result in the same issues. Why is the surcharge occurring – are there blockages, have ground conditions changed the capacity of the pipeline through sinkage, are there other sources entering the pipeline that shouldn't, or are downstream pipelines too small?

3. **The role of time and developments within a system.**

   How will changes impact other parts of the system with time, and what is required to deal with those impacts?

   Pipeline systems are designed for long periods of time, generally longer than the engineer's lifetime. So the infrastructure that is put in needs to consider future uses and changes in society, as well as how the system will be managed.

   For example, a pipeline may need to be replaced as its condition is poor. This pipeline could be lined, but that may reduce the diameter of the pipeline and the potential for growth higher in a catchment.

4. **The lack of transparency (in part or full) about the involved variables and their current values. There will be unknown unknowns.**

   Various stages of design will be required to move from unknown unknowns. At each stage, investigation will provide further information to allow a design to be progressed, but the level of investigation needs to be weighed up against other competing factors such as cost, community disruption, and environmental impact.

   For example, on a pipeline renewal project, the designer will need to identify what ground conditions and services should be physically and positively identified before finalisation of the design and construction, and which ones are suitable to leave as a risk to be managed during construction. This will require identification and clear communication about the risks with the client and other stakeholders.

5. **Conflicting goals.**

   There are likely to be goal conflicts, where altering one part of the system negatively impacts another.

   In many pipeline construction projects for municipal authorities, there could be conflicting goals between the capital delivery teams and the operational teams. There may be pressure on one team to bring costs of a project down which may result in more difficult or expensive maintenance in the future.

   One example is the locating of valves and hydrants on a water main. Putting frequent valves and hydrants on a large water network will allow for increased ability to turn off a watermain if repairs or new connections are needed, with less customer disruption. However, a larger capital cost is associated with this in the purchase and installation of this work, as well as ongoing operational cost to ensure these assets are maintained. Bringing in a wide range of parties into Safety in Design and operational workshops will identify these issues and allow them to be balanced and documented.

Structural engineering

Reinforcement of a historical library

1. **The number of variables involved**

   Description: Reinforcing a historical library to comply with modern seismic standards involves variables such as preserving architectural integrity, structural performance, and compatibility with existing materials and construction techniques.

   Example: Selecting appropriate reinforcement methods that do not alter the historical appearance of the building while meeting seismic safety requirements.

2. **Connectivity of the system – how the parts are connected and work together, impacting each other when the engineer makes changes**

   Description: The historical structure's elements, such as walls, floors, and foundations, must integrate with modern reinforcement techniques without compromising the building's aesthetics or structural performance.

   Example: Installing discrete seismic bracing or retrofitting materials that blend with the existing structure and preserve its historical character.

3. **The role of time and developments within a system**

   Description: Over time, both the preservation of the historical elements and the performance of the new reinforcements must be maintained.

   Example: Planning for long-term maintenance of both the historical features and the new structural reinforcements to ensure ongoing safety and preservation.

4. **The lack of transparency (in part or full) about the involved variables and their current values**

   Description: Uncertainties about the existing materials' condition, historical construction techniques, and potential hidden damages add complexity.

   Example: Conducting detailed inspections and material analysis while recognizing that some hidden defects or material degradations may remain undiscovered.

5. **Conflicting goals**

   Description: Balancing the need for structural reinforcement with preserving the library's historical and aesthetic value, and managing budget constraints.

   Example: Implementing reinforcement techniques that enhance seismic safety without altering the building's historical appearance or exceeding budget constraints.

Townhouse development on a sloped terrain

1. **The number of variables involved**

   Description: Developing townhouses on a steep slope involves variables such as temporary works, soil stability, foundation design, drainage, and erosion control.

   Example: Conducting geotechnical analysis to determine soil stability and designing appropriate foundations and temporary works to prevent H&S issues, settlement and landslides.

2. **Connectivity of the system – how the parts are connected and work together, impacting each other when the engineer makes changes**

   Description: The slope affects drainage and foundation design, which in turn influence the overall structural stability and site accessibility.

   Example: Designing retaining walls that manage soil pressure and integrate drainage systems to prevent water accumulation and erosion.

3. **The role of time and developments within a system**

   Description: Long-term erosion control and drainage management are crucial to maintain the stability and safety of the development.

   Example: Implementing a monitoring system to track soil movement and drainage effectiveness over time.

4. **The lack of transparency (in part or full) about the involved variables and their current values**

   Description: Uncertainties about soil behavior over time, potential water runoff patterns, and long-term erosion rates add complexity.

   Example: Conducting extensive site surveys and modeling to predict long-term soil and water behavior, yet acknowledging some uncertainties will remain.

5. **Conflicting goals**

   Description: Balancing the need for stable and safe construction with aesthetic appeal and cost efficiency.

   Example: Designing aesthetically pleasing townhouses that also incorporate effective erosion control and drainage solutions without exceeding budget constraints.

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