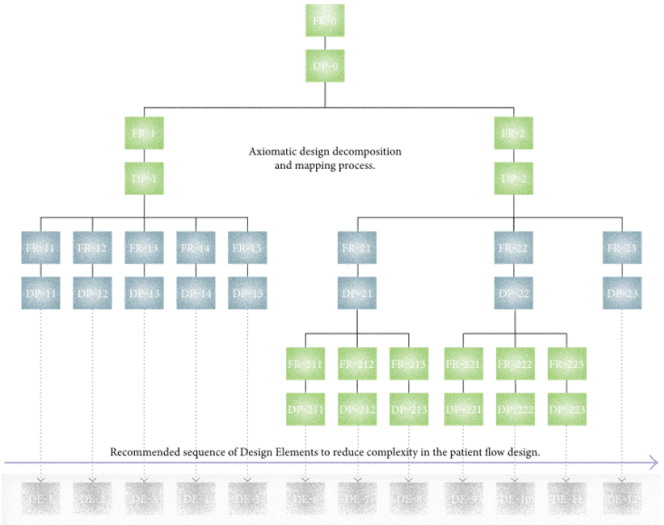
MANAGEMENT CENTER INNSBRUCK



Project Systems Engineering

Lecture Notes 2026

Prof. Erwin Rauch and Prof. David Cochran

PURDUE UNIVERSITY FORT WAYNE

Center of Excellence in Systems Engineering

12 Step Design Process Primer

A guide to understanding and applying the 12 Step Collective System Design Process.

Use this primer alongside the 12 Step Template in Lucid.

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Joseph J. Smith

Version 0.1 · 2026-04-28

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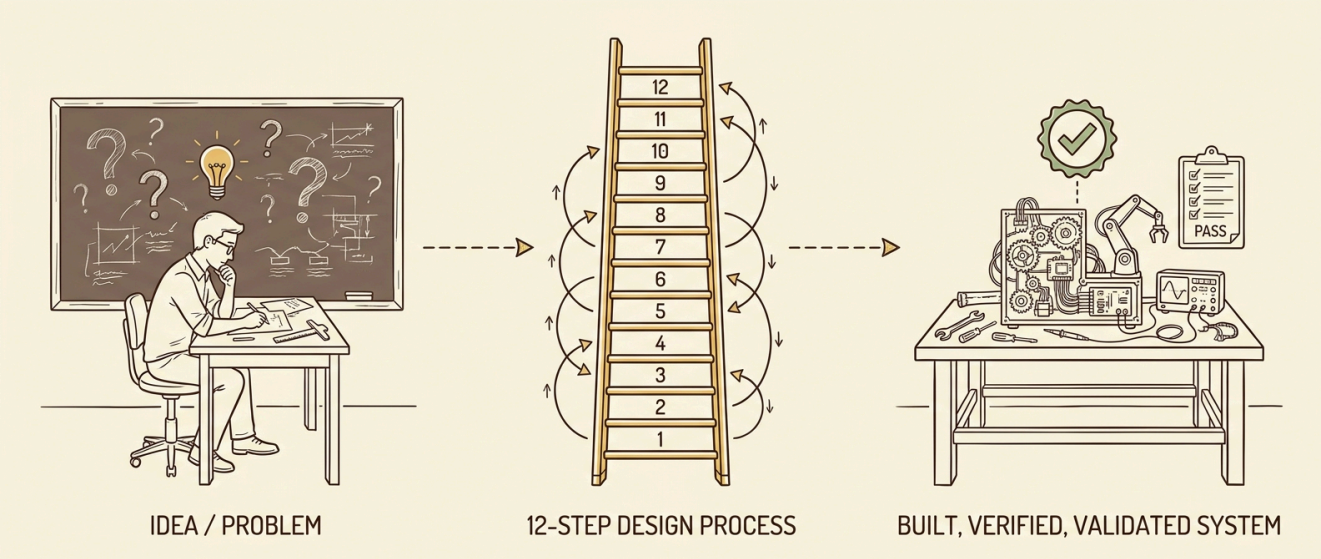
Purpose

FROM IDEA OR PROBLEM TO A BUILT, VERIFIED, AND VALIDATED SYSTEM



THE 12 STEP SYSTEM DESIGN METHODOLOGY:

- Provides one method for transforming an idea or problem into a **build-able, testable, and improvable** design.
- Provides a **Systems Engineering (SE) Lifecycle** approach that includes the best methods for design (e.g., Axiomatic Design, Use Cases, System Boundary, FMEA, DFX techniques).
- Provides a **common language** (the System Design Language) to ensure consistency in how designers describe the problem and solution domains.
- Recognizes that **design is NOT linear** — **12-Step Collective System Design** requires re-design as you learn more.

Flame Model of a System

TWO DIRECTIONS THROUGH THE FLAME

DIAGNOSIS

Starts with the **Work** and the **5 Whys** at each layer of the flame — tracing symptoms **inward** to root cause.

DESIGN

Starts with the **Tone** and works its way **"out of the flame"** — from mindset to thinking to structure to work.

THE FOUR ASPECTS

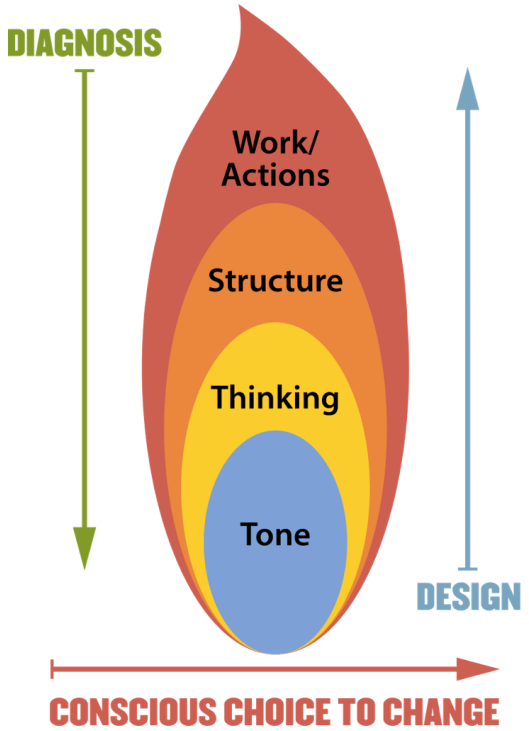
Work: Implemented with Standard Work.

Structure: Defines the operation of the system.

Thinking: Establishes the logical design of the system.

Tone: Perspective — a team consciously establishes and evaluates its **attitude, mindset, and spirit** toward problem solving.

FLAME MODEL OF A SYSTEM



Reference: Cochran, D. S. (2010). "Enterprise Engineering, Creating Sustainable Systems with Collective System Design – Part II," The Journal of Reliability, Maintainability, Supportability in Systems Engineering, Spring Journal. pp. 16–21.

KEY POINTS

- Poorly designed systems fail people — people are NOT the cause of system failures.
- The goal is **collective** agreement on the design — not a "perfect" design in your eyes.
- A well-functioning team comes first; only then can you reach a buildable, testable, and improvable solution.
- All four aspects of a system must work together.

The Engineer's Tone

ENGINEERS' CREED (2021)

As a Professional Engineer, I dedicate my professional knowledge to the advancement and betterment of **public health, safety, and welfare**.

I pledge:

- To give the utmost of performance;
- To participate in none but honest enterprise;
- To live and work according to the highest standards of professional conduct;
- To place service before profit, the honor and standing of my profession before personal advantage, and the public welfare above all other considerations.

In humility, I make this pledge.

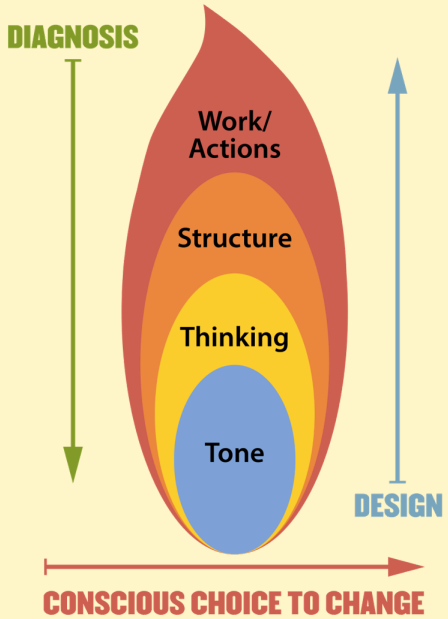
Reference: Engineers' Creed. National Society of Professional Engineers. Retrieved July 24, 2025, from nspe.org/career-growth/ethics/more-ethics-resources/engineers-creed

ON HUMILITY

Note the phrase: **"In humility, I make this pledge."**

Having **humility** as an engineer means:

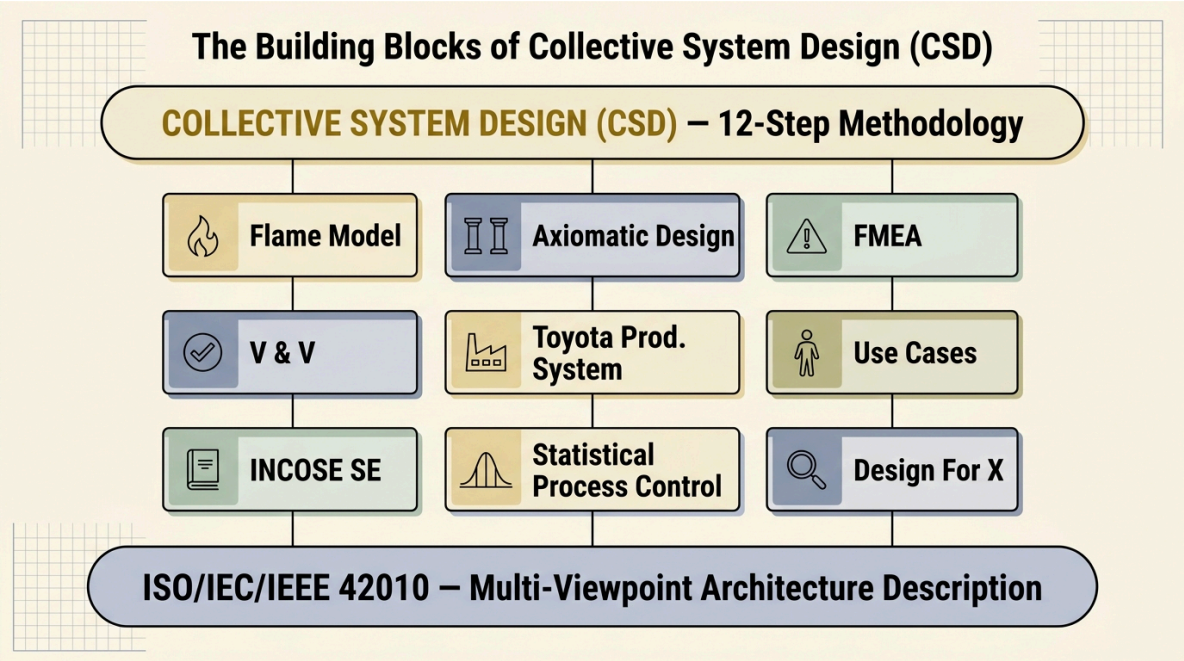
- Recognize that you do **not** have all of the answers.
- Freely admit when you do not know something and search for an answer. **Ask questions!**
- Recognize that someone else knows more than you about solving the problem — you could learn a lot from them.
- Embrace failure as a wonderful opportunity to learn something that you did not know.



Collective System Design — Diagnosis to Design Process

BUILDING BLOCKS OF COLLECTIVE SYSTEM DESIGN

ISO/IEC/IEEE 42010 establishes the foundational principle that a complex system cannot be understood from a **single** perspective. **Collective System Design (CSD)** is built on multiple complementary **viewpoints** — each discipline below contributes a viewpoint we use across the 12 steps.



Each block shown is covered briefly in this section (Foundations of CSD) and used throughout the 12 Steps.

KEY POINTS

- CSD is **not a single technique** — it's a synthesis of multiple disciplines, each contributing a viewpoint.
- **42010** is the *meta-framework*: it tells us a system needs multiple viewpoints to be fully understood.
- Every Step in this deck draws on one or more of these blocks — e.g., Step 4 leans on Axiomatic Design; Step 5 on FMEA; Steps 8–9 on V&V; Step 11 on the Toyota Production System.

ISO/IEC/IEEE 42010 — MULTIPLE VIEWPOINTS OF SYSTEMS

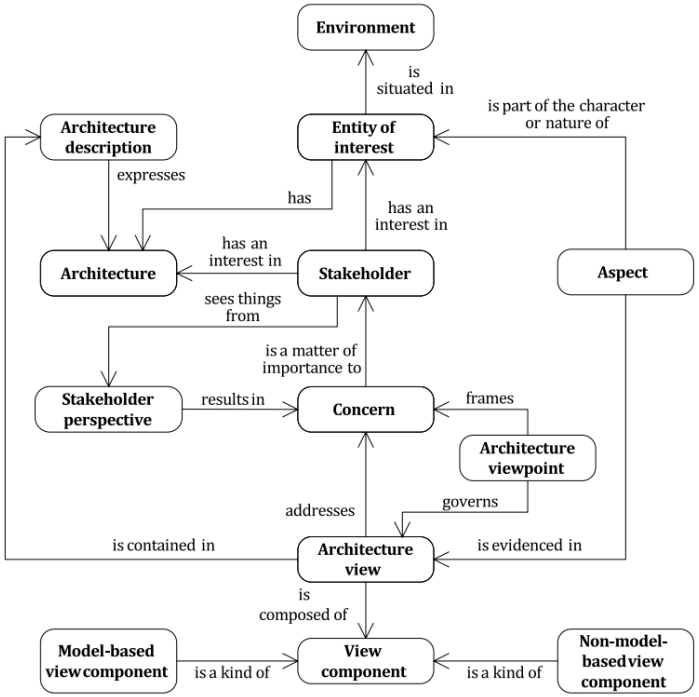
ISO/IEC/IEEE 42010 is the international standard for **architecture description** of systems and software. It introduced the foundational idea that a complex system cannot be understood from a single perspective — instead, the system is described through **multiple viewpoints**, each capturing the concerns of a specific stakeholder.

An **architecture description** per the standard consists of:

- **Stakeholders** — the people with interests in the system.
- **Concerns** — what each stakeholder cares about (cost, safety, maintainability, performance, lifecycle).
- **Viewpoints** — the conventions used to construct a particular kind of view.
- **Views** — the actual representation of the system from a specific viewpoint.

Why it matters for CSD: the idea that a system must be described through **multiple viewpoints** — functional, structural, behavioral, lifecycle — comes directly from 42010. CSD's emphasis on the FR (functional view), the PS (physical view), and decomposition across *structure, behavior, footprint, interface, and lifecycle* rests on this multi-viewpoint foundation.

CONCEPTUAL MODEL



Reference: ISO/IEC/IEEE 42010 — Figure A.1, Conceptual model of an architecture description.

ISO/IEC/IEEE 42010-2011 — THE FOUNDATION EDITION

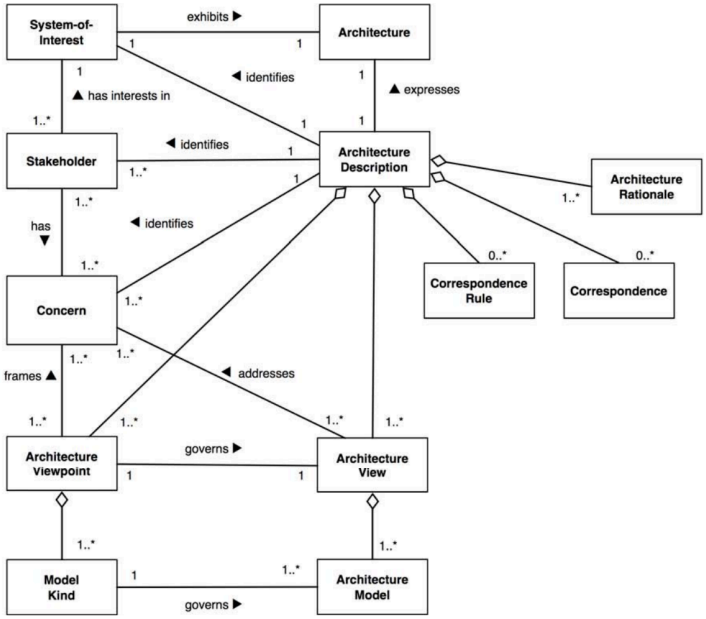
Published in **2011** as the first jointly-issued ISO/IEC/IEEE standard, 42010 unified two earlier documents (*IEEE 1471:2000* and *ISO/IEC 42010:2007*) into one architecture-description framework. It established the vocabulary the systems-engineering community still uses today.

CORE CONCEPTS INTRODUCED

- **System-of-interest** — the entity whose architecture is being described.
- **Stakeholder** — an individual / team / organization with an *interest* in the system.
- **Concern** — what a stakeholder cares about (cost, safety, performance, lifecycle).
- **Architecture viewpoint** — conventions for constructing one kind of view.
- **Architecture view** — the actual representation built from a viewpoint.
- **Architecture model** — one component inside a view (a diagram, a table).
- **Correspondence rule** — a stated relationship between elements across views.

> **The big idea:** a system's architecture cannot be captured in one drawing. It is a **set of views**, each governed by a viewpoint that addresses a stakeholder's concern.

CONCEPTUAL MODEL (42010-2011)



Reference: ISO/IEC/IEEE 42010-2011 — Conceptual model of an architecture description.

> **Why we still teach 2011:** the original framework is the simplest, cleanest version. Once students grasp **stakeholder → concern → viewpoint → view**, the 2022 additions (decisions and rationale) are easy extensions.

MODEL-BASED SYSTEMS ENGINEERING — WHAT & WHY

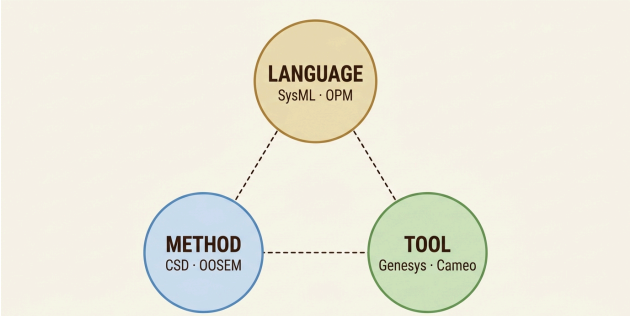
MBSE is the formalized application of modeling to support system requirements, design, analysis, verification, and validation throughout the lifecycle. It replaces the **document-centric** tradition (Word + Excel + Visio handoffs) with an **integrated model** as the authoritative source of truth.

DOCUMENT-BASED	MODEL-BASED
Requirements in Word, architecture in Visio, traceability in Excel. **Sync drift is constant** — each artifact tells its own story.	One **integrated model** with formal relationships. Diagrams, requirements, and traces are **views** of the same underlying data.

WHY IT MATTERS

- **Consistency** — one source of truth eliminates document-sync drift.
- **Traceability** — FRs ↔ PSs ↔ verification cases linked in the model itself.
- **Analyzability** — models can be queried and simulated; documents cannot.
- **Communication** — views generated from one model speak the same language across teams.

THREE PILLARS OF MBSE



All three are needed. A tool without a method — or a method without a language — misses the point.

ACRONYMS & TERMS

MBSE — **M**odel-**B**ased **S**ystems **E**ngineering. Modeling-driven approach to SE across the full lifecycle.

SysML — **Sys**tems **M**odeling **L**anguage. Standard graphical language (OMG-maintained) for specifying, designing, and verifying systems.

OPM — **O**bject-**P**rocess **M**ethodology. Alternative MBSE language combining function, structure, and behavior in one diagram type.

OOSEM — **O**bject-**O**riented **S**ystems **E**ngineering **M**ethod. INCOSE-developed top-down SysML-based method.

CSD — **C**ollective **S**ystem **D**esign. The 12-step method this primer teaches.

Genesys — MBSE authoring tool from Zuken / Vitech with a schema-driven repository (the tool we use).

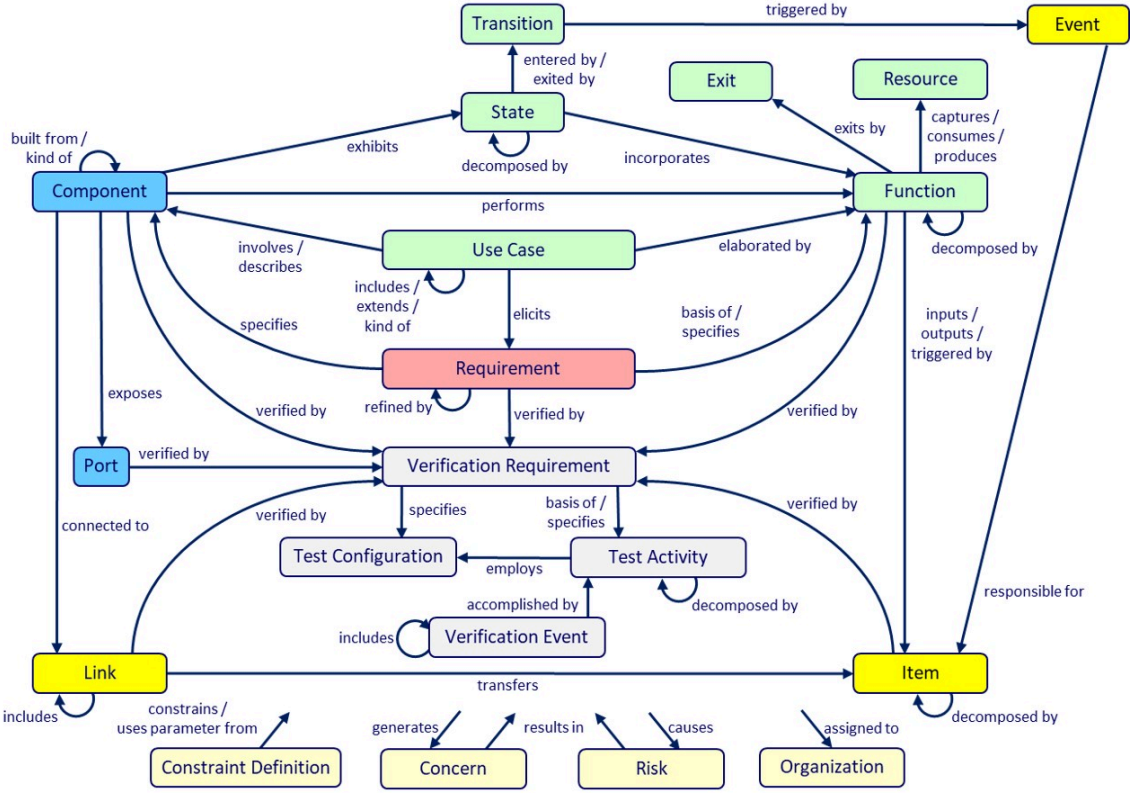
Cameo — *Cameo Systems Modeler*, a SysML-based MBSE tool (now part of Dassault Magic Systems of Systems Architect).

Connection to CSD: the 12-step process IS a method. Pair it with a language (FR / FRm / PS-ALT) and a tool (Genesys MBSE), and you have a working MBSE practice.

WHY CSD CAN BE APPLIED WITH MBSE — THE META-MODEL

MBSE tools don't know what a *"Functional Requirement"* is — they know **typed entities** and **typed relationships**. Plug in a **meta-model** (a schema that names the entity types and how they connect) and the tool can host any methodology that conforms. **CSD already has one** — the Information Architecture section defines every entity and relationship CSD uses.

The bridge: CSD's information model defines *what exists and how it relates.* Genesys's schema enforces *what may exist and how it must relate.* When the two align, the tool becomes a CSD authoring environment.



Every entity is typed. Every relationship is named. The graph IS the meta-model. *Reference: Vitech / Zuken Genesys MBSE schema.*

The payoff: because the meta-model is formal, an MBSE tool like **Genesys** can enforce it. Orphan FRs, dangling PSs, unverified Functions, and Failures with no Mitigation become **schema violations** — the tool flags them automatically.

WHAT IS AXIOMATIC DESIGN?

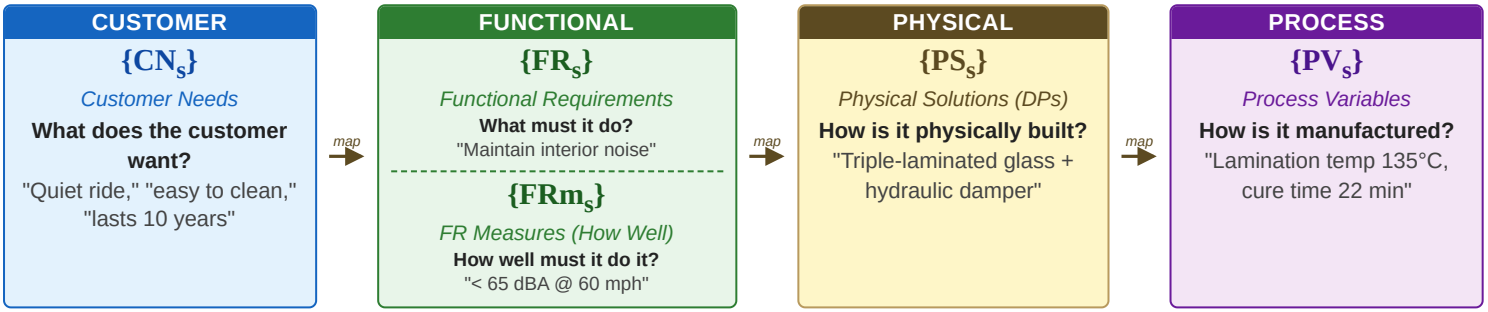
Axiomatic Design is a design approach used to ensure that the resulting design (system) is both **functional** and **process capable**.[1] The methodology uses **two axioms** to guide the design process — the **Independence Axiom** guides the decomposition of the design, while the **Information Axiom** gives a method to ensure the most capable design is chosen.

Design Axiom 1 — The Independence Axiom
Maintain the independence of the Functional Requirements (FRs).

Design Axiom 2 — The Information Axiom
Minimize the information content of the design.

[1] *Suh, N. P. (2001). Axiomatic Design: Advances and Applications. Oxford University Press.*

THE FOUR DOMAINS OF DESIGN



Why it matters: design proceeds **left→right** through the domains. The **Independence Axiom** applies to the FR→PS mapping — choices in one domain must not break independence in the previous one.

AXIOM 1 — THE INDEPENDENCE AXIOM

DESIGN AXIOM 1 · THE INDEPENDENCE AXIOM

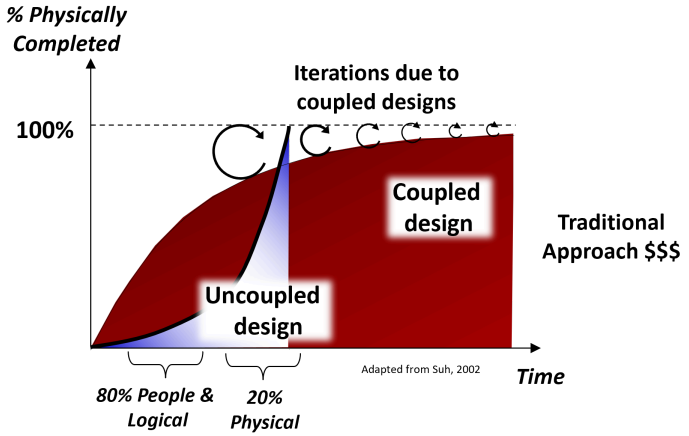
Maintain *the independence of the Functional Requirements* (FRs).

WHY "MAINTAIN"

FRs are **independent to start with** — each describes a distinct function the system must perform.

The **designer** introduces coupling through the choice of **physical solution**. A poorly chosen PS lets one decision affect multiple FRs at once — those **unintended interactions** break independence.

> **Axiom 1's job isn't to *make* FRs independent. It's to *preserve* the independence they already have.**



Coupled designs require costly iteration; uncoupled designs converge directly. (Adapted from Suh, 2002.)

Why it matters · coupled designs require iteration after iteration. Choosing physical solutions that keep the FR × PS mapping **diagonal** preserves independence and lets each FR be tuned without touching the others.

AXIOM 2 — THE INFORMATION AXIOM

DESIGN AXIOM 2 · THE INFORMATION AXIOM

Minimize *the information content of the design.*

INFORMATION CONTENT (I_I)

Defined in terms of the **probability of success** (P_i) of satisfying FR_i with PS_i.[2] P_i is the probability that the outcome falls within the **Common Range (CR)** — the overlap between the **Design Range** and the **System Range (SR)**.

$$I_i = \log_2(1 / P_i)$$

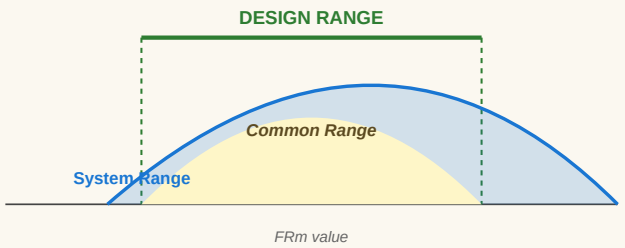
where

$$P_i = P(CR / SR)$$

thus

$$I_i = \log_2(SR / CR)$$

[2] *Suh, N. P. (2001). Axiomatic Design: Advances and Applications. Oxford University Press.*



Probability density function — System Range overlaps Design Range to form the Common Range

Why it matters · a smaller I_i means the System Range fits more snugly inside the Design Range — the design more reliably hits its target. **Among competing solutions that all satisfy Axiom 1, choose the one with the lowest information content.**

SHIGEO SHINGO — SYSTEMS THINKING AT THE OPERATION LEVEL

Shigeo Shingo (1909–1990) was the Japanese industrial engineer whose work with **Toyota** turned the Toyota Production System into something teachable. While Ohno owned the system view, Shingo made it **operational** — he showed how to design *each operation* so the system functions as intended. CSD inherits two ideas directly from him: **functions before solutions**, and **error-proof at the source**.

SMED

Single-Minute Exchange of Die — a structured method to reduce changeover time.

Separate **internal** *setup (machine stopped) from* **external** *setup (machine running). Convert internal → external. Eliminate adjustments.*

> **CSD link:** small batches & flow are only feasible when changeover is short. SMED makes the FR *"produce in customer-pull quantities"* achievable.

POKA-YOKE

Mistake-proofing — design the operation so the defect *cannot* occur.

USB connector that only fits one way. Gas-pump nozzle that won't enter a diesel filler. Surgical-tray count built in.

> **CSD link:** Step 5 FMEA asks "what failure modes does this PS introduce?" Poka-yoke is the **preferred mitigation** — design the failure out, don't inspect for it.

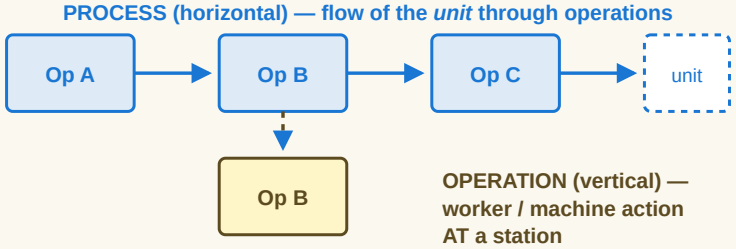
SOURCE INSPECTION

Detect at the **cause**, not the symptom. Catch the condition that *creates* a defect before the defect exists.

Stop the press if the sheet is misaligned. Don't measure the resulting bad part — that's already too late.

> **CSD link:** verification (Step 8) lives at the **FRm** level — we measure the *function*, not the artifact. Catch the cause, not the consequence.

SHINGO'S DISTINCTION: OPERATION VS PROCESS



Shingo named these axes explicitly: the **horizontal axis is the process** *(material flowing through operations) and the* **vertical axis is the operation** *(work performed at a station). His rule:* **improve the process before improving the operation**. *Speeding up Op B without smoothing the flow just builds inventory in front of Op C — the same trap CSD names in "Salt Water PSs."*

The throughline to CSD: Shingo treats every operation as a **function-first** question. *"What is this operation supposed to achieve?"* Once the function is named, the failure modes — and the poka-yoke that prevents them — become obvious.

Reference: Shingo, S. A Study of the Toyota Production System from an Industrial Engineering Viewpoint (Productivity Press, 1989).

FRESH WATER — POURING A NEW SYSTEM INTO THE OLD CONTAINER

The Goal: achieve **all FRs** with the **least resources**, *without compromise*. The **Manufacturing System Design (MSD)** framework names **seven such FRs** — the *fresh-water* alternative to optimizing single operations.

We fail because we try to **pour fresh water** (the new system) into the **old system** (salt water) — and we're left with salt water.

We have to **build a container** — a term coined by **David Kantor and William Isaacs** in their work on dialogue — to hold the new system design.

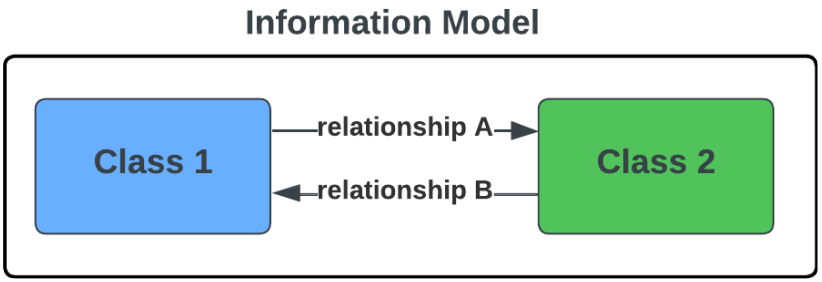
The old system is the one driven by **unit cost of an operation** instead of achieving the functions of the system well.

KEY POINTS

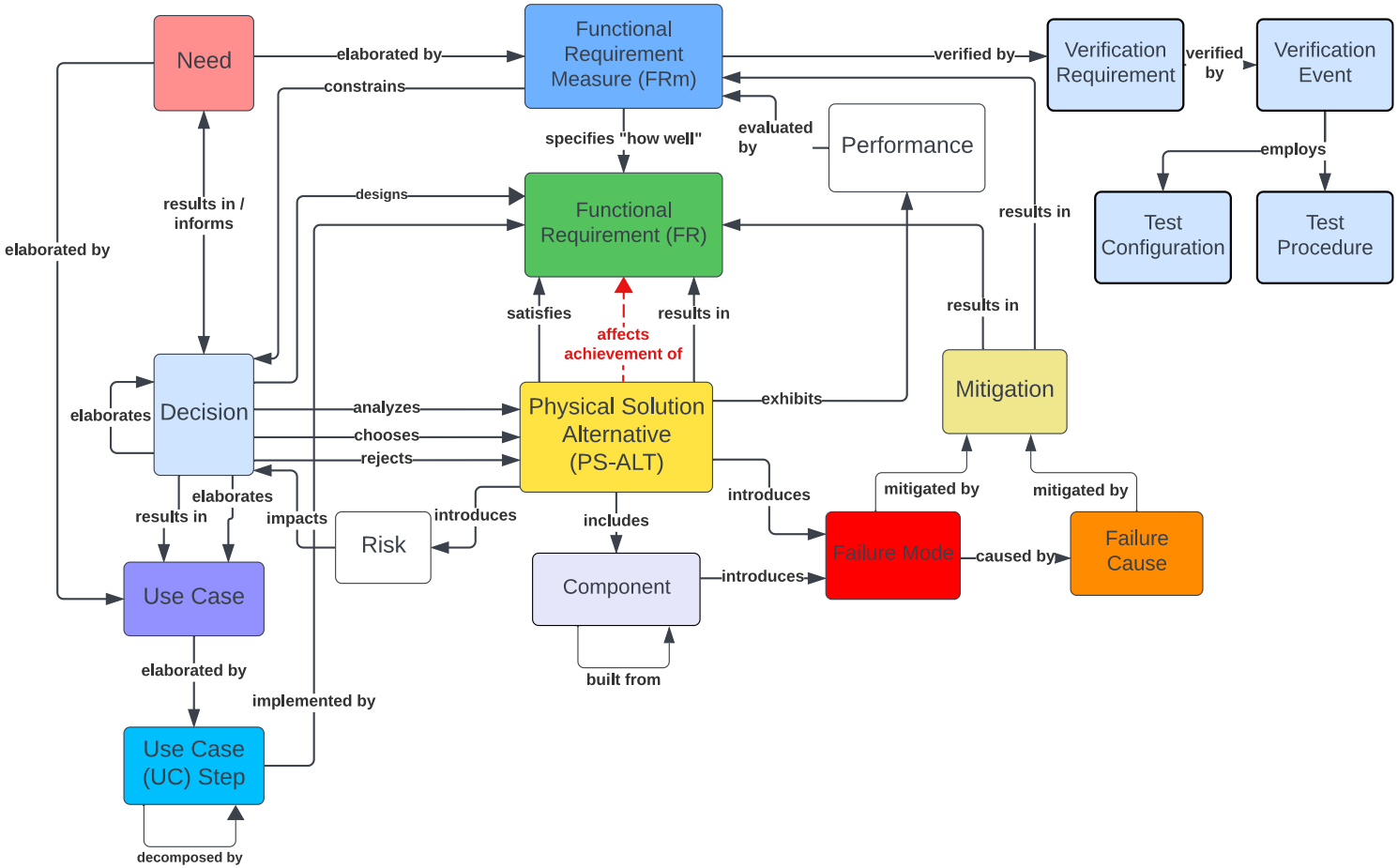
- The **collective agreement** of an FR is the foundation of system change — if the team can't name the FR, they can't achieve it.
- The challenge to implementing systems change within an organization is building a team comfortable working together **without fear** of negatively impacting their careers — Kantor and Isaacs call this a **"container"** at the most fundamental level.
- Without the container, the new methodology (fresh water) gets diluted by the existing culture (salt water). Without the FRs, the design degrades.

KEY DEFINITIONS

Information Architecture	
Term	**Definition**
Collective System Design Language	A language that consists of predefined classes and relationships to classify and relate information relative to a design.
Information Model (Meta Model)	A graphical representation of the classes of information and the relationships between the classes that form a System Design Language.
Information **"Class"**	A category or type of information. For example: Need, Functional Requirement, Physical Solution, Failure Mode.
Information **"Relationship"**	A defined connection between two classes of information. The connection implies that one class has an impact or interaction with the other. Relationships are **bidirectional** and can be read in either direction (e.g., *X "elaborates" Y*, *Y is "elaborated by" X*).



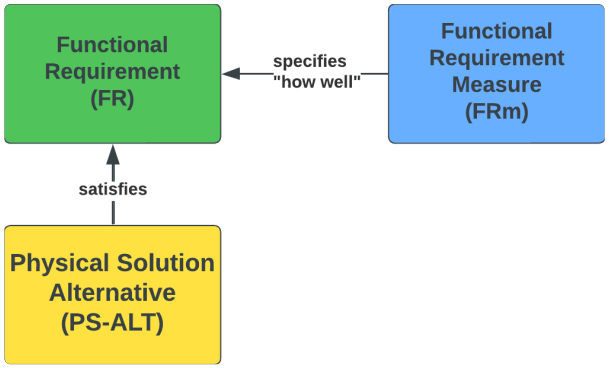
THE COLLECTIVE SYSTEM DESIGN LANGUAGE — FULL INFORMATION MODEL



DEFINITIONS

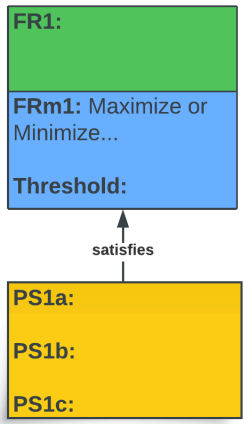
FR — FRm — PS-ALT		
Term	**Abbr.**	**Definition**
Functional Requirement	**FR**	**"What"** must be achieved. An FR represents a required function of the product / system / service.
Functional Requirement Measure	**FRm**	A performance measure that defines **"how well"** an FR is achieved. Each FRm includes a **Threshold** (acceptable performance) and a **Goal** (desired ultimate performance).
Physical Solution Alternative	**PS-ALT**	**"How"** the design (product / system / service) will achieve a stated FR.

RELATIONSHIPS



IN A DESIGN DECOMPOSITION

The diagram below shows how a design relationship is **formatted for use in a design decomposition** — the FR and its FRm (with threshold) are stacked together, and the PS-ALT(s) that *satisfy* the FR sit beneath.

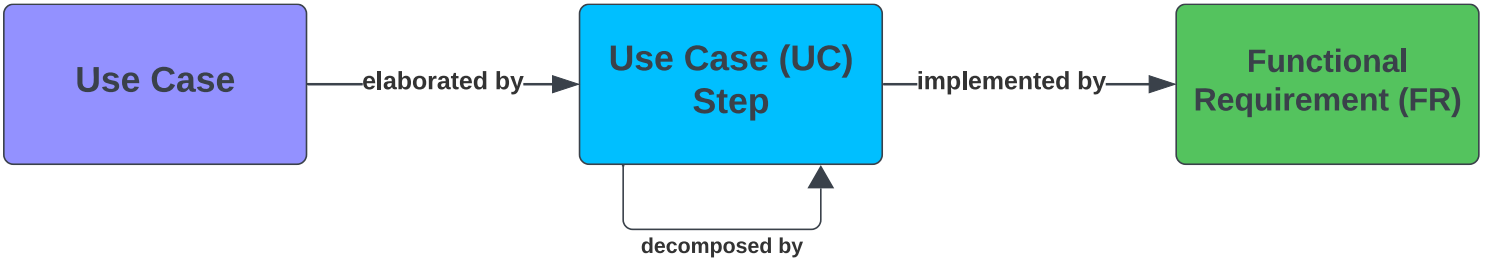


DEFINITIONS

Use Case — Use Case Step — FR		
Term	**Abbr.**	**Definition**
Use Case	**UC**	A scenario for which the design in question will be used.
Use Case Step	**UC.ST**	A step (task / function) performed during a Use Case. The steps the customer and system take together to achieve the desired outcome.
Functional Requirement	**FR**	**"What"** must be achieved — a required function of the product / system / service.

Key insight: Functional Requirements (FRs) are **derived from the customer's interaction with the system, step-by-step**. Walking through each Use Case Step — what the customer does and what the system must do in response — surfaces the functions the design must deliver.

RELATIONSHIPS



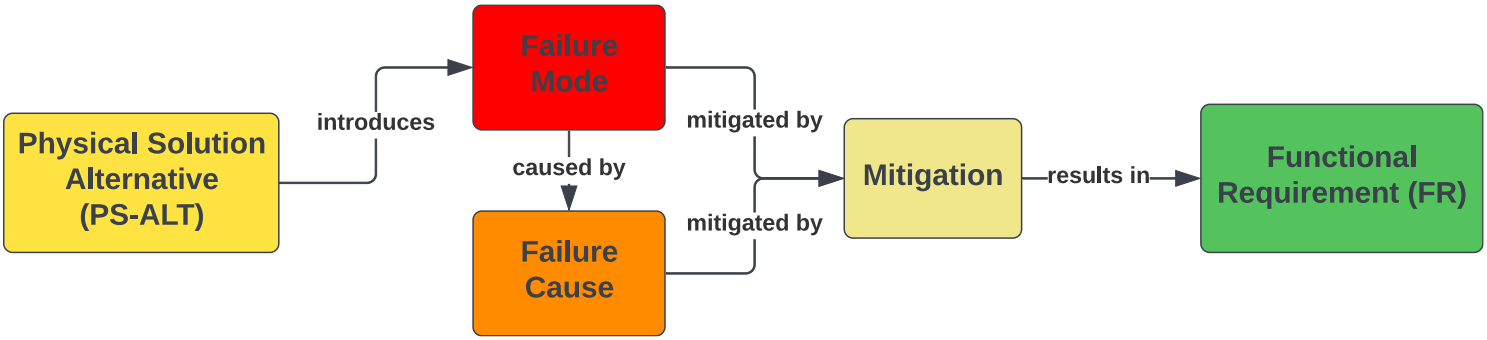
"We don't know the functions if we don't know how we're going to use the product or service."

DEFINITIONS

PS-ALT — Failure Mode — Failure Cause — Mitigation		
Term	**Abbr.**	**Definition**
Failure Mode	**FM**	A way in which the design or process could fail.
Failure Cause	**FC**	The cause of a particular Failure Mode.
Mitigation	**M**	The means to **prevent** a Failure Cause (prevention), or to **reduce the impact** of a Failure Mode (detection).

Key insight: A designer chooses a PS-ALT — **The PS-ALT introduces a Failure Mode**. As soon as a PS is chosen, the designer should immediately ask: *"How could this PS fail?"*

RELATIONSHIPS



"The Designer's Selection of a Physical Solution Introduces Failure."

List of Questions

WHAT DO YOU *NOT* KNOW ABOUT THE PROBLEM OR SOLUTION?

Capture everything you are uncertain about as the design unfolds — assumptions to confirm, gaps to fill, decisions still open. Each question is directed at the person best positioned to answer:

List of Questions

Question	Who should answer the question?	From Step	Answer	Name + Email of the person who provided the answer OR Cited Reference	Date Answered
How much is the customer willing to spend?	Potential customer(s)	1.6	$85	Sarah Smith — SSmith@loa.com	2026-04-12
What type of fittings are standard to residential faucet installations?	Design Team	2.6 – 2.7	3/8" compression on faucet, 1/2" female NPT on supply	Luxuryhome. (2024, October 29). Understanding Faucet Supply Line Sizes: Essential Guide. Luxuryhome Faucet Manufacturer. https://www.luxuryhomefaucet.com/faucet-supply-line-sizes/	2026-04-15

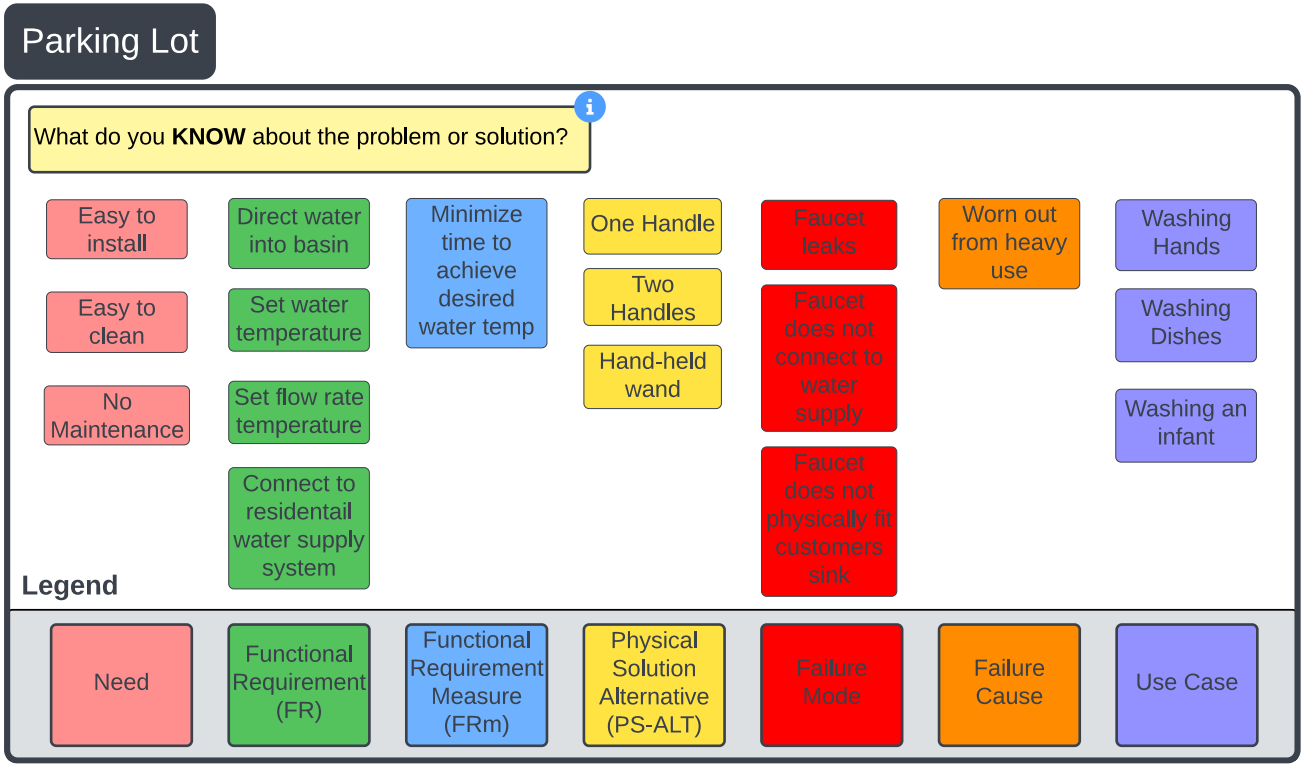
KEY POINTS

- **Ask questions without fear** — the only bad question is one that is *not* asked.
- Always write down the **name** of the person who answered, the **answer given**, and the **date** — the log is the audit trail behind every design decision.

Parking Lot

HOW TO USE THE PARKING LOT

1. The parking lot is tracking what you know (or your ideas) about the design, but you may be unsure where to document the information right now. **Brainstorm and generate as many ideas as possible** — and classify them according to the information class in the Parking Lot.
2. Remove information from the parking lot once it finds its home in the design. The parking lot is tracking **what has not yet been incorporated into the design**.



THE 12 STEPS LIVE IN A SINGLE LUCID TEMPLATE

Every worksheet, table, and diagram referenced in this deck lives in **one Lucid template**. Copy it once, then fill it in as you walk Steps 1→12.

TEMPLATE LAYOUT (TOP → BOTTOM)

AT THE TOP

- **Parking Lot**
- **List of Questions**

THEN STEPS 1 → 12

1	Project Intro & Background	7	Design For X (DFX)
2	Problem Statement	8	Verification Plan
3	Conceptual Alternatives	9	Validation Plan
4	Decomposition	10	Build Plan
5	FMEA	11	Standard Work
6	Detailed Design + BOM	12	V&V + Final Cost

Define (1–3) **Design** (4–7) **Verify & Validate** (8–9) **Build & Close** (10–12)

SETTING UP YOUR LUCID ACCOUNT

Lucidchart

Joe Smith (smitjj09@pfw.edu) handles your Lucid setup. You don't need to create your own account — Joe does these **two things for you**:

1 — SET UP YOUR LUCID ACCOUNT

Joe creates your account. You'll receive an email asking you to **reset your password** to finish setting it up.

> **Heads up:** the email often lands in your **spam / junk** folder. Check there if you don't see it in your inbox.

2 — SET UP YOUR 12-STEP TEMPLATE

Joe creates a **Lucid 12-Step template** for your team and sends invitations to each group member.

- You'll receive an **invitation email** explaining you've been added.
- The template appears under **"Shared with Me"** in Lucid.

Direct all setup questions to Joe. smitjj09@pfw.edu

Password-reset link expired? Email Joe with the address tied to your Lucid account and ask for a fresh reset.

Tips and Tricks for Using the 12 Step Template in Lucid

LUCID SHORTCUTS TO SPEED UP YOUR WORKFLOW

Navigation, Editing, and Formatting Shortcuts	
Action	**What It Does**
Right Click + Hold	Drag the mouse to **center the screen** on the desired content.
Mouse Wheel	Scroll to **zoom in and out** on the content.
×2 Double-Click	Edits **"Grouped"** content. After the double-click, you can click a 3rd time on the specific area you want to enter or edit text in.
`Shift` + `Enter`	Advance to the **next line** when editing a shape or table cell. (Plain `Enter` still works for normal text boxes.)
`Ctrl` + `Shift` + `V`	Paste content while **retaining the formatting** of the 12-Step Template.
`Spacebar` + Drag	**Pan** around the canvas without selecting anything — faster than scroll bars on a busy page.
`Ctrl` + `D`	**Duplicate** the selected shape, cell, or row — useful for adding more table rows or copying a card.
`←` `↑` `↓` `→`	**Nudge** the selected shape by 1px. Hold `Shift` to nudge by 10px for finer-grain alignment.

STEP 1.1 — WHO'S ON THE DESIGN TEAM?

Who is on the design team? What is their background? What role will each member assume for this project?

1.1 — Team Members			
Name	**Background Info.**	**Contact Information** (Email and Phone)	**Role**
David Cochran	PFW SE Center — Director, Professor of Systems Engineering	dcochran@pfw.edu (260) 481-XXXX	Project Lead
Joe Smith	PFW SE Center — Associate Director	smitjj09@pfw.edu (260) 481-XXXX	Electrical Lead
Onkar Sonur	PFW Student — Industrial Engineering Technology Major	sonur01@pfw.edu (XXX) XXX-XXXX	Manufacturing Lead

KEY POINTS

- Step 1 starts with people: capture **name**, **background**, and **role** for every team member.
- Roles establish ownership early — each FR group will trace back to a Lead.
- Leave the open row available; teams grow as scope expands.

STEP 1.2 — PROJECT DESCRIPTION (1–2 SENTENCES)

What is the main problem you are going to solve?

EXAMPLE ANSWER

Our project is to design the next generation of residential water faucets to meet specified use cases. The solution will connect to existing residential water supply systems and deliver water to a basin.

STEP 1.3 — PROJECT MANAGEMENT

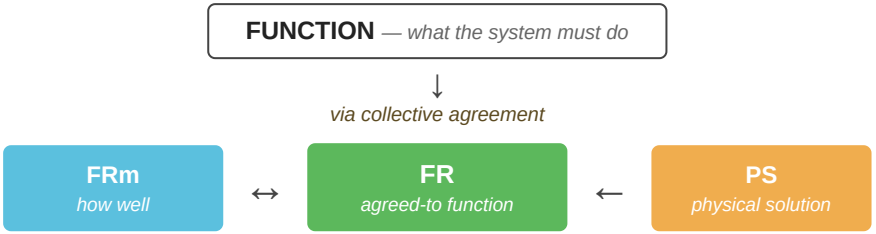
When and what time will you meet with your project advisors?
Tuesdays at 4 pm
Who is your project sponsor and who will be your point of contact?
UC Inc. — Shahab Shah — shah@ucinc.com
When and how often will you meet with your customer / project sponsor?
Every other Thursday at 3 pm

KEY POINTS

- The **Project Description** clarifies in one or two sentences the problem that the project solves.
- Lock in cadence with both **advisors** and the **sponsor/customer** at the start; recurring meetings keep the project from drifting.
- Capture the sponsor's named point of contact and email — ambiguity here causes scope and approval delays.

Collective System Design (CSD) Language

Why this refresher first? **Step 1.4** (next slide) will ask you to label every given "requirement" by its **class of information** — **Need, FR, FRm, or PS-ALT**. Those are the same foundational classes defined by the **CSD Language**. Use the four terms below — **Function, FR, FRm, PS** — as the lens to correctly classify what the customer, SME, stakeholder, or advisor gives you.



- **Function** — what the system must do.
- **Functional Requirement (FR)** — the function the team **agrees MUST** be implemented for the design to be successful.
- **Functional Requirement Measure (FRm)** — *how well* the FR is achieved *(can be more than one FRm per FR)*.
- **Physical Solution (PS)** — what **thing** implements the FR.
- The **designer chooses** the PS to achieve the FR — it is a **decision**.

"Requirements" provided by a **customer**, a **subject matter expert (SME)**, a **stakeholder**, a **project advisor**, or **yourself** are often a mixture of different **classes of information**. As the designer, it is essential that you **understand and can organize** the information you receive. You will use this information throughout the design process to ensure your solution meets the needs of your customer.

> **Step 1.4 —** State any "requirements" you have been given and determine which class of information is the best fit. Sources include the **customer**, **SMEs**, **stakeholders**, **project advisors**, and **yourself**.

1.4 — Given "Requirements"

Stated "Requirement"	**Class of Information** (Need, FR, FRm, PS-ALT…)	**Provided by** (name)	**Must-have or nice-to-have? Why?**	**Date**	**Modified on**
Must be made of titanium	PS-ALT	Joe Smith	Maybe not — what is the FR?	4/1/2026	4/30/2026
Must accelerate from 0–100 km/h in less than 3 seconds	FRm	Joe Smith	Clarify whether this metric is the threshold or the goal…	4/1/2026	4/30/2026
Hold liquid	FR	David Cochran	Yes	4/1/2026	
Energize circuit	FR	David Cochran	Yes	4/1/2026	4/15/2026

KEY POINTS

- **Question every requirement** — especially the ones that look obvious. A stated "requirement" is often a hidden **PS-ALT** (a solution someone already has in mind). Keep asking *"why?"* until you reach the underlying function (the FR). The strongest designs come from challenging given requirements, not accepting them.
- Customer "requirements" usually mix several classes of information — Needs, FRs, FRms, and PS-ALTs — sort each one before you act on it.
- Refer to the glossary at the beginning of this document to better understand the CLASSES of information.
- The Modified-on column is essential — requirements evolve as you talk to advisors and the customer.

1.5 — COST CONSIDERATIONS (PART 1)

1.5 — Cost Considerations — Part 1	
Estimated price that the Market will support	**$100**
Desired profit $/unit	**$50**
Required manufacturing cost/unit that the market will support	**$50**
— OR —	
How much is the client willing to pay for the solution? (i.e., the project budget)	**$2,400**

Values shown are example answers. **Part 2** *(final-cost reconciliation) is completed in* **Step 12**.

HOW TO FILL IT IN

1. **Determine what your customer is willing to pay** for your product / system / service. Base it on research of similar product offerings, or by talking to the customer to understand their budget.
2. **Determine your desired profit per unit**. Make sure the amount is reasonable by understanding common profit margins for your particular product / system / service.
3. **Required manufacturing cost = Estimated price − Desired profit/unit.** This is what it must cost to *produce* the product.

KEY POINTS

- As designers, we want to achieve a **market-acceptable cost** AND the design FRs **without compromise**.
- This trade-off is the engineer's / system designer's central challenge — cost discipline cannot come at the expense of FRs.
- Two valid framings: **market price** (consumer goods) *or* a fixed **client budget** (custom builds). Pick whichever applies to your project.

STEP 1.6 — WHAT STANDARDS MIGHT YOUR SOLUTION HAVE TO MEET?

> **Step 1.6 —** What standards might your solution have to meet?

1.6 — Standards	
Standard	**Description and Link to Standard**
NSF/ANSI Standard 61	Faucets and plumbing products intended for contact with drinking water should be tested and certified to NSF/ANSI Standard 61: Drinking Water System Components. Link to Standard

KEY POINTS

- Standards are unique to the problem you are solving and the solution you are designing.
- Your design choices will impact which standards ultimately apply — e.g., wireless communication vs. hard-wired changes the regulatory picture.
- Capture the link to each standard up front so the team can verify exact requirements during Verification (Step 8).

1.7 — SAFETY CONCERNS AND RESPONSIBILITIES

> **Step 1.7 —** What safety concerns and responsibilities must you consider?

Concerns	Description	FR Introduced
Risk of scalding	Faucet unexpectedly emits hot water on user.	Limit hot-water exposure to the user.
Risk of flooding the home	Faucet leaks from installation issues, wear and tear, regular use.	Prevent water leakage from the faucet.
Growth of potentially harmful germs in residential water system	Design of faucet enables / fosters bacteria growth.	Prevent bacterial growth within the faucet.
Responsibilities	**Description**	**FR Introduced**
Safe Materials	Choose materials that are safe for contact with drinking water.	Use drinking-water-safe materials.
Safe Installation	Ensure installation process accounts for safe procedures (tools, adhesives, no sharp edges).	Enable safe installation of the faucet.
Safe Use	Ensure user does not receive injuries through operation — cuts, abrasions, fatigue.	Operate the faucet without injuring the user.

KEY POINTS

- List safety **concerns** first — the failure modes the design must prevent — before listing the **responsibilities** the design must uphold.
- Each concern should map to one or more responsibilities in the design.
- Safety considerations identified in Step 1.7 feed Step 5 (Design & Process FMEA) and Step 8 (Verification Test Plan).

1.8 — THE "-ILITIES"

> **Step 1.8 —** What lifecycle steps must you consider during the design of your solution?

Lifecycle Step / "-ility"	Description	FR Introduced by "-ility"
Producibility	The solution must be able to be built / produced.	Build the solution.
Scalability	The solution should be scalable to fit different needs and applications.	Scale the solution to different needs.
Portability	The design needs to be portable to perform tasks at different locations.	Transport the solution to different locations.
Reliability	The design needs to work in spite of variation and potential operating conditions.	Operate within specified conditions despite variation.
Maintainability	Maintenance tasks and frequency must be documented for the customer. The design should enable easy maintenance and replacement of high-wear points.	Maintain the solution.
Recyclability	The materials should be able to be recycled.	Recycle the solution's materials.
Disposability	The method to dispose should be made clear to the customer.	Dispose of the solution safely.
Remanufacturability	If possible, some parts may be able to be reused in future applications.	Reuse parts in future applications.

KEY POINTS

- The "-ilities" force you to think about the **full lifecycle** — not just the working product, but how it is built, used, maintained, and retired.
- Different problems weight the "-ilities" differently. Identify the dominant ones for your project early.
- Each relevant "-ility" should later trace to one or more FRs in the Decomposition (Step 4).

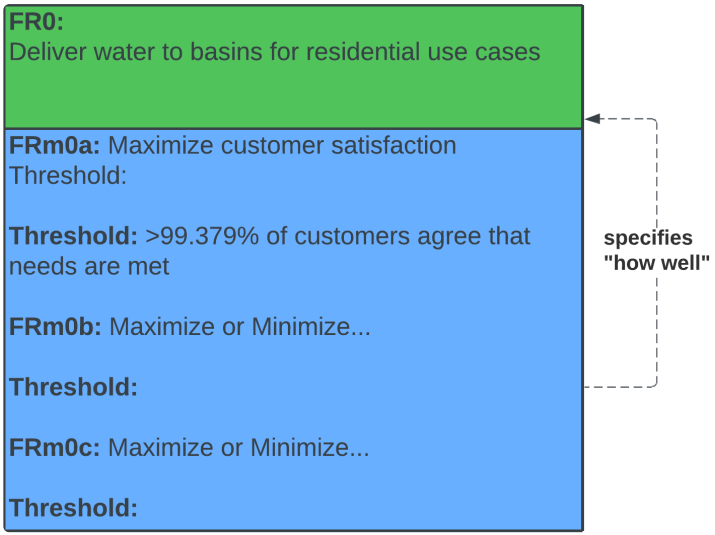
2.0 — PROBLEM STATEMENT

2.0 — Problem Statement	
Step 2.0 — What is the main problem you are solving?	**Who has this problem?**
(Try to keep the problem statement concise — 1–2 sentences.)	

Step 2.1 — What is the main **function (FR0)** that your solution must perform?

Step 2.2 — How will you **measure (FRm0)** the success of your solution in achieving the main function?

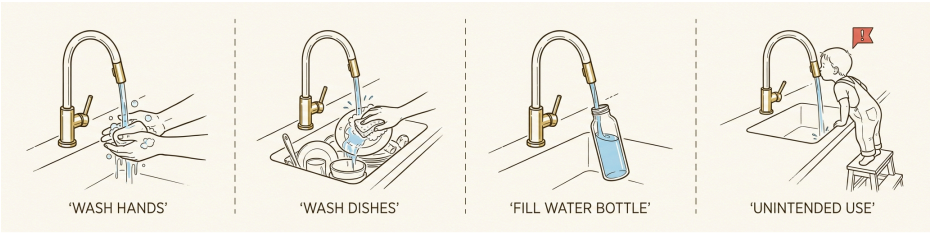
FR0 — THE MAIN FUNCTION



KEY POINTS

- The **Problem Statement** describes the purpose of the project in 1–2 sentences. *If the problem statement is not brief, the problem is not understood.*
- **FR0** is the single top-level functional requirement — everything else in the design decomposes from it.
- **FRm0** is the measurable form of FR0 (there can be more than one FRm0) — the metric(s) you'll use in Verification (Step 8) to confirm the solution achieves the main function.

STEP 2.3 — WHAT USE CASES WILL YOUR SOLUTION PERFORM?



A **Use Case** is a scenario or task a customer performs with your product / system / service. Different Use Cases impose **different FRs**.

The Use Case list should be **exhaustive** — capture every scenario up front to avoid *requirements creep*.

EXAMPLES

Toaster: toast bread · toast a bagel · store when not in use · clean the toaster.

Car: grocery trip · road trip with luggage · pull a trailer · routine maintenance.

> **Important —** Watch for **unintended** Use Cases. A flat-head screwdriver is often used as a chisel or pry tool. Account for these in safety considerations; revise or add FRs as needed.

USE CASES — FAUCET EXAMPLE

Use Cases
Step 2.3 — Use Cases to Support
Wash hands in sink
Wash dishes due to medical procedure
Drink water from sink
Install water filtering system

KEY POINTS

- Use Cases drive Functional Requirements — capture them **exhaustively** before locking down FRs.
- Engaging customers and additional research helps surface Use Cases the team may not see on its own. The designer ultimately decides which Use Cases the design will support.
- Plan for **unintended** Use Cases too — they create new safety considerations and may add or revise FRs.

HOW-TO STATE GOOD FUNCTIONAL REQUIREMENTS (FRS)

- **ALWAYS** start an FR with a **VERB**.
- State the **name of the function** in **active verb — direct object (noun)** format, where the verb represents an explicit **transformation of inputs into outputs** — i.e., *WHAT* is to be done.

Correct

FR: Adjust temperature of water

Incorrect

FR: Turn knob to adjust temperature

Solution embedded in FR statement

Do NOT:

- Include **measures of performance** (i.e., do not describe *"how well"* the FR needs to be performed).
- **Embed** or state **solutions** in the FR statement.
- Use the word **AND**. If you want to say "and" in an FR statement, you are probably describing **two separate FRs**.

GOOD OR BAD FUNCTIONAL REQUIREMENTS? WHY?

Example FRs			
FR	**Good or Bad?**	**Rationale**	**Refined FR or FRm**
Use Titanium			
Maximize acceleration of car			
Decelerate car			
Ensure material is recyclable			
Accelerate car with maximum efficiency			
Hold device securely			
Identify and report error conditions			
Hit nail with hammer			

KEY POINTS — WHAT MAKES A GOOD FR

- FRs **start with a verb** + direct object (e.g., *Adjust temperature*).
- Don't embed a **solution** (e.g., *Use Titanium*, *Turn knob*).
- Don't include a **measure of performance** ("how well") — that belongs in the FRm.
- Don't use **"AND"** — usually a sign of two separate FRs.

GOOD OR BAD FUNCTIONAL REQUIREMENTS? — ANSWERS

Example FRs			
FR	**Good or Bad?**	**Rationale**	**Refined FR or FRm**
Use Titanium	**Bad**	PS is embedded in the FR. Does not represent a function that must be performed.	**FR:** Support structure under load **FRm:** Minimize weight **Threshold:** <10 kg
Maximize acceleration of car	**Bad**	*Maximize* is describing the function and should be included in the **FRm** instead.	**FR:** Accelerate car
Decelerate car	**Good**	A clear function of a car with no metrics of "how well."	—
Ensure material is recyclable	**Bad**	*"Recyclable"* describes a choice of material which is better stated as an FRm: *Maximize use of recyclable material*.	—
Accelerate car with maximum efficiency	**Bad**	*Maximum efficiency* describes "how well."	**FR:** Accelerate car
Hold device securely	**Bad**	*Securely* describes "how well."	**FR:** Hold device
Identify and report error conditions	**Bad**	Two functions are stated as one. Avoid the use of **AND**.	**FR:** Identify error conditions **FR:** Report error conditions
Hit nail with hammer	**Bad**	Starts with a verb, BUT a hammer and nail are **solutions**.	**FR:** Install fastener OR **FR:** Fasten structural components together
Maintain water level	**Good**	Starts with a verb and explains what the system must do.	—

FUNCTIONAL REQUIREMENT MEASURES (FRM) — GOING DEEPER

Definition: An FRm is a **performance measure that defines how well the system must perform the FR**.

Expression: Measurable characteristic stated as a **vector including units** (e.g., *Minimize temperature in °C*) above the **threshold**. *(1:m relationship — one FR may have many FRms.)*

Key Points:

- An FRm provides a measure to **quantify the performance** required to successfully deliver a function (achieve the FR).
- A **vector** that expresses, in measurable terms, how well an FR must be performed — including **threshold, maximize, minimize**, or a target range / level of desired performance (goal).
- FRms enable a designer to **determine which alternative solution best satisfies the FR**.

Start with the FR + **What we are measuring (with units)** + **Direction of "Goodness"** + **Threshold** = **FRm**

Functional Requirement	FRm: What are we measuring? (include units)	FRm: Maximize or Minimize? *(Direction of Vector)*	FRm Threshold — What is considered acceptable?
Accelerate car	Acceleration (m/s^2)	Maximize	0 to 100 km/h < 3.1 sec (> 7.94 m/s^2)
Stop car	Stopping distance (m)	Minimize	100 to 0 km/h < 50 m

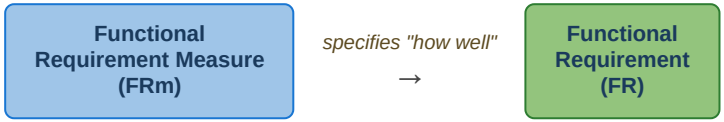
KEY PERFORMANCE INDICATORS (KPIS) AND FRM'S

Are KPIs also FRm's? No, not necessarily.

KPIs are measures to assess if a **predefined goal** is achieved. A goal *could* be an FR, but in many cases the relationship between a goal and an FR of the system is **not well understood**.

If we cannot relate the KPI and its goal to an **FR of the system**, improvement is often ineffective — *we don't know what to fix because we don't know what the system isn't* **doing (FR)** *well.*

Remember: an **FRm** specifies *"how well"* the system must perform an FR, and an **FR** states **what a system MUST DO** to deliver value to the customer.



For any given **KPI**, the **FR** of the system should be understood. Therefore, **KPIs should be derived from FRs of the system** and would represent FRm's.

EXAMPLE

Example KPI — Abandon rate of calls for customer service *(how many customers drop the call before reaching an operator)*

What is the FR? **FR:** Answer customer calls

How would we measure success?

FRm: Minimize wait time for customer to reach operator — **Threshold:** < 30 seconds

STEP 2.4 — VALUE PROPOSITION

In Step 2.4, the designer identifies **discriminating factors** (unique and attractive features) of the design in relation to each supported Use Case from Step 2.3.

For each Use Case, answer: *"What value does my product provide that an existing product does not?"* and *"Why would the customer buy my product over an existing one?"*

> **Tip —** One method is to state the value proposition in **mathematical terms**: *A* + *B* + *C*, where each term is a component of value that pleases the stakeholders in that Use Case. Determine discriminating factors **per Use Case**, not for the product overall.

USE CASES — FAUCET EXAMPLE

Use Cases	
Step 2.3 — Use Cases to Support	**Step 2.4** — Value Proposition
Wash hands in sink (before meal)	Ease of flow / temperature adjustment + flow rate consistency + operational lifetime
Wash hands prior to medical procedure (antiseptic hand wash)	Hands-free turn-off + precision of flow / temperature adjustments
Wash dishes in sink	Ease of flow rate & directional adjustment + temperature stability
Bathe infant	Over-temperature (scald) prevention + hands-free operation
Install water delivery system	Ease of installation + minimal tool requirements + fits wide variety of sink basins

KEY POINTS

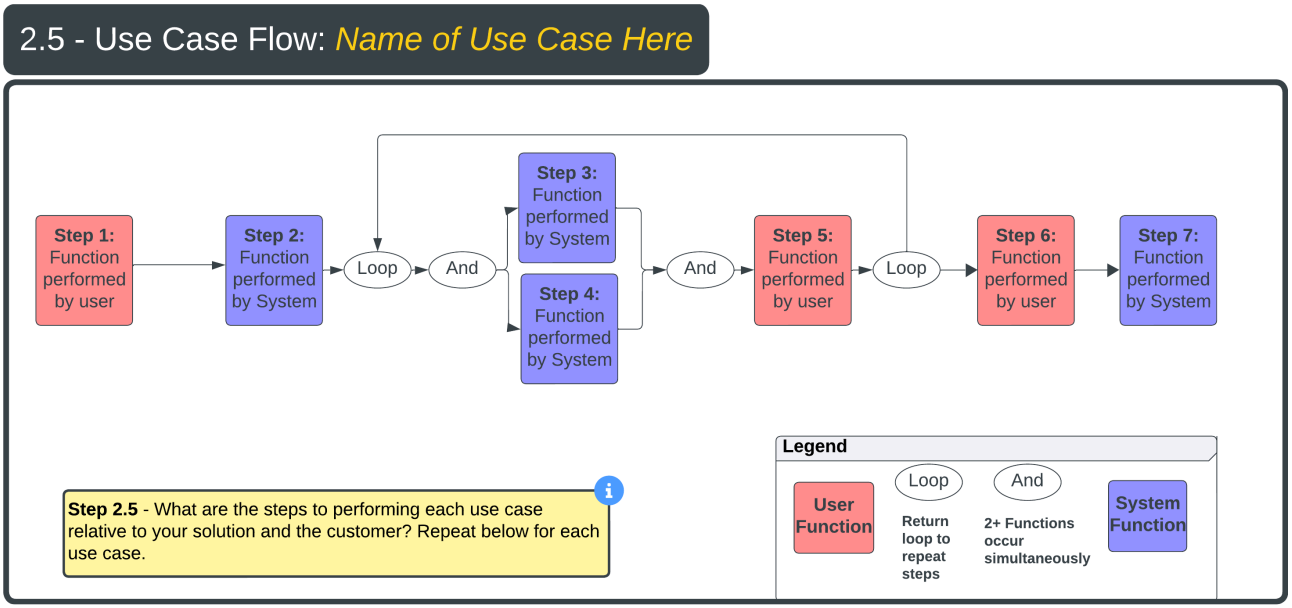
- The Value Proposition is **per Use Case**, not for the product as a whole — different Use Cases can highlight different value.
- Stating value as *A* + *B* + *C* forces clarity on what each component contributes; vague language hides weak value.
- Example — for a toaster, the designer would explain how the new toaster out-performs others at toasting bread, toasting a bagel, storage, and cleaning.

STEP 2.5 — USE CASE FLOW

A **Use Case Flow** describes how the product (or service) is used — or experienced — by the customer for each Use Case, as a series of steps.

A Use Case Flow diagram should include the steps (Functions) that the **user performs** in addition to the steps (Functions) that the **system / solution** must perform.

USE CASE FLOW TEMPLATE



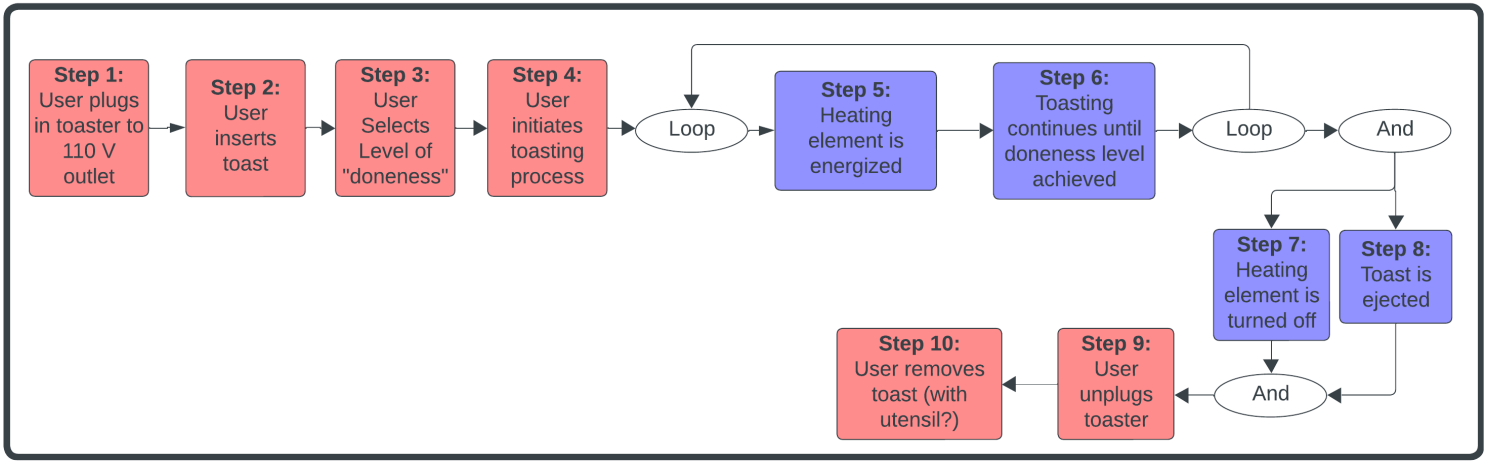
KEY POINTS

- Capture **both** user-performed steps and system-performed steps — the boundary between user and system is what defines the design's interface requirements.
- Each Use Case (from Step 2.3) should have its own Use Case Flow.
- The Functions surfaced in the Flow feed directly into the Functional Requirements (FRs) used in the Decomposition (Step 4).

USE CASE FLOW — TOASTER EXAMPLE

For example, with a **toaster**, think about how to describe the use of the toaster to someone who has **never used one before**. Be sure to explain to the user what their tasks are in addition to what the toaster will do in response.

2.5 - Use Case Flow: *Toaster - Make a slice of toast*

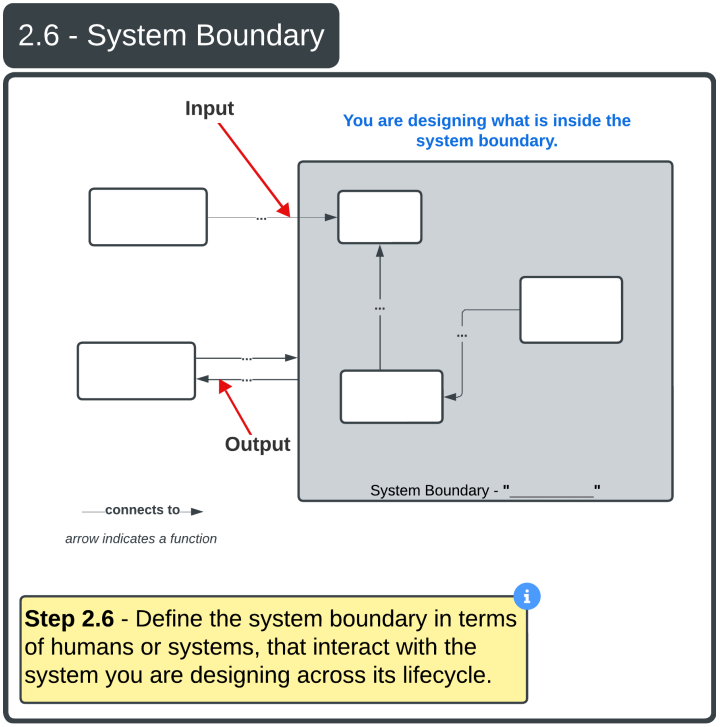


KEY POINTS

- Use Case steps are described from the **viewpoint of the customer** and detail what the customer wants/needs the system to do, step-by-step.
- Each Use Case should be represented with a **unique** Use Case Flow diagram.
- Review or simulate the Use Case Flow **with the customer** to ensure you are delivering the desired experience.
- The more rigor the designer applies to capturing Use Case steps, the more the team truly understands the Functional Requirements needed to deliver the desired user experience.

STEP 2.6 — SYSTEM BOUNDARY DIAGRAM

A **System Boundary** diagram captures all elements required for the system to function. The designer decides which elements live **inside** the boundary and which stay **outside**; arrows crossing the boundary represent **inputs** (into the system) and **outputs** (from the system). For every external element, the designer must define a working interface.

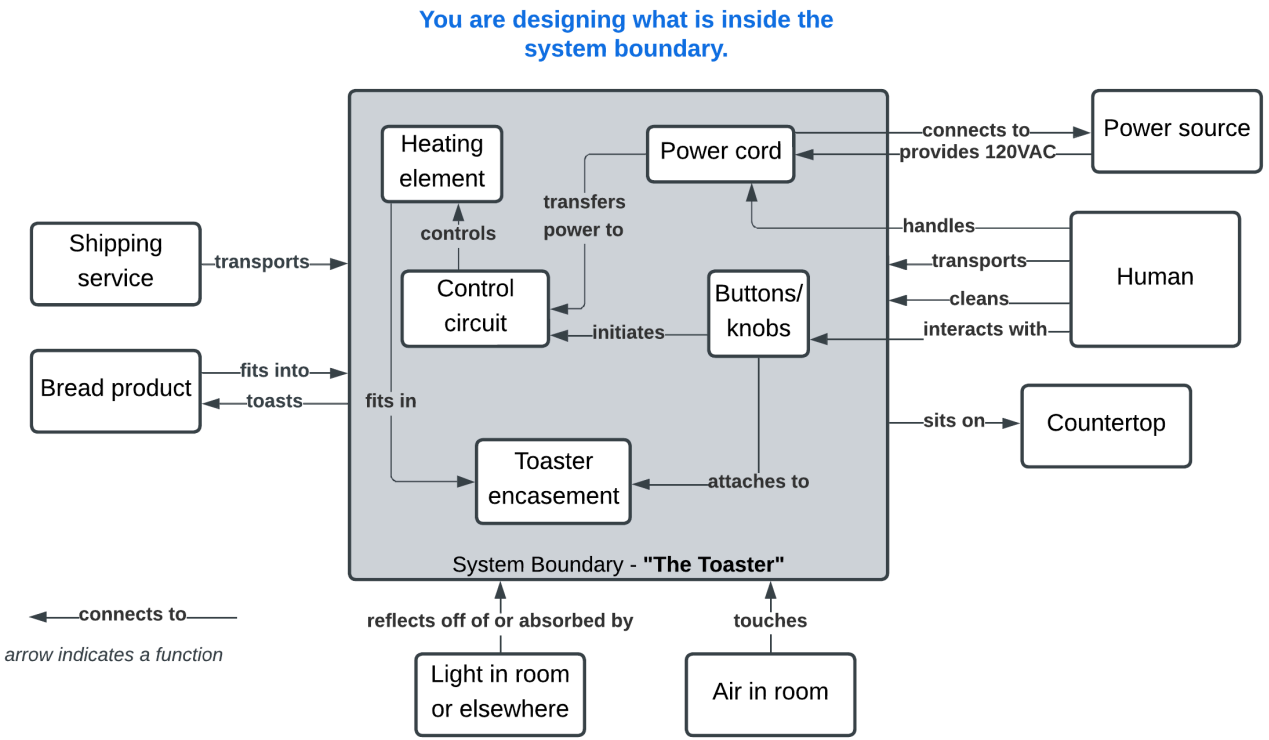


KEY POINTS

- The designer chooses what is inside vs. outside the boundary.
- Every external element needs a working interface.
- Arrows in → inputs; arrows out → outputs.

SYSTEM BOUNDARY — FAUCET EXAMPLE

Step 2.6 - System Boundary - *Toaster Example*



Step 2.6 - Define system boundary in terms of external actors, human or systems, that interact with the system you are designing across its life cycle.

STEP 2.7 — INTERFACE FAILURES (TOASTER EXAMPLE)

Why this slide? Understanding what could **go wrong** at each interface uncovers FRs and PSs we hadn't thought of — address them before they become field failures.

Step 2.7 — For each interface on the system boundary diagram, identify points of failure.

Interface	What Could Go Wrong
Power cord connects to power source	Cord is not long enough; long power cord cannot handle the power consumption.
Power outlet provides 120 VAC to power cord	Power source cannot deliver enough power.
Toaster sits on counter top	Toaster does not fit due to length, width, or height.
Air to toaster	Humidity / contaminants corrode or add friction to moving components.
Bread product to toaster	Bread does not fit; toaster inadequately toasts bread.
Shipping service to toaster	Toaster dropped in transit; crushed at bottom of shipping truck.
Power cord to control circuit	Connection cannot handle power; connection weakens or breaks through use.

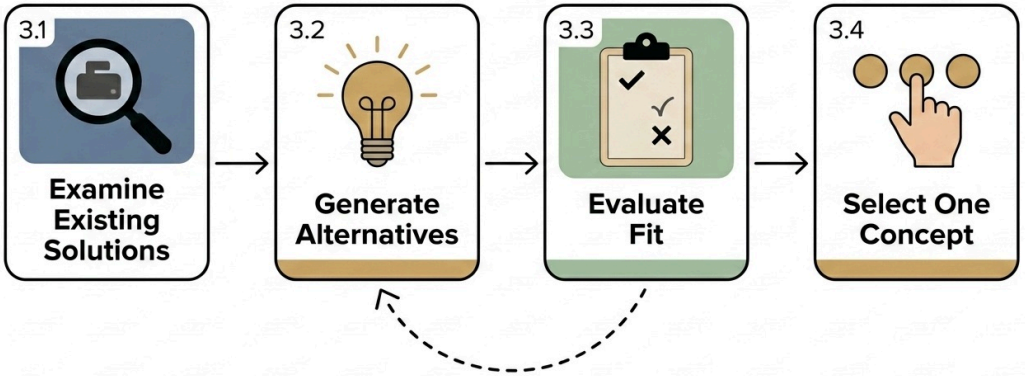
KEY POINTS

- Interfaces should map directly to the System Boundary diagram — one row per crossing.
- There can be a **1-to-many** relationship: each interface may have several failure modes.
- Common causes: incompatible materials, dimensions, fittings, threads; insufficient strength or current capacity; incompatible voltages (high/low, AC/DC, phase, frequency).
- Mechanical interfaces are also points of **friction** — failures may not show up until many cycles in.

STEP 3 — WHY WE BEGIN WITH EXISTING SOLUTIONS

When we look at **Conceptual Design Alternatives (CDAs)**, we first examine **existing solutions to the problem statement** — practicing **humility** and respecting what others have done before us. **Step 3.1** covers those existing solutions, their **deficiencies**, and why we would solve the problem differently. Then **3.2** generate alternatives → **3.3** evaluate against what we know → **3.4** select one to take forward.

WHAT STEPS 3.1 → 3.4 DO TOGETHER



*The dashed arrow from **3.3** → **3.2** is the iteration loop — if the fit matrix surfaces a weakness, generate another concept.*

Your project may differ — same framework. The deck uses a faucet and toaster as running examples, but Steps 3.1–3.4 work for any complexity level. Worked example: an **autonomous lunar robot**.

3.1 Existing rovers (Curiosity, Perseverance, VIPER); deficiencies (limited autonomy, Earth-link latency).	**3.2** CDAs: tracked rover, legged walker, hopping drone, swarm of micro-rovers.	**3.3** Score each CDA against lunar-day survival, mass < 500 kg, regolith handling, comms blackout tolerance.	**3.4** Pick one (e.g., legged walker for craters); justify why and why-not the others.

KEY POINTS

- Begin with **humility** — existing solutions reveal proven approaches and the deficiencies you can target.
- Step 3 is **iterative** — if 3.3 surfaces a weakness, loop back to 3.2 and add another concept.
- The selected CDA from 3.4 becomes **PS0** — the parent solution decomposed in Step 4.

STEP 3.1 — EXISTING SOLUTIONS

Complete the "Existing Solution" templates below by addressing the following questions:

3.1a — How are other people solving the problem (as stated in Steps 1.1 and 2.1)? *Include pictures, drawings, links, textual descriptions, etc.*

3.1b — Are there any deficiencies in the current solutions that you would like to overcome?

3.1c — Why would you solve the problem any differently than the existing solutions?

Existing Solution 1	Existing Solution 2	Existing Solution 3
Description of Solution	**Description of Solution**	**Description of Solution**
Deficiencies	**Deficiencies**	**Deficiencies**
Why would you solve the problem differently?	**Why would you solve the problem differently?**	**Why would you solve the problem differently?**

KEY POINTS

- Existing solutions reveal proven approaches and the deficiencies you can target.
- Three solutions is a starting point — **add more Existing Solutions** if the breadth and depth of the design space isn't covered.
- The "why differently" answer becomes part of your value proposition (Step 2.4).

STEP 3.1 EXAMPLE — EXISTING SOLUTION 1 (SMART TOASTER)

Existing Solution 1 — WHALL 2-Slice Smart Touchscreen Toaster (Target)

Description of Solution

- Touchscreen digital control; extra-wide 1.5″ slots
- Removable crumb tray; high-lift lever for short bread
- Bagel / Defrost / Cancel functions; 6 shade settings
- Self-centering bread carriage; customizable sound alerts
- 850 W stainless steel; cost ~$50–$60

Deficiencies

- Multiple reviews say bread only toasts on one side — reviewers would return the toaster.
- Water / contaminants on the user's hands make the touchscreen hard to use.
- Interface not intuitive — bread types are at the top but the "Bread type" button is at the bottom; needs training (poor fit for hotels, Airbnbs, guests).

Why Would You Solve the Problem Differently?

- Bread should toast on **both** sides — the basic job must work first.
- UI should be simpler and usable without training.
- Users may want more than 2 slices, or to control each slice **independently**.

STEP 3.2 — CONCEPTUAL DESIGN ALTERNATIVES

Step 3.2 — Using what you know about the problem from Steps 1 and 2, and what you have learned about existing solutions, generate **at least 3 conceptual design alternatives**. You may have one design in mind, but challenge yourself to think about other ways to solve the problem.

*A conceptual design is a **solution approach** — high-level, not detailed. Capture the approach, not the explicit system. For example: write **"space-based fire detection,"** not **"6U CubeSat."***

Conceptual Design 1	Conceptual Design 2	Conceptual Design 3
Description of Conceptual Design 1	Description of Conceptual Design 2	Description of Conceptual Design 3

KEY POINTS

- Generating multiple alternatives forces the team to consider **different approaches** rather than defaulting to the first idea.
- Detail comes later (Step 4 onward); at this stage, the goal is breadth of thinking.

STEP 3.3 — CONCEPTUAL DESIGN EVALUATION

Goal: Evaluate each Conceptual Design from 3.2 against what we already know (Steps 1–3.1). Score each cell ✓ / **Partial** / ✗; what you cannot answer becomes an **open question**.

✓ met · **Partial** some evidence, gaps remain · ✗ not met / violated.

Conceptual Design Fit Matrix				
Criterion Group	**What to Evaluate (Source)**	**Concept A**	**Concept B**	**Concept C**
Hard Constraints	Given requirements (1.4), cost ceiling (1.5), standards (1.6), safety (1.7)			
FR0 Performance Fit	FR0 + FRm thresholds (2.0–2.2) — concept hits the performance level?			
Use Case Fit	Each Use Case / Step (2.3, 2.5) — concept enables the flow?			
Boundary Fit	System Boundary + Interface failures (2.6, 2.7) respected and mitigated?			
Closes Existing Gaps	Deficiencies of existing solutions (Step 3.1)			
Open Questions	What we still don't know — log on the List of Questions slide			

KEY POINTS

- Every concept must answer to **something already documented** — no FRs needed yet (those come in Step 4).
- This matrix (or table) forces traceability and surfaces the weakest concept **before** Step 3.4 selection.
- Empty cells are not failures — they're **questions to log** in the List of Questions and resolve before selection.

STEP 3.3 EXAMPLE — TOASTER FIT MATRIX

Scenario: Three conceptual toaster designs evaluated against everything known from Steps 1–3.1. **Use cases:** toast bread · toast a bagel · store · clean.

Conceptual Design Fit Matrix — Toaster

Criterion Group	What to Evaluate (Source)	**A — Vertical Pop-up** (4-slice, dials)	**B — Conveyor** (continuous belt)	**C — Halogen Drawer** (horizontal grill)
Hard Constraints	Given req's (1.4), cost (1.5), standards (1.6), safety (1.7)	✓ ~$60, UL listed, well under $100.	✗ commercial units >$300, over budget.	**Partial** BOM ~$80–$110, on the edge.
FR0 Performance Fit	FR0 + FRm thresholds (2.0–2.2) — even doneness in target time?	**Partial** vertical elements risk one-side under-browning.	✓ both faces toast at once, even browning.	✓ halogen above + below; meets time threshold.
Use Case Fit	All Use Cases & Steps (2.3, 2.5) — bread, bagel, store, clean	✓ covers all four; familiar, stores easily.	✗ large footprint hurts storage; cleaning is messy.	**Partial** drawer eases cleaning; bigger than pop-up.
Boundary Fit	System Boundary & Interface failures (2.6, 2.7)	✓ standard countertop fit; shippable.	✗ exceeds countertop length budget (2.7).	**Partial** drawer pull-out needs counter clearance.
Closes Existing Gaps	WHALL deficiencies from 3.1 (one-side, wet-hand UI, 2-slice, no per-slice)	**Partial** dials fix UI; per-slice possible; one-side issue persists.	✓ both-side inherent; physical controls; >2 slice throughput.	✓ both-side solved; 4–6 slices; per-zone control feasible.
Open Questions	What we still don't know — route to List of Questions	*Per-slice independent doneness worth dial complexity?*	*Can a conveyor be miniaturized to residential price?*	*Halogen energy draw + bulb life vs nichrome?*

Which concept emerges? **Concept C — Halogen Drawer** scores ✓ on the highest-priority rows (FR0 Performance Fit and Closes Existing Gaps) and only Partial elsewhere. **Concept B** hits two hard ✗ on Hard Constraints and Use Case Fit — *auto-rejected*. **Concept A** is the cheapest but doesn't close the one-side-browning gap the project exists to fix. Full why-and-why-not is on Step 3.4 (next slide).

STEP 3.4 — CONCEPT SELECTION (TOASTER EXAMPLE)

Step 3.4: Choose one of your conceptual designs from Step 3.2. Justify **why** you chose it — reference the Step 3.3 fit matrix — and explain **why not** the others.

Selected Concept — C: Halogen Drawer Toaster

Why C wins:

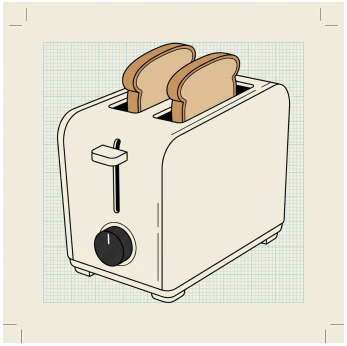
- **FR0 Performance Fit (✓):** halogen heat above and below produces even browning — meets the FR0 doneness threshold without form-factor compromise.
- **Closes Existing Gaps (✓):** solves the one-side browning failure documented in Step 3.1; drawer holds 4–6 slices with per-zone control feasible.
- **Partial scores addressable downstream:** the **BOM gap** closes in Step 7 (DFM / Cost Reduction); drawer-clearance becomes an Interface in Step 4 decomposition.

Why NOT A — Vertical Pop-up

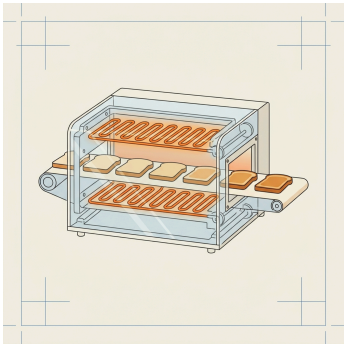
Cheapest, fits all use cases — but vertical elements **do not solve the one-side browning problem**. Selecting A leaves the customer with the same deficiency the project exists to fix.

Why NOT B — Conveyor

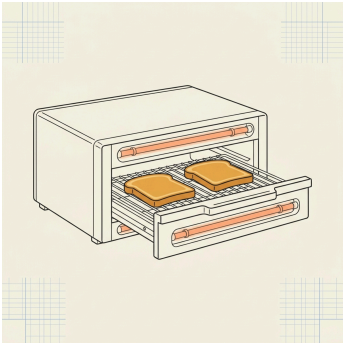
Best at FR0, but fails **three of five** criterion groups: exceeds budget (>$300), exceeds countertop length, and breaks "store when not in use." Two hard ✗ — cannot proceed without total redesign.



A — Vertical Pop-up



B — Conveyor



C — Halogen Drawer ✓

Step 4 - Design Decomposition

THE CSD ALGORITHM

1 — START WITH WHAT YOU ALREADY HAVE

- Copy **FR0** & **FRm0** from **Step 2**; copy **PS0** from **Step 3.4**.

2 — DECOMPOSE TO THE NEXT LEVEL

- **List FRs** the parent PS must deliver — consider its **SBFIL**: *Structure, Behavior, Footprint, Interface, Lifecycle*.
- For each FR, write **FRm(s)** — **Threshold** (acceptable) and **Goal** (desired ultimate).
- For each FR, list **candidate PSs** (PSa, PSb, PSc…).
- **Coupling check —** Does picking PS for FR1 affect the achievement of FR2? Decouple before deciding.
- **Choose** the best PS for each FR via decision analysis.

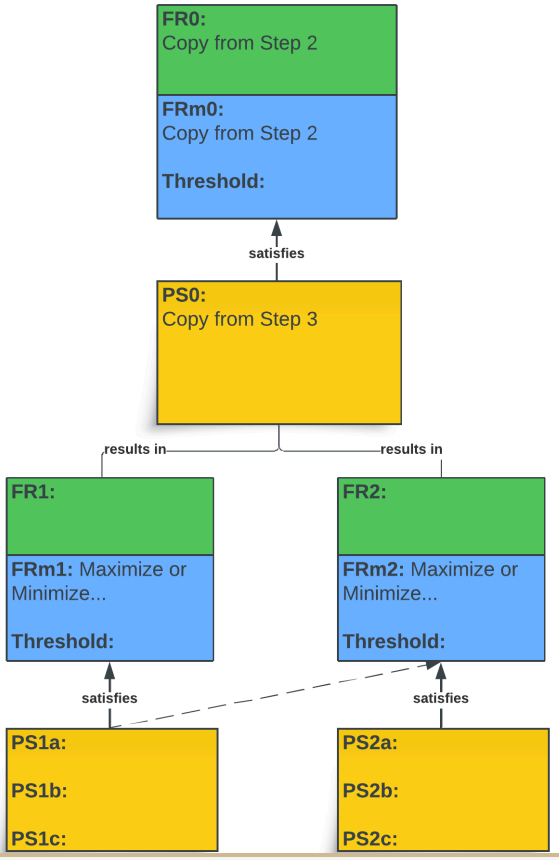
3 — REPEAT 2 DECOMPOSE

For each **child PS**, repeat **2 Decompose** to drop down another level. **Stop when the PS is atomic** — you know enough to **buy** or **build** it.

4 — BACK EVERY CLAIM WITH EVIDENCE

Every chosen **PS** claims it will achieve its **FR** (to the **FRm** threshold). Back the claim with prototypes, simulations, cited research, data sheets, or models. Without evidence, the claim is a guess.

THE BASIC DECOMPOSITION



KEY POINTS

- The **CSD Algorithm repeats** — the chosen child PS becomes the next **parent PS** of the next-lower-level FRs (minimum 2 FRs) and runs through **2 Decompose** again.
- A level isn't done until every child has **FR + FRm + Threshold + PS**; anything missing means the level is incomplete.
- Run the **coupling check** before decision analysis to choose PS — decoupling is what makes the rest of the process work.

FIVE TYPES OF FR × PS MAPPINGS (AXIOMATIC DESIGN)

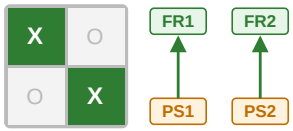
Axiom 1 — The Independence Axiom: Maintain Independence of Functional Requirements. The mapping **{FR} = [DM]{PS}** should be diagonal — each PS affects only one FR. When this holds (or when [DM] is upper- or lower-triangular), the design is **predictable**.

KEY QUESTION FOR AXIOM 1

"Does the choice of PS_j affect the achievement of FR_i within a branch at a specific level?"

Remember: **FRs are independent to start with** — it is the choice of **physical solution** that breaks (or preserves) that independence.

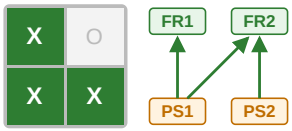
✓ ACCEPTABLE — Independence Preserved



Uncoupled

Each PS controls exactly one FR. Tune any FR **independently**.

→ **Predictable**

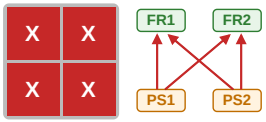


Path Dependent

PS_1 affects both FRs. Set **in sequence**: FR_1 first.

→ **Predictable (in order)**

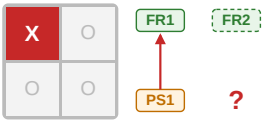
✗ UNACCEPTABLE — Violates Axiom 1



Coupled

Every PS affects every FR. Tuning one breaks the others.

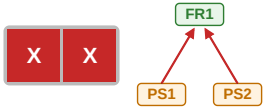
→ **Not Predictable**



Incomplete

A required FR has **no** PS to satisfy it.

→ **Misses FRs**



Redundant

Two or more PSs solve the **same** FR.

→ **Added Cost / Time**

FAUCET EXAMPLE — SAME FRS, DIFFERENT PHYSICAL SOLUTIONS

Functional Requirements (shared by both designs):

FR_1: Control the water flow rate **Q** *(without affecting water temperature)*

FR_2: Control the water temperature **T** *(without affecting flow rate)*

✗ COUPLED — Two-Handle Faucet

$PS_1 = \Phi_1$: Hot Water Valve Adj.

$PS_2 = \Phi_2$: Cold Water Valve Adj.

*Each handle changes **both** flow and temperature.*

$$\begin{bmatrix} Q \\ T \end{bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \begin{bmatrix} \Phi_1 \\ \Phi_2 \end{bmatrix}$$

FR1 FR2 PS1 PS2

✓ UNCOUPLED — Single-Handle Faucet

$PS_1 = \Phi_1$: Handle **lifting**

$PS_2 = \Phi_2$: Handle moving **sideways**

Lift = flow only. Swivel = temperature only.

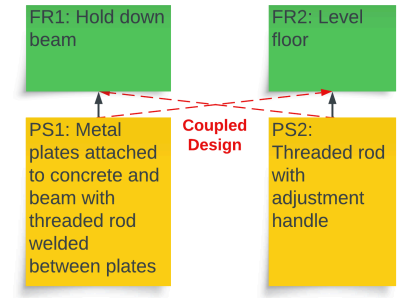
$$\begin{bmatrix} Q \\ T \end{bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \begin{bmatrix} \Phi_1 \\ \Phi_2 \end{bmatrix}$$

FR1 FR2 PS1 PS2

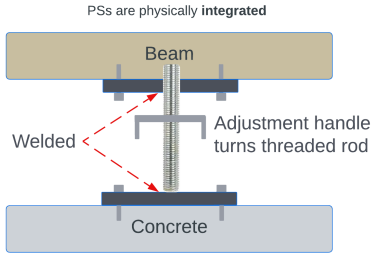
Lesson: The FRs were independent to start. The **two-handle PS choice** coupled them; the **single-handle PS choice** preserved their independence. *Same problem, different design quality — driven entirely by the physical solutions.*

BARN BEAM EXAMPLE — PHYSICAL INTEGRATION COUPLES FUNCTIONS

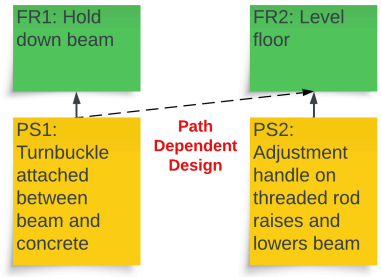
Functional Requirements: **FR_1:** Hold down the beam · **FR_2:** Level the floor



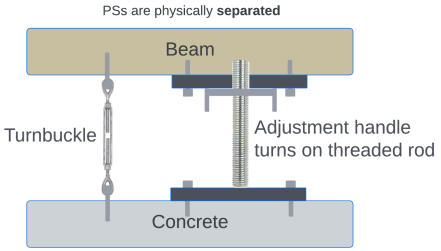
Unacceptable Design



Not Buildable! Cannot achieve both FRs with this design.



Acceptable Design



Loosen turnbuckle then use adjustment handle to adjust floor height. Both FRs are achieved with this sequence.

✗ UNACCEPTABLE — Rod welded at beam and plate

Threaded rod is **hard-welded** to both the plate and the beam — one rigid assembly. To level the floor (FR_2) you'd have to change rod length, but the rod is locked by the welds. Unweld and the beam is no longer held down (FR_1). **Both FRs cannot be satisfied at once.**

✓ ACCEPTABLE — Rod NOT welded at beam or plate

The threaded rod is **free-floating** — **turnbuckle** (PS_1) and **adjustment handle** (PS_2) are separate parts. Loosen the turnbuckle → adjust handle to level → re-tighten turnbuckle. Sequence matters — but both FRs are achieved. *Path Dependent (Acceptable).*

Key Insight: Independence is not just about choosing *different* mechanisms — it requires that the physical solutions can be **manipulated independently**. **Welding (integrating) parts couples them; separating them preserves independence.** The PS choice creates the coupling, even when the FRs themselves are independent.

TWO DISTINCT MECHANISMS BEHIND A POPULATED DESIGN MATRIX

The previous two examples both produced full off-diagonal entries in the design matrix — but for genuinely different reasons. Naming the difference helps you spot coupling earlier *and* choose the right fix.

INHERENT COUPLING

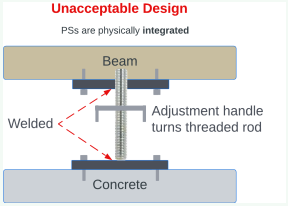
The PSs **cannot, by the nature of the chosen mechanism**, target a single FR. The coupling is **visible from the design spec itself** — no implementation needed to see it.

Recall the faucet: each valve is a "restriction on a flow path." By construction, turning either valve changes both flow rate *and* mix temperature — the spec already shows two FRs running through one knob.

EMERGENT COUPLING

The PSs are **intended as single-FR controls**, but **implementation physics** introduces unintended cross-effects that *only appear once the system is built or analyzed*.

Recall the barn beam: two beams designed to carry two independent loads — until the **welded** implementation creates a shared structural response. The coupling appears only after the build choice.

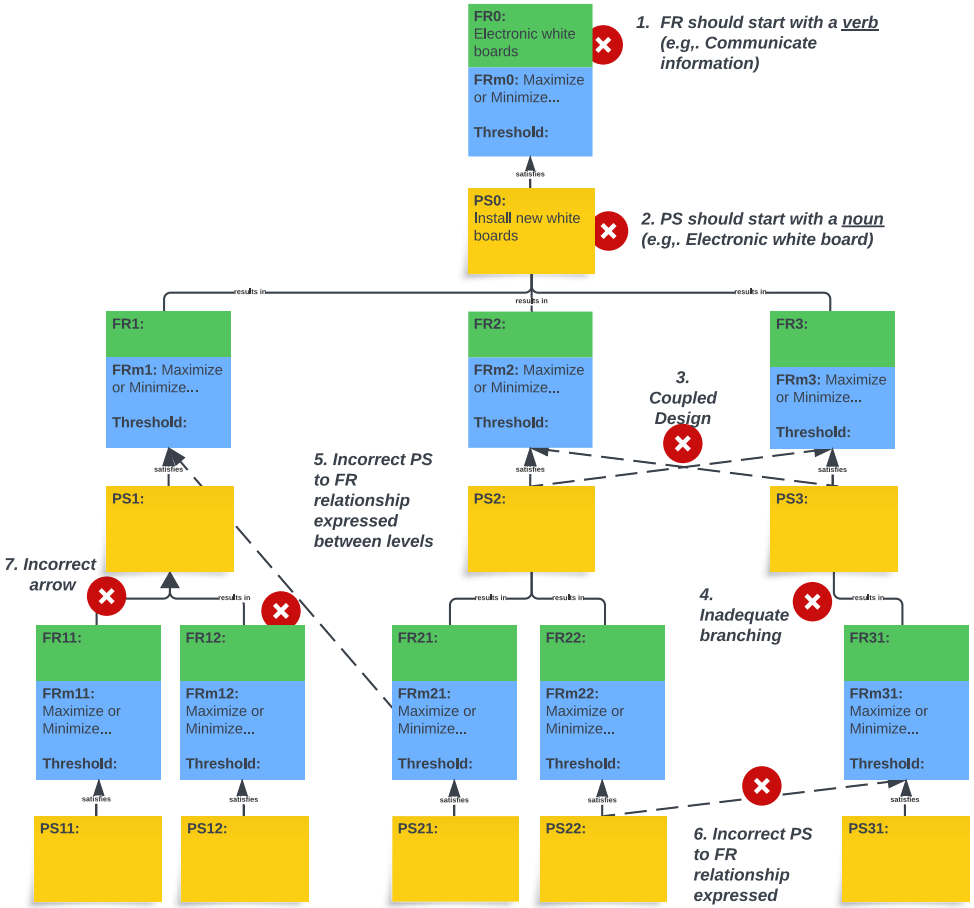


Why the distinction matters:

- **Inherent coupling** can be **caught at the spec stage** — the design matrix flags it before any prototype. Fix by re-choosing the mechanism.
- **Emergent coupling** is what the design matrix is genuinely built to **discover** — physics or geometry introduces an off-diagonal that the abstract decomposition didn't anticipate.

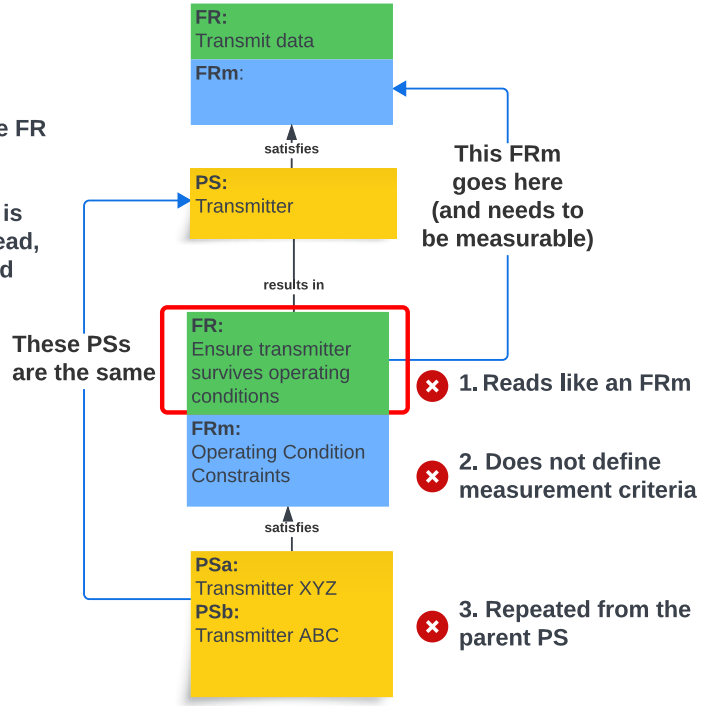
COMMON PROCEDURAL ERRORS IN A DESIGN DECOMPOSITION

1. **Incorrect FR wording:** An FR begins with a **verb** — an *action* or *transformation*.
2. **Incorrect PS wording:** A PS begins with a **noun** — something observable / quantifiable that achieves an FR.
3. **Unacceptable cases:** Check for *coupled, incomplete, redundant, not process-capable* within a branch **before** the next level.
4. **Inadequate branching:** A design only decomposes if **two or more FRs** expand on the preceding PS.
5. **PS → FR across levels:** Relationship arrows must **not** cross levels.
6. **PS → FR across branches:** PS-to-FR only within the **same branch, same level**.
7. **Incorrect arrow: Arrows** = PS → FR within branch + level. **Lines** (no head) = PS decomposed into child FRs.



DESIGN DECOMPOSITION ISSUES

In this example, the FR in the red box is actually stating an FRm. The function is not identified, instead, an FRm is identified that describes the parent FR.



Key Point: A decomposition should represent a **real, buildable system**. If any of these errors are present, it cannot.

READING THE EXAMPLE

Parent: **"Transmit data"** (FR) → **"Transmitter"** (PS). Three errors break the decomposition:

1. **"Ensure transmitter survives operating conditions"** reads like an FR but is actually an **FRm**.
2. The FRm below (*"Operating Condition Constraints"*) has **no measurable threshold** — a label, not a measurement.
3. Child PSs (*Transmitter XYZ*, *Transmitter ABC*) just **rename the parent PS** — product selection, not decomposition.

HOW-TO FIX — DON'T LOCK IN A SPECIFIC PART AS THE PARENT PS

CASE A — Cart Before the Horse

FR0: Cool the CPU

↑

PS0: Brand-X 92 mm PWM Fan (SF-9200)

↓ *decompose*

FR1: Spin @ 2000 RPM	**FR2:** Fit 92×25 mm bracket	**FR3:** Accept PWM @ 25 kHz
↑	↑	↑
PS1: SF-9200 motor	**PS2:** SF-9200 frame	**PS3:** SF-9200 driver

What's wrong: PS0 is a **specific commercial product**. The "FRs" derived aren't real system functions — they're **constraints inherited from that product**. The team is locked in.

CASE B — System Designer

FR0: Cool the CPU

↑

PS0: Cooling System *(function-bearing assembly)*

↓ *decompose*

FR1: Move air across heat sink	**FR2:** Conduct heat from CPU	**FR3:** Mount to chassis
↑	↑	↑
PS1: Fan / pump / liquid loop…	**PS2:** Heat sink / vapor chamber…	**PS3:** Bracket / clip / screws…

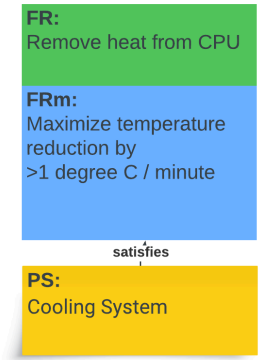
Why this works: PS0 is named for **what it does**, not **what it is**. Each child FR is a real system function — **multiple candidate PSs** can be evaluated.

How to fix Case A: instead of naming a specific commercial part as PS0, ask ***"what does it do?"*** — that function-bearing answer becomes PS0 (Case B). Then decompose the **functions** of that subsystem — not the constraints of one off-the-shelf product.

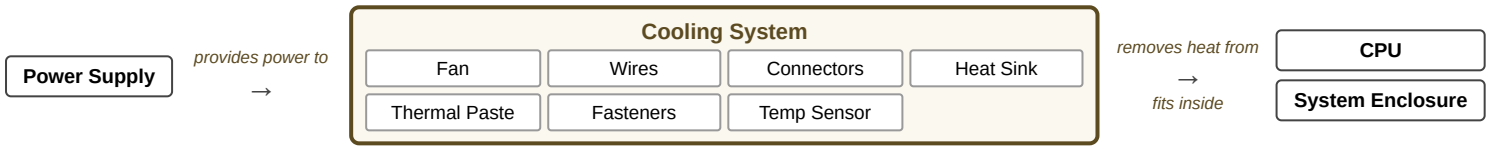
DECOMPOSITION FIX (CONT.) — THE DESIGNER'S MIND FOR "COOLING SYSTEM"

Designer's Thinking: What does the cooling system have to do? Look at an existing system and identify the parts typically required — in most cases, each part performs a unique function.

Each PART or PART Feature (PS) = 1 Function (FR)



In the designer's mind while decomposing the "Cooling System" PS:



Level 2 — Cooling System decomposed (each part = one function):

Part	FR — *what it does*	PS — *candidate solutions*
Fan	FR1.1: Move air across the heat sink	Axial fan · centrifugal fan · liquid pump
Heat Sink	FR1.2: Conduct heat from CPU surface to airflow	Aluminum finned · copper finned · vapor chamber
Thermal Paste	FR1.3: Bridge the CPU↔heat-sink thermal interface	Silicone paste · phase-change pad · liquid metal
Wires	FR1.4: Carry power to the fan	Twisted-pair AWG18 · ribbon cable
Connectors	FR1.5: Connect fan to motherboard / power	JST 3-pin · 4-pin PWM header
Fasteners	FR1.6: Secure cooling system to motherboard / chassis	Spring-loaded screws · push-pin clips · backplate
Temp Sensor	FR1.7: Sense CPU / fan temperature	Thermistor · on-die DTS · thermocouple

*For each part the designer asks: **What is its purpose (FR)?** · **Does my system need this function?** · **Is there a better PS to consider?***

DECISION ANALYSIS FOR CONCEPTUAL DESIGN ALTERNATIVES

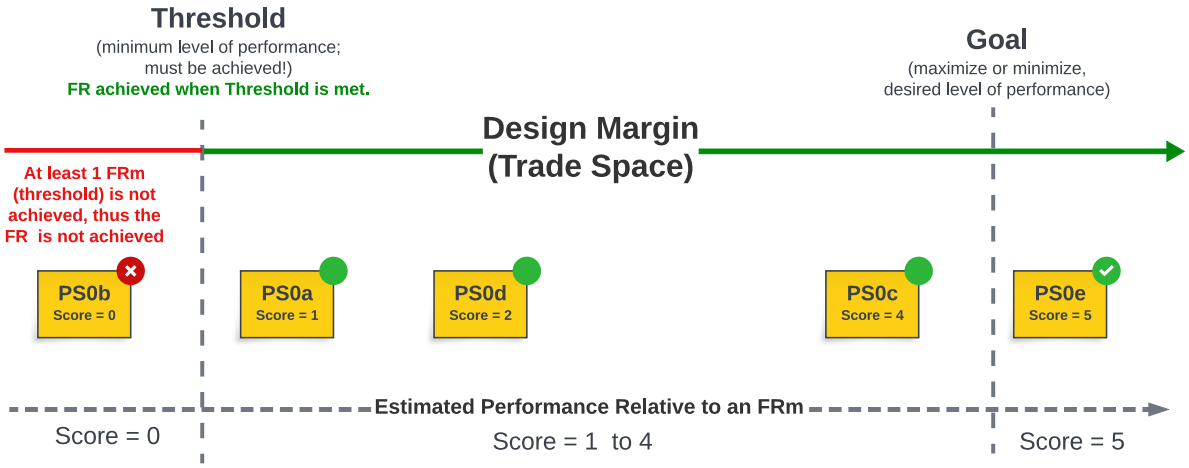
To facilitate the designer's systemic thinking, we **quantify the derived FRs and PS-ALTs** into a decision analysis spreadsheet. The next slide walks through how it is read — **Threshold**, **Goal**, 0–5 score per FRm. *Fillable template in the 12-Step* **Lucid** *template.*

Decision Analysis	FUNCTIONAL REQUIREMENT (FR):	State FR here	PS-ALT:			PS-ALT:			PS-ALT:		
			PS-ALT Description:			PS-ALT Description:			PS-ALT Description:		
Criteria			PERFORMANCE								
Weight	Source	FRm Number	FRm Description	FRm THRESHOLD GOAL	ESTIMATED PERFORMANCE BASIS OF ESTIMATE	Score	Weighted Score	ESTIMATED PERFORMANCE BASIS OF ESTIMATE	Score	Weighted Score	ESTIMATED PERFORMANCE BASIS OF ESTIMATE	Score	Weighted Score
				Threshold	*Estimate here*			*Estimate here*			*Estimate here*		
				Goal	*Basis of estimate here*			*Basis of estimate here*			*Basis of estimate here*		
				Threshold									
				Goal									
				Threshold									
				Goal									
				Threshold									
				Goal									
					Total Score			*Total Score*			*Total Score*		

Legend	
Weight	1 to 5 scale
Score	0 to 5 scale
Weighted Score	Weight × Score

RISK ASSESSMENT		
Failure Mode	Failure Mode	Failure Mode
Selection / Rejection Rationale	*Accept or Reject? Why?*	*Accept or Reject? Why?*	*Accept or Reject? Why?*

KEY POINTS FOR CONDUCTING A DECISION ANALYSIS



QUALITATIVE FRm — Likert Rubric Example

FR: Enable user control.
FRm: User-perceived ease of use (1–5 Likert).

Threshold: ≥ 3 (acceptable — most users complete tasks unaided).
Goal: ≥ 4.5 (delight — users complete tasks confidently and recommend).

Survey 5+ users; use the median Likert score as the FRm value.

RUBRIC (ANCHOR EACH LIKERT LEVEL)

5 — Excellent	User completes all tasks quickly, no training needed.
4 — Good	Tasks completed; brief moments of hesitation.
3 — Acceptable	Tasks completed with manual / one nudge.
2 — Poor	Tasks attempted; user gives up on at least one.
1 — Failing	User cannot complete the task.

KEY POINTS

- Score on a **0–5** scale: **0 = unacceptable** (below threshold — auto-rejects the alternative); **1–4 = inside the trade space** (between threshold and goal); **5 = meets or exceeds the Goal**.

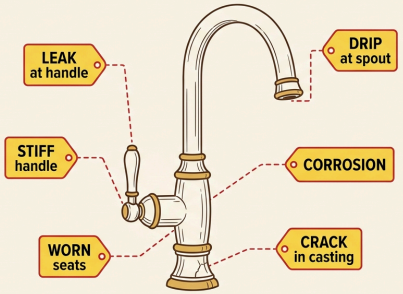
DECISION ANALYSIS — WORKED EXAMPLE

Example	FR:	Transport humans and belongings from point A to point B	**PS-ALT:** PS0a: Tesla Model S Plaid **PS-ALT Description:** Fully electric vehicle designed for high performance			**PS-ALT:** PS0b: BMW M3 **PS-ALT Description:** Internal combustion engine sports car designed for high performance			**PS-ALT:** PS0c: Toyota Corolla **PS-ALT Description:** Compact car with internal combustion engine designed for fuel efficiency and reliability		
Criteria			**PERFORMANCE**								
Weight	**Source**	**FRm Number**	**FRm Description**	**FRm THRESHOLD GOAL**	**ESTIMATED PERFORMANCE BASIS OF ESTIMATE**	**Score**	**Weighted Score**	**ESTIMATED PERFORMANCE BASIS OF ESTIMATE**	**Score**	**Weighted Score**	**ESTIMATED PERFORMANCE BASIS OF ESTIMATE**	**Score**	**Weighted Score**
3	Owner / Driver	FRm0a:	Maximize acceleration	0 to 100kmh < 3.5 sec (>7.94 m/s²) THLD	2.3 sec (12.08 m/s²)	**5**	**15**	3.4 sec (8.17 m/s²)	**3**	**9**	7.3 sec (3.81 m/s²)	**0**	**0**
				0 to 100kmh (>8.96 m/s²) GOAL	*Stated Goal*			*Stated Goal*			*Stated Goal*		
4	Owner / Driver	FRm0b:	Minimize refueling / recharge time	< 35 min THLD	~30 min (DC fast charge)	**1**	**4**	~5 min (gas pump)	**5**	**20**	—		
				< 10 min GOAL	*Stated Goal*			*Stated Goal*			—		
5	Family	FRm0c:	Minimize stopping distance	Threshold	**45m**	**3**	**15**	**45m**	**3**	**15**	*Stated Goal*		
				Goal	*Stated Goal*			*Stated Goal*					
					Total Score	**34**		*Total Score*	**44**		*Total Score*	*REJECTED*	
					RISK ASSESSMENT								
					Failure Mode			**Failure Mode**			**Failure Mode**		
					Charger not available on a long road trip			Gov. restricts access to premium fuel					
Selection / Rejection Rationale					Rejected — barely meets refueling threshold; long charge times limit point-A-to-point-B use, lower Total Score			**Accepted** — highest Total Score (44); meets all FRm thresholds with acceptable risk			Rejected — Score 0 on FRm0a (acceleration); per scoring rules, alternative is immediately disqualified and not evaluated further		

Legend	
Weight	1 to 5 scale
Score	0 to 5 scale
Weighted Score	Weight × Score

STEP 5 — FMEA: IDENTIFYING RISK TO THE DESIGN AND THE PROCESS

Next we use **FMEA — Failure Mode and Effects Analysis** — to identify approaches to mitigate risk for both the **Design** (**DFMEA**) and the **Process** (**PFMEA**). FMEA helps us identify possible **FRs** and **PSs** that must be included in the design to mitigate identified risks.



DFMEA — Design FMEA

Targets failures introduced by the chosen **physical solution**. Asks: *"How could this PS fail to satisfy its FR?"*

PFMEA — Process FMEA

Targets failures introduced by the **process** that produces the design. Asks: *"How could this manufacturing step fail to produce the design as intended?"*

WHAT'S COMING

TERMINOLOGY

Failure Mode, Failure Cause, Mitigation, RPN inputs.

RPN SCALE

Severity, Likelihood, Detectability scoring.

WORKED EXAMPLE

DFMEA & PFMEA for the water faucet.

KEY POINTS

- FMEA is **predictive** — it surfaces failure modes *before* they occur in the field.
- Each Failure Mode and its Mitigation may add new FRs and PSs to the design that must be included to manage the identified risk.
- DFMEA and PFMEA together cover both **design-introduced** and **process-introduced** failures.
- **Loop-back trigger:** if FMEA surfaces a Mitigation that adds a new FR, **loop back to Step 4** and decompose it into the design.

OVERVIEW

The objective of FMEA is predictive failure prevention.

A PS-ALT introduces a **Failure Mode**, caused by a **Failure Cause** and mitigated by **Mitigation**.

KEY TERMS

FMEA: Failure Mode and Effects Analysis — a risk-mitigation approach to surface ways a product / system / service can fail and identify methods to mitigate.

Failure Mode: the actual failure. *e.g., "brakes do not stop the moving car."*

Failure Cause: what caused the failure. *e.g., "low brake fluid level."*

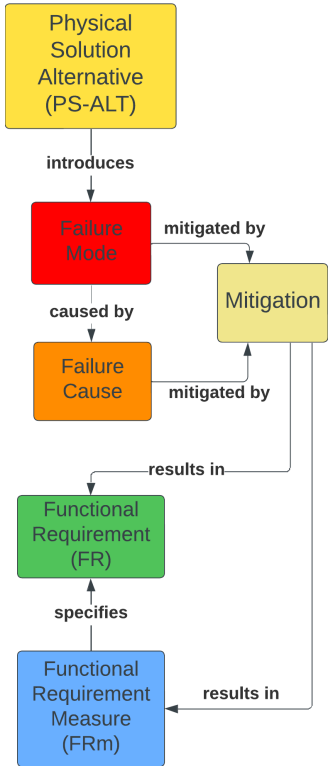
Mitigation: planned method to prevent the cause. *e.g., "low-fluid sensor."*

> **RPN = Severity × Likelihood × Detectability**

Severity: consequences of the failure mode (1–10).

Likelihood: how likely the failure occurs (1–10).

Detectability: can the failure mode be detected? (1–10).



Excerpt from the Information Model, specific to FMEA.

KEY POINTS

- The **PS-ALT** chosen **introduces the Failure Mode** — failures are not pre-existing properties of the FR; they appear with the choice of physical solution.
- The class diagram on the right is an **excerpt from the Information Model**, specific to FMEA — it shows the same FR / FRm / PS-ALT relationships, with Failure Mode / Failure Cause / Mitigation added.

RISK PRIORITY NUMBER (RPN) SCALE

Ranking	Severity	Likelihood of Failure	Detectability
1	No effect	Remote: Failure is unlikely	Almost certain detection
2	Minor defect noticed by discriminating customers		Very high chance of detection
3	Minor defect noticed by some customers	Low: Relatively few failures	High chance of detection
4	Minor defect noticed by most customers		Moderately high chance of detection
5	Reduced secondary function performance	Moderate: Occasional failures	Moderate chance of detection
6	Loss of secondary function		Low chance of detection
7	Reduced primary function performance	High: repeated failures	Very low chance of detection
8	Loss of primary function		Remote chance of detection
9	Hazardous with warning	Very high: failure is almost inevitable	Very remote chance of detection
10	Hazardous without warning resulting in serious injury or death		Cannot detect

⚠ A Severity of 9 or 10 requires corrective action regardless of the RPN Number.

Adapted from: Roessingh, Jan & Kist, Richard. (2016). *Optimal Staffing for Future Military Operations - Implications for the Maritime Domain.*

More ranking criteria/descriptions can be found here.

KEY POINTS

- Designs fail because the PS-ALT does not achieve the intended FR or exhibits undesirable behavior in the process.
- Risk identification and mitigation needs to be considered during the design approach.
- Risk mitigation can be employed for both the design (Design FMEA) and the process (Process FMEA) to manufacture the design.
- **Score by team consensus** — if any team member's score differs by **more than 2 points**, document each rationale in the FMEA *Notes* column before settling on a final score.

Step 5 - Design and Process FMEA

DFMEA AND PFMEA FOR THE SINGLE-HANDLE FAUCET

FAILURE IDENTIFICATION				AS-IS RISK ASSESSMENT						AFTER MITIGATION				
FMEA Type	PS-ALT	Failure Mode	Failure Description	S	Failure Cause	P	Detection Method	D	RPN	Improvement to mitigate Failure Cause	Improvement to mitigate Failure Mode	New P	New D	New RPN
DFMEA design failure	Single-Handle Faucet	Leakage at handle-body interface	Water leaks at 2-axis handle-body interface	**8**	Worn seats and springs	7	Visual test	6	**336**	Extended-life Type Y seats and springs. *FR: Ensure seats and springs exceed useful life of product.*	—	2	6	**96**
PFMEA process failure	Casting Process	Physical crack in faucet body	Mfg. process results in a cracked faucet body	**8**	Incorrect ratio in mixture	5	Visual test	9	**360**	Standard Work for mixing powdered alloy ingredients. *FR: Mix alloy ingredients. FRm: Maximize repeatability of alloy ingredient mixing.*	Crack-detection process. *FR: Check for casting integrity.*	2	2	**32**

Legend: **S** = *Severity* · **P** = *Likelihood (Probability)* · **D** = *Detectability* · **RPN** = *S* × *P* × *D*

Design Failure (DFMEA) — introduced by the chosen **physical solution**. Mitigations change the **design**.

Process Failure (PFMEA) — introduced by the **manufacturing process**. Mitigations change **process controls**.

KEY POINTS

- Notice that the **Failure Severity does not change** between the DFMEA and PFMEA case — the failure is the failure. What changes is **where it's caused** (in the design vs. in the manufacturing process).
- DFMEA targets failures introduced by the chosen **physical solution**; PFMEA targets failures introduced by the **process** that produces the design.

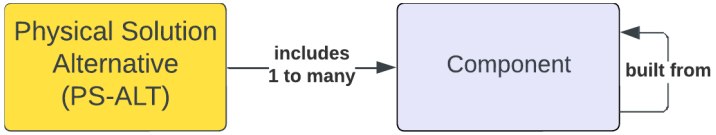
Step 6 - Detailed Design

OVERVIEW — TWO QUESTIONS

- **What** are all the parts of the system?
- **How** do the parts fit together (and perform FR0)?

Detailed Design translates the **Logical Design** (Decomposition) into the **Physical Architecture**.

FIGURE 1 — DETAILED DESIGN



STEP 6.1 — DERIVE THE BOM

Derive Physical Architecture Components from the Decomposition; capture as a **Bill of Material (BOM)**. Components come from your **PSs** — one PS may yield multiple components.

Example: a "toolbox" PS may include a socket wrench, 10/12 mm sockets, flat-head screwdriver, etc.

BOM EXAMPLE

Component	Spec	Qty	Ord?	Recv?
Supply Connections	3/8" comp. on faucet, 1/2" female NPT on supply	2	2	Yes
Power Supply	110 VAC in, 12 VDC out, >200 W	1	1	No

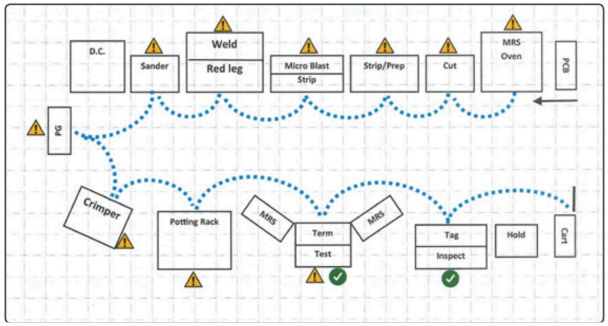
KEY POINTS

- Detailed Design translates Logical Design (Decomposition) into Physical Architecture.
- Step 6.1 — Components are derived from the PSs and captured in a Bill of Material (BOM).
- One PS may yield multiple components depending on level of decomposition.

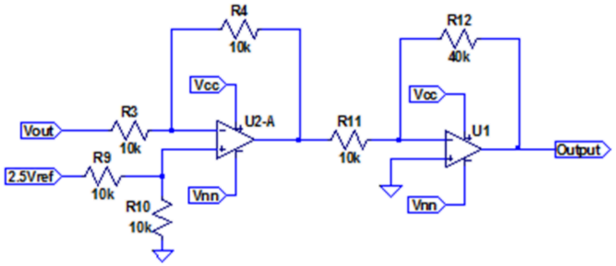
STEP 6.2 — ARRANGE THE BOM COMPONENTS

Determine what diagrams/methods are appropriate to communicate your design. Use these diagrams/methods to arrange the BOM components to communicate the physical architecture — *i.e., how do these components fit together to implement the PSs to achieve the FRs?*

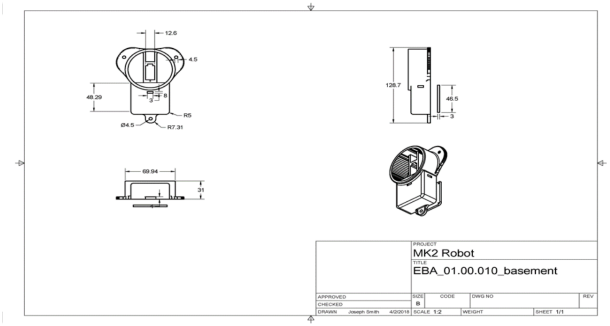
Cell Layout for Manufacturing System Design



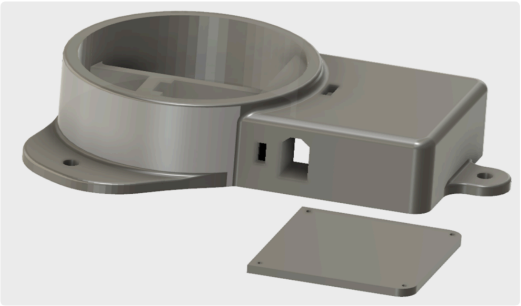
Circuit Diagram for Electrical System



2D CAD Model



3D CAD Model



KEY POINTS

- Pick diagrams/methods that effectively communicate how the components fit together.
- Goal: show how components implement the PSs to achieve the FRs.

FROM DETAILED DESIGN TO REFINED DESIGN

In **Step 6** you produced a **detailed design** and bill of materials — parts, dimensions, tolerances, materials, and interfaces.

Step 7 refines that design through one or more **Design For X (DFX) lenses** — each lens is a **design viewpoint** that examines the design from one stakeholder's concerns. *X* is whatever quality matters most for your project (assembly, manufacturability, cost, serviceability, etc.).

CHOOSE YOUR LENSES

Every project context is different. **You decide** which DFX method(s) to apply based on:

- The **customer's primary concern** (cost, quality, lead time, ease-of-use).
- What **Step 5 FMEA** revealed about likely failure modes.
- How the design will be **made, assembled, serviced, and updated**.

*No single DFX method covers every concern — combine the lenses that matter for **your** design.*

ONE DESIGN, MANY LENSES

DFX METHODS COVERED IN THIS DECK

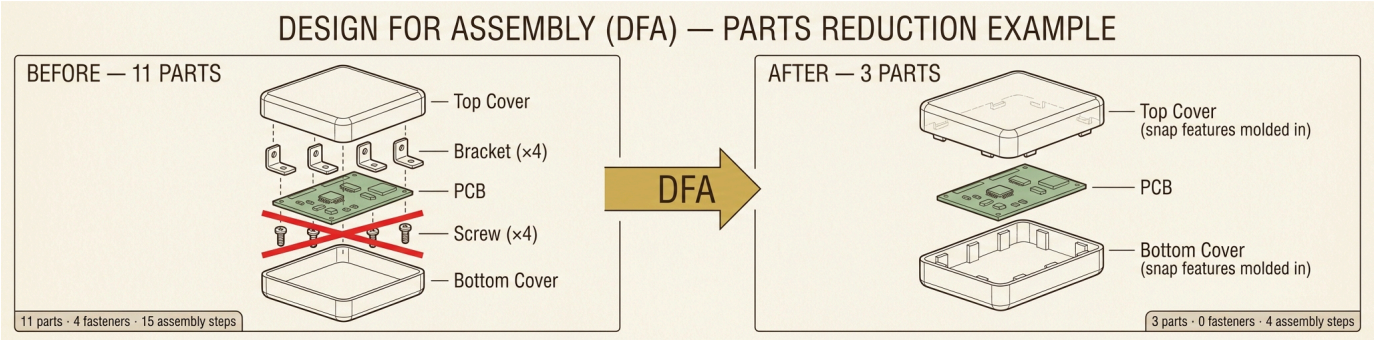
DFA — Assembly	**DFM** — Manufacturing
DFAM — Additive Mfg.	**Software** Design
MSD — Mfg. System	**Cost** Reduction

KEY POINTS

- Step 7 **refines** the detailed design from Step 6 — it doesn't replace it.
- Apply only the DFX methods that fit your project context — not every method applies to every design.
- The DFX lens you skip becomes the design risk you carry forward.

GOAL OF DFA

Reduce the number of components and interfaces — resulting in fewer parts and fewer assembly steps.



DFA PROCESS — THREE QUESTIONS PER COMPONENT

#	Question	Answer (Y / N)
1	Does the component have to **move** relative to other components in the assembly?	
2	Is the component made of **different material** for aesthetic or functional reasons?	
3	Does the component have to be **separate** to guarantee access for repair, maintenance, or other components?	

> *If the answer is **"no"** to all three questions, the part should most likely be combined with an adjacent part.*

KEY POINTS

- DFA refines an existing design to reduce complications and cost during assembly.
- Goal: fewer parts and interfaces → fewer assembly steps, lower cost, simpler BOM.
- Three reasons to keep a part separate: relative motion, different material, or required service access.

GOAL OF DFM

Reduce unnecessary design complexities that impact manufacturing in terms of quality, cost, lead time, etc.

#	Question	Answer
MATERIAL		
1	What are the applicable material choices for your design?	
2	What material did you choose for your design and why?	
3	What impact does your material choice have on the manufacturing process?	
PROCESS CONSIDERATIONS		
4	What manufacturing process/technology will you use to produce your design to achieve the desired cost?	
5	List (or illustrate) the manufacturing processes/operations required to produce your design.	
DESIGN CONSIDERATIONS		
6	What characteristics of your design affect the manufacturing processes?	
7	Based on your understanding of the manufacturing processes, how have you removed unnecessary complexity in your design?	
ENVIRONMENT		
8	What impact does the operating environment have on your design?	
COMPLIANCE AND TESTING		
9	What standards must your design meet?	
10	Identify the basic tests that your design must undergo.	

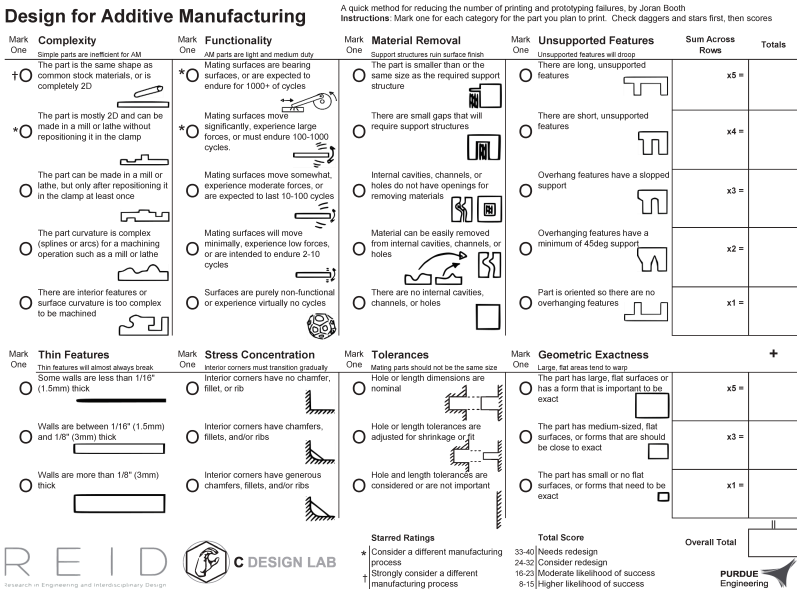
KEY POINTS

- DFM addresses complexity that drives quality issues, cost, and lead time during manufacturing.
- Five categories to evaluate: Material, Process, Design, Environment, and Compliance/Testing.
- The questions force explicit decisions about material, process, and design — informing the manufacturing strategy.

GOAL OF DFAM

Assess the potential quality of a part to be made using an **Additive Manufacturing (AM)** process by giving intuitive feedback and indirectly suggesting changes to improve the design.

DFAM WORKSHEET



Worksheet figure available in Lucid Chart for full readability. Reference: Booth, Alperovich, Reid, & Ramani (2016). DETC2016-60407 [PDF]

KEY POINTS

- DFAM helps novice and intermittent AM users avoid common print and prototyping failures.
- Eight worksheet categories — mark one option per category, sum across rows for an overall score.
- Total score maps to a recommendation: needs redesign, consider redesign, moderate likelihood, or higher likelihood of success.

GOAL OF SOFTWARE DESIGN

Create a blueprint that outlines the structure, behavior, and interactions of the software components needed to achieve the desired functionality — while meeting quality attributes such as reliability, scalability, and maintainability.

Principle	Question	Answer
Modularity	How will you break the system into smaller parts for easier understanding and reuse?	
Separation of Concerns	How will you organize the system for simpler maintenance and testing?	
Correctness	How will you ensure the software behaves as intended?	
Efficiency	How will you make the software perform tasks effectively?	
DRY (Don't Repeat Yourself)	How will you avoid repeating code to keep things clear and reusable?	
Scalability	How can we ensure the software functions as designed in spite of increased demand?	

KEY POINTS

- Software Design is the DFX equivalent for software-bearing systems — a blueprint of structure, behavior, and interactions.
- Six principles guide the blueprint: Modularity, Separation of Concerns, Correctness, Efficiency, DRY, and Scalability.
- Each principle pushes a specific quality attribute — reliability, maintainability, performance, or scalability.

Objective: form a team to choose solutions that achieve all 7 FRs reliably first. Then work to improve solutions to achieve the least cost without compromising the achievement of the FRs.

7 FRS OF MANUFACTURING SYSTEM DESIGN (COCHRAN)

FR0: Continually Improve	**FR1:** Provide a Safe and Healthy Work Environment	**FR2:** Produce the customer-consumed quantity every shift	**FR3:** Produce the customer-consumed mix every shift	**FR4:** Do not advance a defect to the customer of your work	**FR5:** Immediately identify abnormal conditions and resolve them for the long term	**FR6:** Achieve FR1 through FR5 in spite of variation
↑	↑	↑	↑	↑	↑	↑
PS0:	**PS1:**	**PS2:**	**PS3:**	**PS4:**	**PS5:**	**PS6:**

DISCUSSION QUESTIONS

Q1: Do you agree with the 7 FRs? Would you add or remove any?

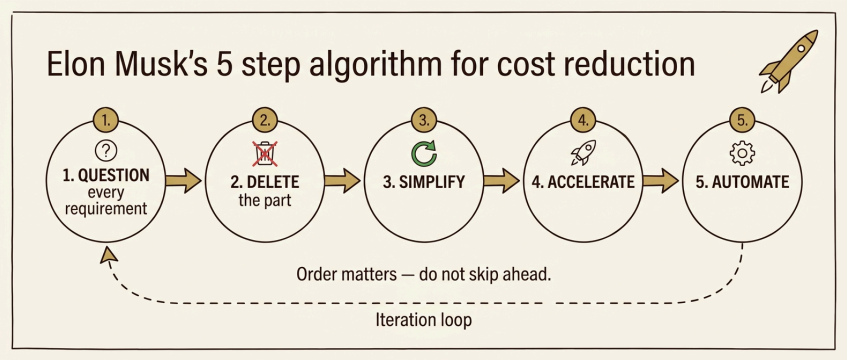
Q2: State your PSs for achieving the FRs of your Manufacturing System Design.

KEY POINTS

- Manufacturing System Design specifies the FRs (functional requirements) the production system must meet.
- The **objective is to form a team** to choose solutions that achieve **all 7 FRs reliably first**; then work to improve solutions to achieve the **least cost without compromising** the achievement of the FRs.
- Each FR drives a corresponding PS (physical solution) — the means by which the requirement is achieved.

Step 7 — The Elon Musk Algorithm for Cost Reduction

THE 5-STEP ALGORITHM



Five sequential steps for reducing complexity and cost — popularized by Elon Musk. **Order matters: do not skip ahead.**

#	Step	Description
1	**Every requirement traces to a named owner**	Every requirement must come from a **named person responsible for the requirement** — not a department (not "the legal department" or "the safety department"). Requirements from smart people are the most dangerous because they're less likely to be challenged. Make them less dumb.
2	**Delete any part or process you can**	You may have to add them back later. If you don't end up adding back at least **10%**, you didn't delete enough.
3	**Simplify and optimize**	Only after Step 2 — a common mistake is to simplify or optimize something that **shouldn't exist**.
4	**Accelerate cycle time**	Every process can be sped up — but only after the first three steps. *"I mistakenly spent a lot of time accelerating processes that I later realized should have been deleted."*
5	**Automate**	Comes last. Don't automate before requirements have been questioned, parts/processes deleted, and bugs shaken out.

Reference: Isaacson, W. (2023). Elon Musk. Simon & Schuster.

KEY POINTS

- Order is critical — most cost-reduction failures come from automating or optimizing what shouldn't exist.
- Step 1 is people-driven: every requirement must trace to a named person who can be questioned.
- If you don't add back ~10% of what you deleted in Step 2, you didn't delete enough.

Step 8 - Verification Test Plan

VERIFICATION — DID WE BUILD IT RIGHT?

Verification is a set of activities that determines whether a system **as built** achieves the required characteristics and design specifications.

Two key questions:

- Did we build the product / system **correctly** — to the design specifications?
- Does the design **meet specifications (FRms)**?

GLOSSARY

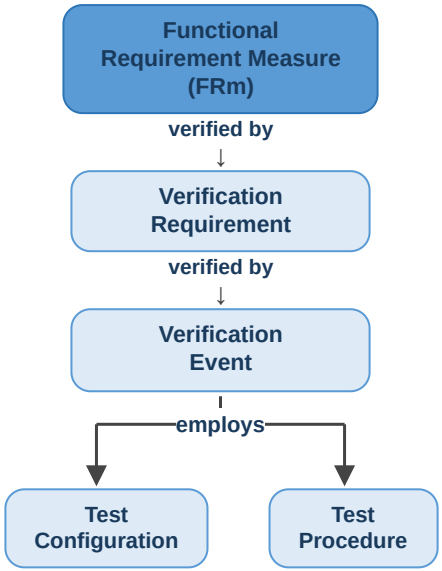
Verification Requirement — defines the characteristic of the system to be verified.

Verification Event — the specific event (test) that satisfies the requirement.

Test Configuration — items, devices, software, and people required to run the test.

Test Procedure — the step-by-step process to conduct the verification event.

VERIFICATION INFORMATION MODEL



KEY POINTS

- Verification answers two questions: **Did we build it right?** and **Does it achieve the FRm's?**
- Verification compares the system **as built** to its design specifications — not to user needs (that's Validation, Step 9).
- Each FRm gets a Verification Requirement, Event, Configuration, and Procedure.
- **Loop-back trigger:** if a verification test fails, **loop back to Step 6 / 7** — and may also include **Steps 2–5** — to revise the design choices that produced the failing PS.

Step 8 — Verification Example: Faucet Leak Test

VERIFICATION PLAN — WORKED EXAMPLE

FR3.2: Control water outflow rate.	**FRm3.2a:** Maximize number of successful (leak-free) valve cycles. **Threshold:** >20k cycles	**VERIFICATION REQUIREMENT** Verify no water leaks from faucet.	**VERIFICATION EVENT** Faucet Leak Test	**CONDUCTED BY** Joe Smith

TEST CONFIGURATION

- Dual-Handle Faucet
- 360° Lighted Test Stand
- Handle-Adjustment Robot
- Handle-Gripping Fixture
- Hot & Cold Water Supply Lines
- Water Colorizer
- Leak-Test Operator

TEST PROCEDURE (STANDARD WORK)

1. Mount faucet in leak test stand
2. Connect test supply lines
3. Activate colorizer
4. Test hot water leakage:
   a. Check leakage with faucet off (30 s, all angles); document status
   b. Repeat 30 s inspection at 20%, 40%, 60%, 80%, and 100% flow rate
   c. Robotically cycle 10k times (full-open ↔ full-closed)
   d. Repeat incremental flow rate test at 10k cycles
   e. Cycle 10k more times; repeat incremental flow rate test
5. Repeat steps 4a–4e for cold water

KEY POINTS

- Each FRm traces to a Verification Requirement → Event → Configuration → Procedure.
- The Test Procedure is detailed enough that a different operator could repeat the test and reach the same results.
- The Test Configuration enumerates **everything** needed to run the test: hardware, fixtures, software, and people.

Step 9 - Validation Test Plan

VALIDATION — DOES IT MEET THE CUSTOMER'S NEED?

Key question: *Does what we built do what the customer needs / wants?*

Validation is the process of determining if the product / system / service meets the **needs and wants of the customer**.

VALIDATION — DOES IT MEET THE CUSTOMER NEED?

VALIDATION PLAN — WORKED EXAMPLE

OBJECTIVE OF TEST	VALIDATION EVENT	CONDUCTED BY	CONDUCTED WITH
Gather user feedback regarding use of faucet.	User Feedback: Standard Operation of Faucet	Joe Smith	Shahab Shah Onkar Sonur

TEST CONFIGURATION

Event space, faucet installed in sink basin.

TEST PROCEDURE

1. Organize and host an event.
2. Simulate the different use cases.
3. Ask specific, pointed questions tied to the FRm's.
4. Capture all observations and answers.

TEST RESULTS

Both users agreed that the faucet met their need and functioned as expected.

DESIGN VALIDATED?

Yes. *Customer signature required.*

KEY POINTS

- **Validation (Step 9)** answers *"Did we build the right thing?"* — **Verification (Step 8)** answered *"Did we build it right?"*
- Validation is conducted **with the customer/user**, not by the engineering team alone.
- A "Yes" decision should be backed by a customer signature on the validation record.
- **Loop-back trigger:** if Validation reveals the customer's needs were misunderstood, **loop back to Step 1** (and possibly Step 2 use cases) — refine the FRs/FRms and re-run the affected downstream steps.

Step 10 - Build a High-Quality Solution

TO CONFIRM WHETHER YOU ARE READY TO BUILD THE HIGH-QUALITY SOLUTION

Use these planning questions to confirm you are ready to build — and to surface gaps in skills, tools, and help *before* the build starts.

Step 10.1 — What do you not know regarding how to build your design?

Step 10.2 — Do you have the necessary skills? What else will you require?

Step 10.3 — Do you have the necessary tools? What else will you require?

Step 10.4 — What parts of the build will require additional help or skill? Who will you need help from, and what is the required timing for that help?

Step 10.5 — Put together a timeline to build and test your high-quality solution. Include who is responsible for each task and by when. Allow ample time to troubleshoot and revise the design and prototype — estimate how long the build will take, then **multiply by 3**.

Step 10.6 — Follow the timeline and build the high-quality solution.

Step 10.7 — Notify project advisors and/or course instructor when you are not meeting the timeline.

KEY POINTS

- Build planning starts with what you **don't** know — the goal is to surface gaps in skills, tools, and help *before* the build begins.
- A realistic timeline budgets time for troubleshooting and revision, not just for the build itself — **because stuff happens**.
- Communicate early when the timeline is slipping — **advisors, instructors, and clients** can help recover, but only if they know.

Step 11 - Standard Work Instructions

OVERVIEW

Use the Standard Work Template to provide the customer with the instructions required to facilitate each **Use Case**. Use Cases may include assembly, maintenance, installation, normal use, etc.

WHAT IS STANDARD WORK?

Standard Work defines the normal method for conducting a process.

It describes the **content**, **sequence**, and **timing** of all work.

STANDARD WORK TEMPLATE

Standard Work for:			*Name of Use Case Here*
Step #	**Work Element**	**Key Point**	**Info-graphics**
1	Description of Step 1	Key point regarding Step 1	
2			
3			

KEY POINTS

- Standard Work represents the **best way we know how to do the work right now**.
- Standard Work is a record of all problems that have already been solved.
- Standard Work provides the foundation for **improving the work methods** — because we know how the work is done right now, we can make improvements to better achieve the desired outcomes.

Step 11 — Standard Work Example: Water Faucet

SAME FAUCET, TWO USE CASES

Standard Work for: Installation

Step #	Work Element	Key Point	Time (sec)
1	Turn off hot and cold supply lines.	Turn knobs counter-clockwise.	
2	Remove old faucet if required.	Supply lines may still have water that will leak.	
3	Remove new faucet from packaging.	Be careful not to lose the gaskets or mounting screws.	
4	Mount new faucet to counter top with supplied fasteners.	Pass supply lines through the counter-top holes one at a time if clearance is tight.	
5	Connect supply lines to Hot and Cold valves.	Do not over-tighten. Snug the connections and check for leaks.	

Standard Work for: Operation

Step #	Work Element	Key Point	Time (sec)
1	Turn on Hot and Cold valves as desired.	Hot water may initially be cold due to the location of the water heater.	2
2	Adjust temperature and flow with the valves.	To increase temperature, decrease cold flow or increase hot flow.	5
3	Proceed with planned activity with water.	—	*varies*
4	Turn off hot and cold valves.	Make sure valves come to a physical stop so the faucet does not drip.	2

KEY POINTS

- The same product needs **multiple** Standard Work documents — one for each Use Case (Installation, Operation, Maintenance, ...).
- The Key Point column captures the *why* — the failure mode that gets prevented by doing the step correctly.
- Standard Work is written from the customer's perspective: it must let a first-time user complete each Use Case without prior training.

REFERENCE ONLY WHEN PRINTED

Standard Work Template

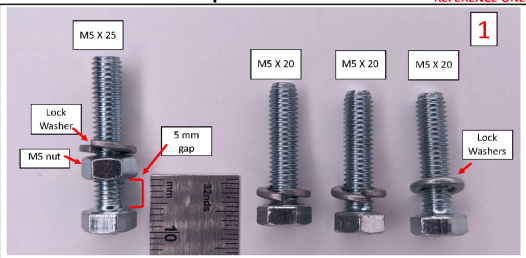
REFERENCE ONLY WHEN PRINTED

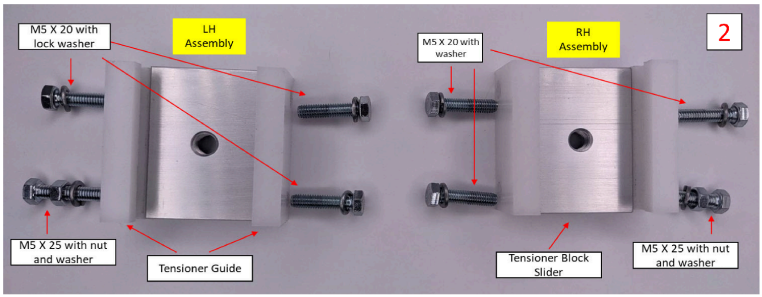
PLANT NAME:	Shuttleworth	DOCUMENT ID:		REV.
DEPARTMENT:	Sub-Assembly			1
PROCESS:	Tension Block Assembly - Right & Left	PG.	1 of 1	REVISION DATE: 03/02/23

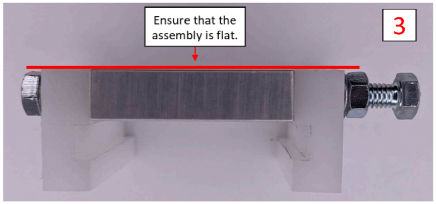
#	WORK ELEMENTS	ICON	KEY DETAILS/POINTS SAFETY/QUALITY/TECHNIQUE/COST
1	Locate necessary tools and materials. Tools: 8mm and 13mm wrench and block tensioner jig Materials: LH and RH Hardware Kits		RH and LH Kits are identical.
2	Preassemble bolts as illustrated in Figure 1. Required hardware includes: (1) M5 X 25mm, (3) M5 X 20mm, (4) M5 Lock Washers, (1) M5 Nut, (1) tensioner block slider, and (1) tensioner guide		Note the 5mm gap between bolt head and nut on M5 X 25 bolt. This step must be completed twice to produce preassembled bolts for both the RH and LH assemblies.
3	Attach tensioner guide to tensioner block slider with hardware from step 2 as illustrated in Figure 2.		Ensure that the 5 mm gap is maintained during the assembly process.
4	Tighten the M5 bolts while ensuring that the assembly remains flat as illustrated in Figure 3.		Ensure the assmebly is flat.
5	Check that assembly slides freely on aluminum tensioner block jig as illustrated in Figure 4.		Ensure M5 X 25 bolt head is parallel with aluminium tensioner block jig as illustrated in Figure 4.
6	Check off the Aluminum Tensioner Block Test on the QC sheet if tensioner block slides freely. If not, do not check off and notify lead of issue		
7	Locate and preassemble idler pully,M8 X 25, M8 Lock Washer, and M8 Thrust Washer as illustrated in Figure 5.		Preassemble for both RH and LH assemblies
8	Bolt the idler assembly from step 7 to tensioner assembly from step 5 as shown in Figure 6.		Keep assembly on aluminum tensioner block jig for tightening process as illustrated in Figure 7.
9	Ensure idler spins freely. If yes, sign spin test on QC sheet. If not, notify lead.		Thrust washer may be located incorrectly if pulley does not spin freely.

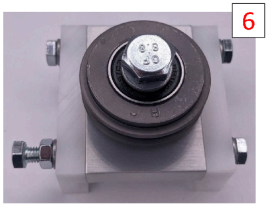
SYMBOL KEY: SAFETY / ERGO | IN-PROCESS STOCK | QUALITY CHECK | PICTURE REF.

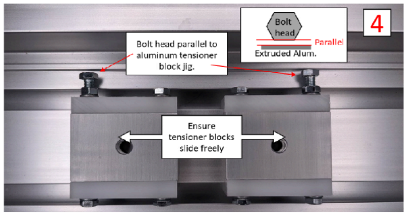
Approved by: Date:

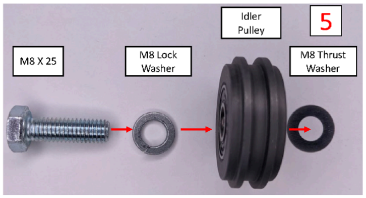












Step 12 - Verification, Validation, and Final Cost

STEP 12 — WRAP-UP TASKS

Step 12.1 — Conduct your verification tests as outlined in your Verification Test Plan, on schedule.

Step 12.2 — Conduct your validation tests as outlined in your Validation Test Plan, on schedule.

Step 12.3 — List all improvements you would like to make to the design going forward. Are there additional Use Cases that must be included?

Step 12.4 — Write down **Lessons Learned** during the design / build / test process. Capture the **best practices and Standard Work** to follow on the next project.

Step 12.5 — Complete the Final Cost Considerations Table.

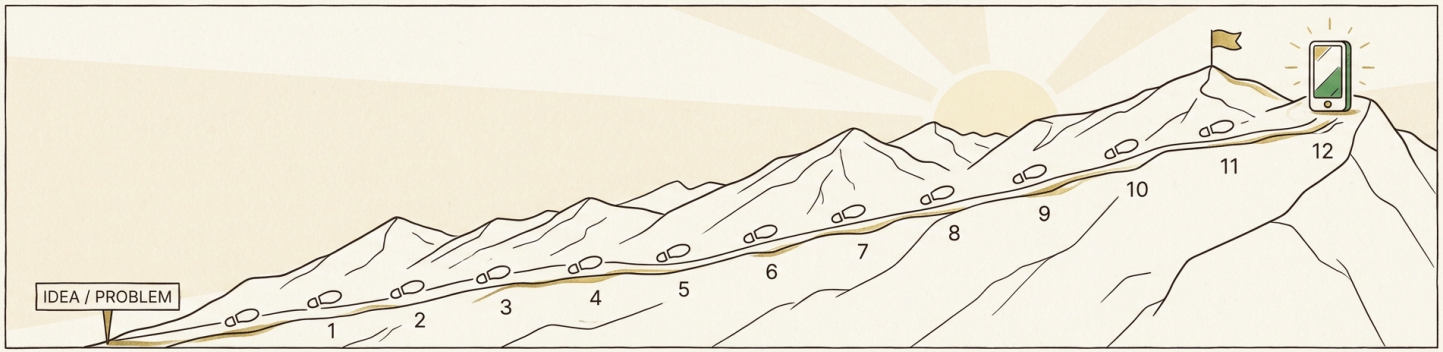
FINAL COST CONSIDERATIONS

1	Price the market will support	*From Step 1.6*
2	Desired profit $/unit	*From Step 1.6*
3	Required manufacturing cost the market will support	
4	Estimated cost to manufacture one unit	*Your estimate*
5	How much must you reduce manufacturing cost to meet market price and desired profit?	*A negative number is a surplus — good.*
	— OR —	
6	How much is the client willing to pay for the solution? (project budget)	
7	What was the total cost to produce the High-Quality Solution?	
8	What methods will you use to reduce manufacturing cost and be environmentally sustainable?	

KEY POINTS

- Step 12 is the execution wrap-up: run the verification + validation tests, then finalize the cost.
- 12.3 is the project's **improvement backlog** — future-state designs and any missed Use Cases get captured here.
- Two parallel cost paths — **market-price** (consumer goods) *or* **client-budget** (custom builds). Capture whichever applies.

12 STEPS COMPLETE — WHAT DID WE BUILD?



12 STEPS COMPLETE — REFLECT BEFORE YOU CLOSE.

You walked the design from a **fuzzy customer need** to a **verified, validated, built** system — all in one common language. Take a moment to reflect before we close.

What changed in your design as you walked through the steps? Where did **iteration loop back** (FMEA → Step 4? Verification → Step 6/7? Validation → Step 1?)?

Which FR / FRm was hardest to nail down? Which PS-ALT was the toughest to choose between?

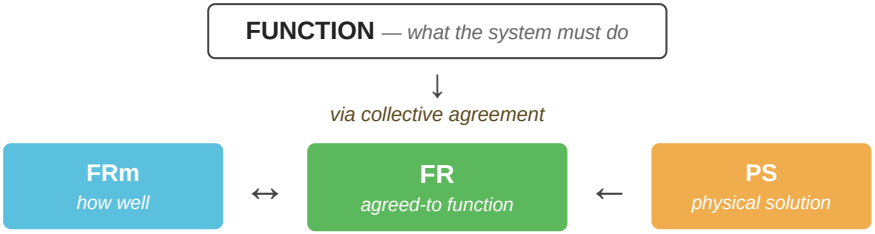
Did the team converge on a **collective** understanding of the design? Where did agreement break down — and how did you recover?

If you started over, what would you do differently in **Step 1** that would have saved time downstream?

Next: the **Why FRs?** section steps back from the methodology and asks the deeper question — *why does designing around Functional Requirements, instead of unit cost, lead to better systems?*

RECAP — COLLECTIVE SYSTEM DESIGN (CSD) LANGUAGE

Quick Recap: The CSD Language... gives every member of the team the same words and the same relationships. The four terms below — **Function, FR, FRm, PS** — are the foundation.



- **Function** — what the system must do.
- **Functional Requirement (FR)** — the function the team **agrees MUST** be implemented for the design to be successful.
- **Functional Requirement Measure (FRm)** — *how well* the FR is achieved *(can be more than one FRm per FR)*.
- **Physical Solution (PS)** — what **thing** implements the FR.
- The **designer chooses** the PS to achieve the FR — it is a **decision**.

WHY FRS? — FOR THE DESIGN OF SYSTEMS

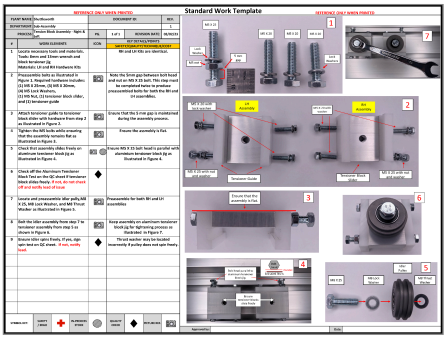
Where do FRs come from? FRs are derived from **Use Cases**, **Customer Needs**, **Risk Mitigation**, and **Constraints** (the non-FRs). **Enterprise Systems** and **Product Design** have similarities — both translate FRs into PSs — but they diverge in how those PSs are implemented.

(Reminds me of Art Linkletter — "Where do babies come from?")

FOR ENTERPRISE SYSTEMS — *e.g., manufacturing systems and product-development systems — BMW, SpaceX, Purdue Univ., healthcare systems*

Enterprise Systems rely on **Standard Work** to implement the chosen PSs. Standard Work defines the **normal operating condition** and establishes:

- **Content** — *what* we do; "the work"
- **Sequence** — the *steps* of the work
- **Time** — process time relative to **demand**
  - Cycle Time **(CT)** · Takt Time **(TT)** · **CT ≤ TT**



FOR PRODUCTS — *e.g., wet-floor sensor, reusable launch vehicle, aircraft, a hammer*

For products, the **PSs must achieve the FRs and their FRms** — the *"how well."* The FRm set is also called:

- **Design Specification**
- **Design Range** — *Suh*
- **Performance Requirements** — *INCOSE*

THE TRAP — POURING FRESH WATER INTO SALT WATER

Existing culture — driven by **unit cost of one operation** rather than the **functions** of the system — pulls every action back toward salt water. **FR language is the antidote:** stating the function explicitly — and the FRm that makes it measurable — surfaces the **unconscious thinking** behind common solutions before it shapes the design.

EXAMPLES — ACTIONS DRIVEN BY UNCONSCIOUS THINKING

Action / Solution	Unconscious Thinking
High Speed Machines	"The more the better" — Unit Cost Equation
Outsource to Low-Wage Countries	Reduce Labor Cost
Automation	Absorb less overhead, reduce labor cost
ERP Systems	Computerization of existing inventory & accounting practices
AI in Higher Education	"Let's use the shiny new technology"

In **every** case above, the implementation of the Action / Solution resulted from **unconscious thinking** — *NOT* from defining and understanding the function first, and its **collective-agreement FR**.

CASE EXAMPLE — "SALT WATER PSs" (GLAZING CUPS)

FR: Glaze cups.

As the team drives **unit cost** down, each FRm target steers them toward a particular PSs — watch where they converge.

UNIT COST EQUATION (Glazing op)

$$\frac{\text{Cost}}{\text{Unit}}(op) = \frac{\text{MTL} + \text{LABOR} + \text{OVHD}}{n}$$

OVERHEAD ABSORPTION

$$\text{OVHD}_{op} = (\text{OVHD Cost Pool}) \cdot \frac{\text{DL\_Time}(op_i)}{\Sigma_{i=1}^{n} \text{DL\_Time}(op_i)}$$

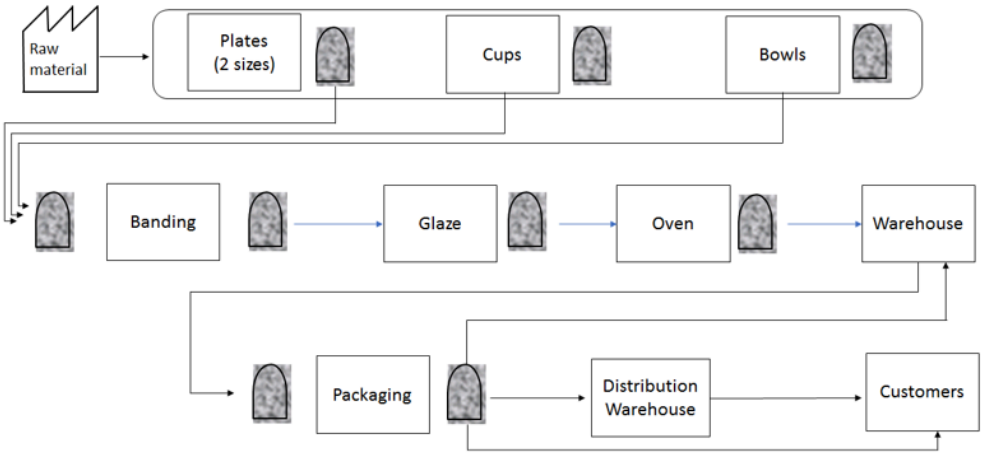
FRm: "the more the better" $n \to \infty$ · **PSs:** High Speed Machine

FRm: Labor Cost (LC), $LC \to 0$ · **PSs:** Low-wage country *and/or* Automation

FRm: Direct-Labor Time per Operation, $\text{DL\_Time}(op_i) \to 0$ · **PSs:** Automation *— tied to OVHD absorption: $DL\_Time(op_i)$ drops ⇒ OVHD per op pushed onto remaining ops.*

Cup Line — parts produced fast

Warehouse — 6 months of inventory



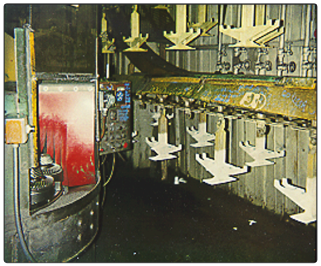
Forming / Grinding / Glazing departments

THE MESSAGE — an alternative to optimizing the cost of single operations while ignoring the consequences.

THE FALSE & UNCONSCIOUSLY HELD ASSERTION

$$\text{Min(Total Cost)} = \sum_{i=1}^{n} \text{Min(Unit Cost(op}_i\text{))}$$

Minimizing each operation in isolation does **NOT** *seek to improve the functions of the system.*



Shot Peen, Sterling MI — ***"WELCOME TO HELL"*** **sign at the dept. entrance**

EXAMPLES — CAN YOU THINK OF OTHERS?

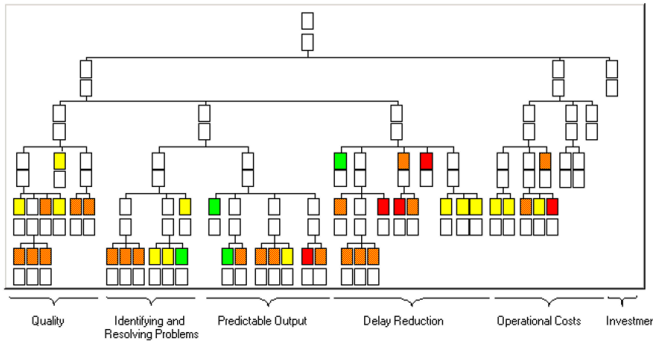
- → **Plastic bottles at "low cost"** — while filling up the oceans (300-mile Pacific Garbage Patch). [citation]
- → **Making cups really fast** — while hurting workers, poor quality, long lead times, and a warehouse of potentially obsolete parts.
- → **Shot Peen, Sterling MI** — the *"WELCOME TO HELL"* sign (above) is the worker's-eye view of single-op optimization.

WHY DO WE KEEP MESSING UP?

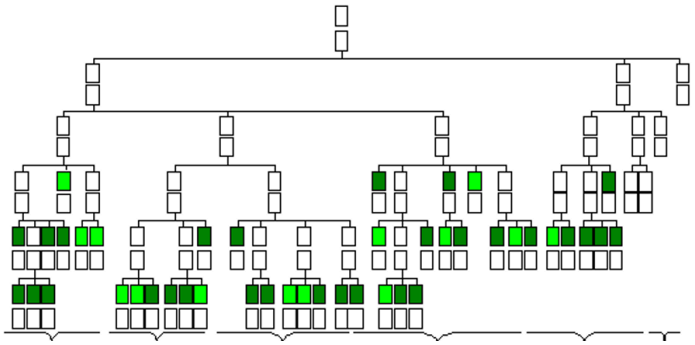
- → **No language for system design** that defines functions *first*, before unit cost of an operation.
- → The **false belief** shown above is held **unconsciously** — teams act on it without questioning.
- → We are **not conscious** of our **normative / normalized behaviors**.

Why FRs? By defining the FRs we establish the criteria to evaluate the **entire system** against customer needs — instead of local sub-optimization driven by the Unit Cost Equation. *Compare the two plants below: red / yellow mark FRs not yet achieved; green marks FRs satisfied.*

PLANT M — BEFORE



PLANT L — AFTER



PATHWAYS TO A BETTER DESIGN — TWO PATHS FORWARD

Design is about decision making — understanding the **functions** to meet, then choosing how to meet them. Two paths drive every improvement:

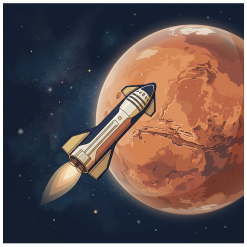
PATH 1 — NEW FUNCTIONS

Identify **new FRs** the system must perform — functions that didn't exist before, or weren't being satisfied.

EXAMPLE — MUSK & MARS

FR: Ensure the long-term survival of human consciousness by making humanity a multiplanetary species.

PS: Self-sustaining, large-scale colony — Mars.



PATH 2 — BETTER PSs

Keep the **same FR**, but choose a **better physical solution** — one that achieves the function more effectively.

Example: FR: Obtain water — *better PS = electric motor for water pump*

USE CASE — We have a well, and need to obtain water

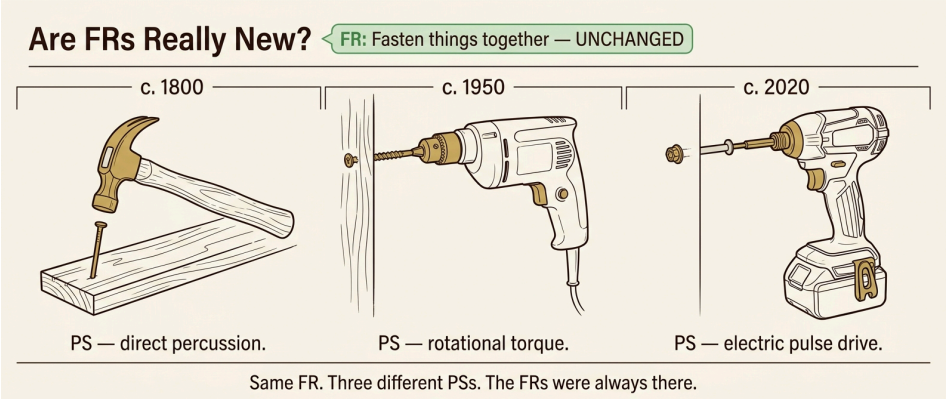
PS Option 1 — Hand Pump

Manual lever pumps water from the well. **FR satisfied**, but it's labor-intensive.

PS Option 2 — Electric Pump

Electric motor automatically moves water. **Same FR** — better PS.

ARE THERE REALLY ANY *NEW* HIGH-LEVEL FUNCTIONS?



The provocation: when we say we have a "new design," we often mean a new **PS**. The **high-level FR underneath** almost never changes.

EXAMPLE — Fasteners & Hammers

A new kind of **fastener (PS)** → a new kind of **hammer (PS)**...

> **High-level FR:** *Insert fastener / fasten together*
> *— did* **not** *change.*

MFG CASE STUDY REITERATES

There are solutions that **achieve** the core MFG functions — and solutions that **don't**.

The FRs were the same in both cases. What differed was the **PS choice**.

So: Maintain independence of FRs means:

- **FRs are constant.**
- We as humans **don't always know them**.
- We have solutions that **couple, are redundant, or are incomplete** — and we *"dance on the mess"* by **changing FRms** instead of fixing the underlying design.

[Nam did not say this here — an extension to Suh's framework.]

FRs are timeless. PSs are our latest attempt to satisfy them.

So what is the alternative to the **Unit Cost Equation** being used to drive system design and investment decisions?

Walla! — The **CSD Language** and the **collective agreement** of the FRs that a system **MUST** achieve.

Tada! — The **7 FRs of Manufacturing System Design**:

FR0: Continually Improve	**FR1:** Provide a Safe and Healthy Work Environment	**FR2:** Produce the customer-consumed quantity every shift	**FR3:** Produce the customer-consumed mix every shift	**FR4:** Do not advance a defect to the customer of your work	**FR5:** Immediately identify abnormal conditions and resolve them for the long term	**FR6:** Achieve FR1 through FR5 in spite of variation
↑	↑	↑	↑	↑	↑	↑
PS0:	**PS1:**	**PS2:**	**PS3:**	**PS4:**	**PS5:**	**PS6:**

Takt Zeit: *not "more is better."*

Match the **demand pace**, don't maximize output. This is the reason for **enterprise-design FRs**.

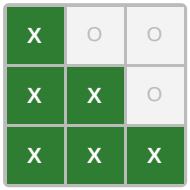
The recurring question (Axiom 1):

"Does PS_j affect the achievement of FR_i?"

THE ENTERPRISE DESIGN IS PATH-DEPENDENT

Most enterprises are large systems — many people, many elements. The enterprise design itself is **path-dependent**: the order in which the 7 FRs are addressed determines whether downstream FRs are achievable at all.

✓ PATH-DEPENDENT (TRIANGULAR)



FR1 first →
FR2 next →
FR3 next →

Predictable when set in order.

✗ THE TRAP

Without recognizing path-dependency, teams default to **"reduce inventory"** as the PS for "Become Lean."

But the **real FRs** are the **7 FRs of MSD** — **FR4 (don't advance defects)**, **FR5 (identify abnormal conditions)**, and **FR6 (achieve in spite of variation)** must be in place **before** FR2 / FR3 / FR0 are achievable.

KEY POINT

- Without recognizing path-dependency, people focus on **reducing inventory** as the PS for FR: "Become Lean" — when the real FRs are the **7 FRs of MSD**, sequenced.

FOR PRODUCTS — THE CONTEXT EVOLVES, SO THE DESIGN EVOLVES

The **context of product use** must be understood. Most product designs **evolve** to satisfy:

- **FRms becoming more stringent**
- **PSs adopting new tech and innovation**

USE CASE 0 — *The well*

FR: Provide access to water · **FRm:** Drinkable water · **PS:** Well

A and B evolved based on "Well" as the original PS.

USE CASE A — *At the well*

FR: Provide access to water
FRm: Don't freeze going outside to well in winter
PS: Indoor Plumbing System

Decomposed into:

FR1: Remove H_2O from earth **PS1:** Hand Pump *(path-dependent)*	**FR2:** Ensure water flow to tap **PS2:** Indoor Plumbing

PS1: Hand Pump

USE CASE B — *Water inside the house*

FR: Provide access to water
FRm: Don't freeze going outside in winter; **latency < 1 sec**
PS: Indoor Plumbing System

Decomposed into:

FR1: Remove H_2O from earth **PS1:** Electric Motor *(path-dependent)*	**FR2:** Ensure water flow to tap **PS2:** Indoor Plumbing

PS1: Electric Motor

GLOSSARY — COLLECTIVE SYSTEM DESIGN CORE TERMS

Function — what the system must *do*.

Functional Requirement Measure (FRm) — a measurable performance target on an FR. Includes **units**, a direction (max / min), a **Threshold**, and a **Goal**.

Goal — the **desired ultimate** performance for an FRm. Meeting the goal = excellent.

PS-ALT — an alternative Physical Solution candidate evaluated alongside others before one is chosen.

Use Case Step — one action within a use case — what the user or system does next.

Interface — a crossing of the system boundary; a connection between the design and an external element.

Coupled Design — one PS affects multiple FRs at once; design behavior is unpredictable.

Path-Dependent Design — PSs are independent only when adjusted in a specific sequence; acceptable but fragile.

Failure Mode — a way the design or process could fail (e.g., "valve leaks").

Mitigation — the design or process change that prevents the failure cause or detects the failure mode.

Functional Requirement (FR) — a function the team has **agreed** the system must perform. Begins with a verb.

Threshold — the **acceptable** level of performance for an FRm. Below threshold = unacceptable.

Physical Solution (PS) — the chosen physical thing that delivers an FR. Begins with a noun.

Use Case — a scenario in which the customer interacts with the system to achieve an outcome.

System Boundary — the line that defines what is **inside** the design and what stays outside (and crosses as inputs / outputs).

Decomposition — breaking a parent PS into its child FRs and child PSs across multiple levels.

Uncoupled Design — each PS affects exactly one FR; behavior is predictable.

Conceptual Design Alternative (CDA) — a high-level approach to solving the problem (Step 3.2). One of several to evaluate.

Failure Cause — the underlying reason for a failure mode.

Stakeholder — any person with an interest in the system (customer, operator, maintainer, regulator, …).

GLOSSARY — METHODOLOGY & ACRONYMS

FMEA — Failure Mode and Effects Analysis. A predictive failure-prevention technique used in Step 5.

PFMEA — *Process* FMEA — failures introduced by the manufacturing / assembly process.

Severity — how bad the failure mode's consequences are (1–10).

Detectability — how easy it is to detect the failure before it harms the customer (1–10).

Process Capability (C_{pk}) — statistical measure of a process's ability to stay within spec limits (USL / LSL).

Information Content (I) — $I = \log_2(\text{System Range} / \text{Common Range})$ — lower I means a more capable design.

DFX — Design For X (Step 7). X = Assembly (**DFA**), Manufacturing (**DFM**), Additive Manufacturing (DFAM), Manufacturing System Design (**MSD**), Software, Cost, etc.

Takt Time — available production time ÷ customer demand — the rate at which work must flow.

BOM — Bill of Materials; the complete parts list of a design (Step 6.1).

ISO/IEC/IEEE 42010 — the international standard establishing the multi-viewpoint principle for system architecture.

TPS — Toyota Production System — the lean-manufacturing tradition Standard Work / Takt are drawn from.

CDA — Conceptual Design Alternative (Step 3).

DFMEA — *Design* FMEA — failures introduced by the chosen physical solution.

RPN — Risk Priority Number = **Severity × Likelihood × Detectability** (each scored 1–10).

Likelihood — how often the failure is expected to occur (1–10).

Axiomatic Design — Suh's design framework. Two axioms: **Independence** and **Information Content**.

USL / LSL — Upper / Lower Specification Limits.

V & V — **Verification** ("did we build it right?") + **Validation** ("did we build the right thing?").

Standard Work — documented best-known method for a recurring task; defines content, sequence, and time (Step 11).

Cycle Time (CT) — time taken for one repetition of the work; CT ≤ Takt = balanced.

KPI — Key Performance Indicator; a measure of an organization's progress against a goal. KPIs should derive from FRms.

INCOSE — International Council on Systems Engineering — publishes the SE Handbook referenced for performance-requirements language.

SME — Subject Matter Expert.

12 Step Design Process Primer

Collective System Design at Purdue University Fort Wayne

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Feedback always welcome.

Now go build something that achieves all the FRs — for the least cost, without compromise.