ChE 413
Chemical Engineering Product Design

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EPFL

Lecture 3
Final steps in product design

1. Risks
2. Final specifications for product manufacture
3. Economic considerations (optional for project)
4. Life cycle analysis (optional for project)
5. The full business plan (not needed for project)

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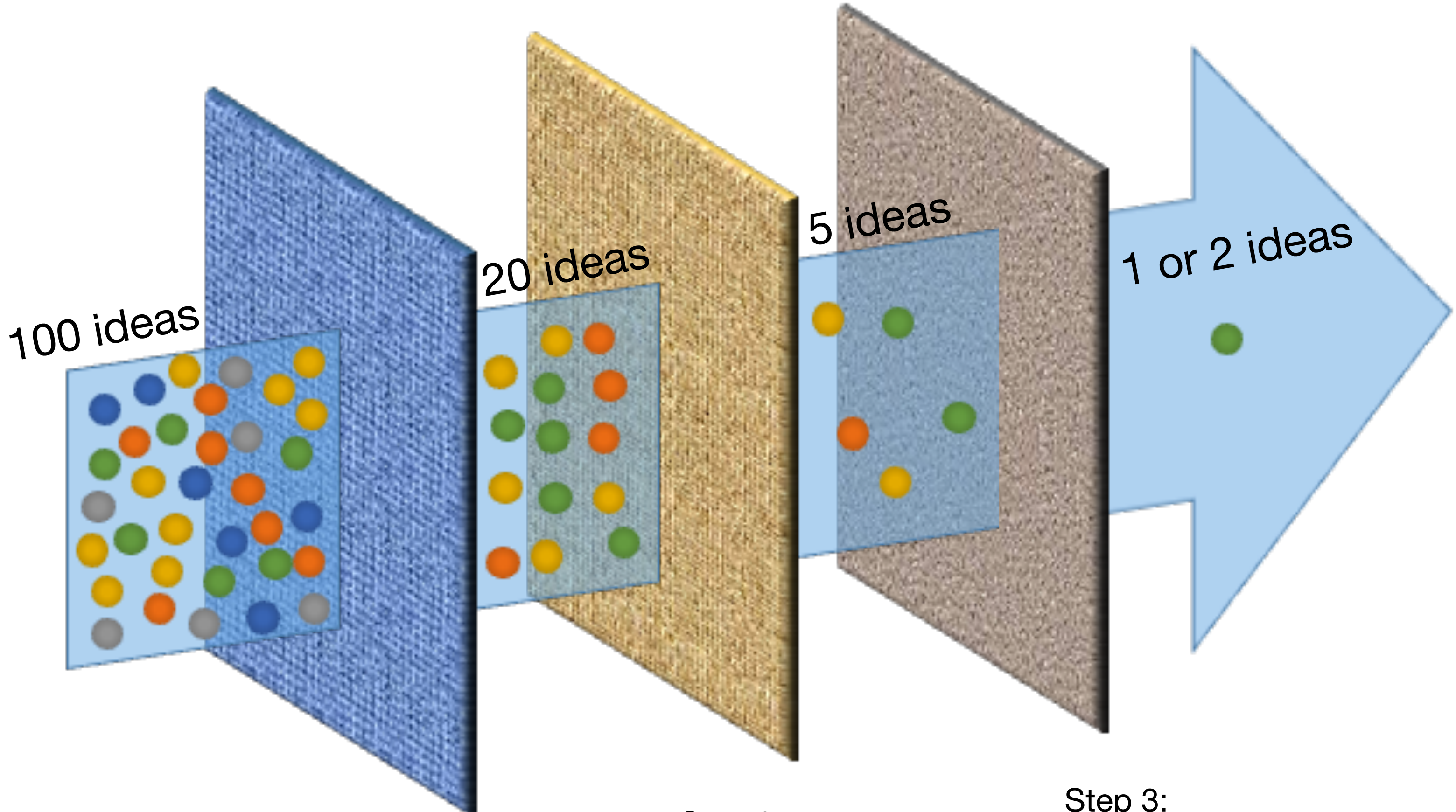
Screening ideas until final selection



Step 1:
Remove redundant, folly, and inconsistent ideas

Step 2:
Evaluate ideas using **selection matrix technique** with approximations

Step 3:
Reapply **selection matrix technique** with detailed calculations and consider risk factors

Risks involved in project ideas

We may not be sure that all aspects of all product options will function as desired. For example,

- We may be uncertain of the details of a chemical synthesis.
- We may not know if a mixing step can be as quick as we need,
- We may not know if the heat transfer to a fluid of unusual rheology will be as fast as predicted from standard correlations.

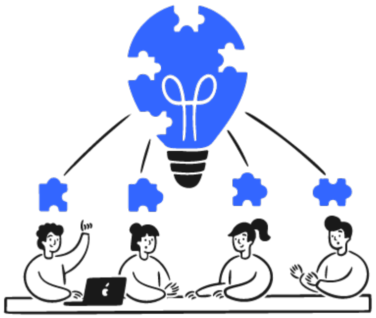
Selecting between products with varying degrees of risk is required. We consider this risk in our selection in two ways:

- ***Risk identification****: We must identify all risks.*
- ***Risk assessment*** : We must judge how serious a particular risk is, and how much this risk will affect our product.
- ***Risk management*** : We want to reduce the risk as much as we can, perhaps by some quick experiments/calculations

Risk identification

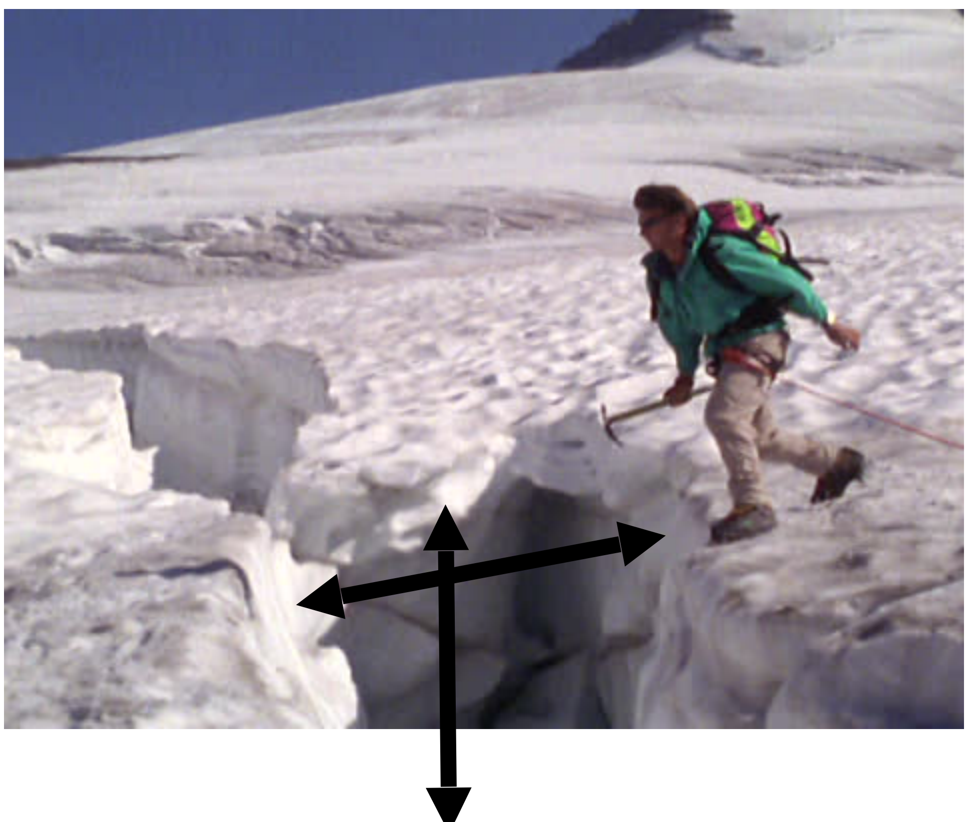
Identify and catalog all risks.

- The identification of risk begins by making a list of any possible difficulties.
- Making this list includes the same techniques used in the generation of ideas. We must discuss the risks with our core team and with others in our organization
- Typically involves cross-functional collaboration within the product team to ensure a diverse range of perspectives are considered during the risk identification process.
- For example, we include discussion with manufacturing, who up to now may have been less involved with product design than other groups.



Risk assessment

- Assign a probability and a consequence of each risk.
- Decide if these risks can be estimated with engineering tools, or if they simply generate uncertainty.
- Compare our possible products in terms of both cost and time.



Width : the probability of something going wrong

Depth : the magnitude of the consequence if it does go wrong

Risk assessment

Risk probability (Should range from 0 to 1)

- ≤ 0.3 if the probability of the risk happening is negligible.
- ~0.5 if the probability of the risk is significant.
- ≥ 0.9 if the probability is likely.

A probability less than 0.01 is defined as happening once in 10,000 years.
A probability of 0.7 will happen once in 10 years, i.e., within the normal lifetime of chemical-process equipment.

Risk consequence (should also range from 0 to 1):

- ≤ 0.3 if the consequence is small.
- ~0.5 if the consequence of the risk is significant.
- ≥ 0.9 if the consequence is severe enough to kill the project.

Risk level = [Risk probability] × [Risk consequence]

- We will normally decide to analyze in detail only those risks which are above a specified level, perhaps 0.5.
- The risk level of such "significant" risks is clearly arbitrary, and again must be decided by consensus.

Risk assessment

We must now separate these into categories, those which **can be judged by chemical or engineering analysis**, and those which cannot.

Can be analyzed by chemical engineering analysis:

- A heat transfer correlation which might be inappropriate,
- A chemical reaction which could be slower than expected,
- A product which could be unexpectedly viscoelastic.
- In these cases, we can judge how serious the risk level is using chemical and engineering analyses.

Cannot be analyzed by chemical engineering analysis:

- If our chemical raw materials are only available from one supplier,
- We will be at risk when our manufacturing requires new licenses,
- When we expect litigation from the local community to delay our facilities' expansion.
- Major policy changes affecting the market - e.g., carbon capture market in United States.

Risk assessment

For all significant risks, the core team must guess **the extra time and money** which such risks imply. Doing so requires our judgment, based on our collective experience (**speed is money** in several cases).

- For example, if we suspect heat transfer correlations are in error, we may judge that it will take one engineer six months to develop corrected correlations.
- If we expect a public hearing about our request for a building permit, we may anticipate a three month delay from experience of earlier struggles.

Risk management

Having identified and attempted to quantify both the risks and their potential consequences, we must decide on the appropriate response.

- Reduce the risk before proceeding with product development.
- Accept the risk and proceed without delay (time/speed is money).

Analogy: mountain climbing and avalanches

Climbing courses will correctly put a strong emphasis on safety: extensive use of ropes, ice screws, and snow stakes will be encouraged. However, using these safety measures takes time, and the safety gear is heavy, slowing progress further. The longer one spends on a glacier, the more chance there is of being caught in an avalanche; this is increasingly true later in the day as the sun softens the snow. To a considerable extent, safety is speed and delay can be fatal.

Risk management

Accept the risk and proceed without delay (time is money).

- Delay in product design, even for good reasons of risk management, can kill our product ideas.
- After risk assessment, we may wish to proceed directly to the manufacturing stage.
- If the risk is high, keep the investment low. As the risk decreases, raise the investment.
- Break the risk into increments, deciding where you will stop work if unsuccessful.

Table 4.4–1 ***Risk during new drug development.***

Status	Chemical status	Quality status	Risk
Preclinical efforts	Major process work needed	Few methods available	High
Phase I clinical trials	Laboratory procedures available	Analytical development necessary	High
Phase II to Phase III clinical trials	Pilot plant production	Analytical methods in place	Moderate
Late-stage clinical trials	Production process fixed	Methods validated	Low
Mature product	Plant process available	Quality control key	Low
Generic drug	Patents available	Methods sometimes available	Moderate

Source: Charles M. Boland, Cedarburg Laboratories, quoted in *Chemical and Engineering News* Feb. 14, 2000.

Risk management

Example: Power for off grid homes

In many European countries, electricity companies are required to provide power to homes at a fixed connection fee and standard cost per unit consumed, regardless of their remoteness. Laying many kilometers of cable to connect a single house to the national grid is clearly uneconomic.

Investigate alternative sources of electric power for isolated (off-grid) homes.

Needs. Ignoring electric heating, all other normal domestic requirements, such as cooking, lighting, cooling, etc. require typical power to average 3 kW, with a peak loading of 15 kW (mainly a result of cooking).

Ideas screening and selection give three leading contenders:

- Diesel generator,
- Wind power,
- Fuel cell.

Risk management

Example: Power for off grid homes

Table 4.4–2 ***Risk assessment for wind power*** The most serious risks are regulatory and reliability.

Risk	Probability	Consequence	Risk level
Customer acceptability	0.5	0.5	0.25
Regulatory acceptability	0.5	0.7	0.35
Maturity of technology	0.1	0.3	0.03
Reliability	0.7	0.3	0.35

Risk assessment for the fuel cell These risks assume hydrogen can be handled safely.

Risk	Probability	Consequence	Risk level
Customer acceptability	0.3	0.5	0.15
Regulatory acceptability	0.1	0.3	0.03
Maturity of technology	0.5	0.7	0.35
Reliability	0.5	0.5	0.25

Risk management

Detailed Example: milk concentrator

Your team works for a company in New Zealand that would like to develop a solution for a Farm to concentrate their milk

Typical farm:
4000 kg/day milk

concentration

1000 kg/day concentrated milk

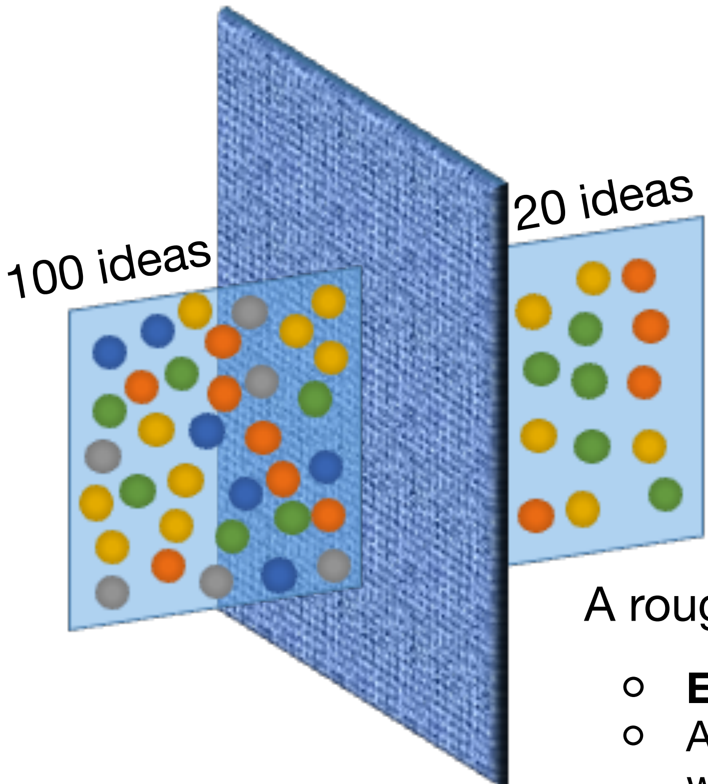
Less shipping cost

Cheese factory

Risk management

Detailed Example: milk concentrator

Your team works for a company in New Zealand that would like to develop a solution for Farm to concentrate their milk



After first selection we are left with 4 ideas:

- Evaporation
- Absorption
- Spray drying
- Reverse osmosis

A rough matrix selection yields the best approach:

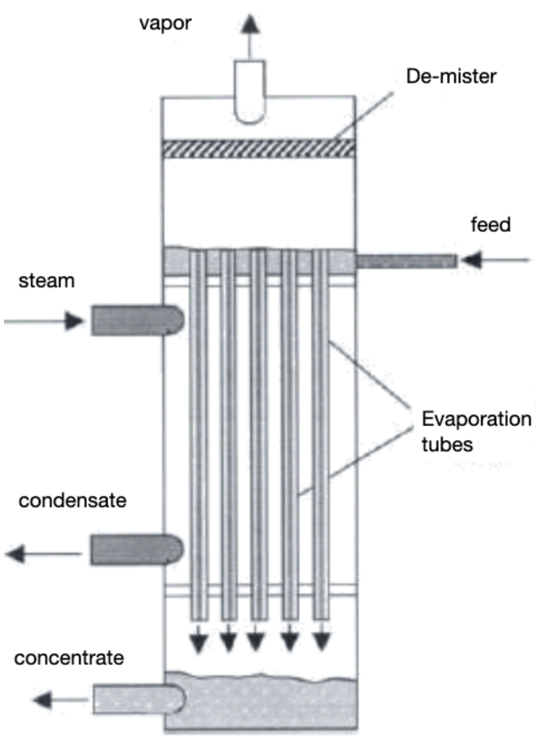
- **Evaporation – the best idea to move forward**
- Absorption – absorbents are not sufficiently selective for water.
- Spray drying – not enough solid content in milk for this technique to work.
- Reverse osmosis – membrane fouling is too problematic.

Risk management

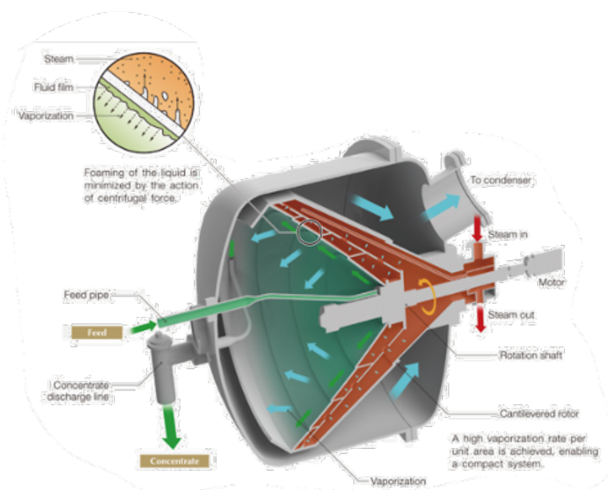
Detailed Example: milk concentrator

Evaporation
- Falling-film evaporator (benchmark)
- Centrifugal evaporator
- Membrane evaporator

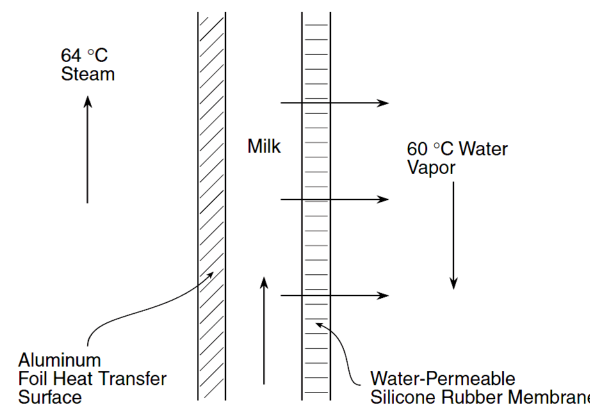
Which one should we choose?



Falling-film evaporator



Centrifugal evaporator



Membrane evaporator

Risk management

Detailed Example: milk concentrator

Solution consists of 3 steps:

1. Determine the general specifications for each of the evaporator designs.
2. Find the size and cost for each of the designs based on these general specifications.
3. Consider the risks involved with each of the designs.

After steps 1 and 2:

Your team performs a detailed energy/cost analysis based on the price of heating and transportation, together with what is know about the maximum temperature that milk should heated to not curdle and retain properties suitable for cheese making, and concludes that *in any case* the evaporator should be run at 60°C using steam which is available at 64°C.

Gather information about milk's properties:

Viscosity increases from 0.9 mPa s to 10 mPa s during evaporation
Density 1000 kg/m^3
Thermal conductivity 0.6 W/(m K)

Risk management

Detailed Example: milk concentrator

The total heat that must be transferred in each process, Q, is :

$$Q = UA_s(T_{steam} - T_{milk}) = \Delta H_{vap} * N_{milk}$$

↑ Evaporation rate

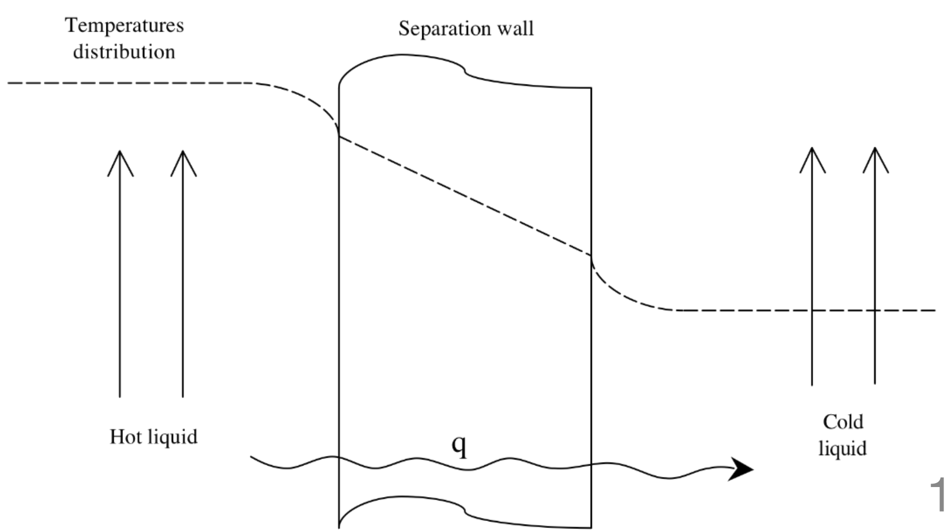
ΔH_{vap} = 2430 kJ/kg (at 60 °C)

$N_{milk} = 3000\ kg/day = 0.035\ kg/s$

$T_{steam} - T_{milk}$ = 4 °C

$$\Rightarrow \quad UA_s = 21.3\ kW/°C$$

$$\frac{1}{U} = \frac{1}{h_{steam}} + \frac{1}{h_{wall}} + \frac{\delta_{milk}}{k_{milk}}$$



Risk management

Detailed Example: milk concentrator

Falling-film evaporator (benchmark)

The design equation for this type of evaporator (can be found in textbooks):

$\delta_{milk} = 2\ mm$ → U = 280 W/ (m °C) → A_s = 75 m^2

Centrifugal evaporator

Similar relation for δ_{milk} but replace g with the centrifugal acceleration…

$\delta_{milk} = 25\ \mu m$ → U = 3400 W/ (m °C) → A_s = 6 m^2

Membrane evaporator

$\delta_{milk} = 600 \mu m$ → U = 800 W/ (m °C) → A_s = 26 m^2

Your team also finds that this device can be built for about 10 NZ$/m^2

Thus it is quite attractive for your application. However what about the risks?

Risk management

Detailed Example: milk concentrator

Falling-film evaporator (benchmark) – few risks and established technology.

Centrifugal evaporator – established technology but very expensive.

Membrane evaporator – since this new technology it is risky what are the main risks?

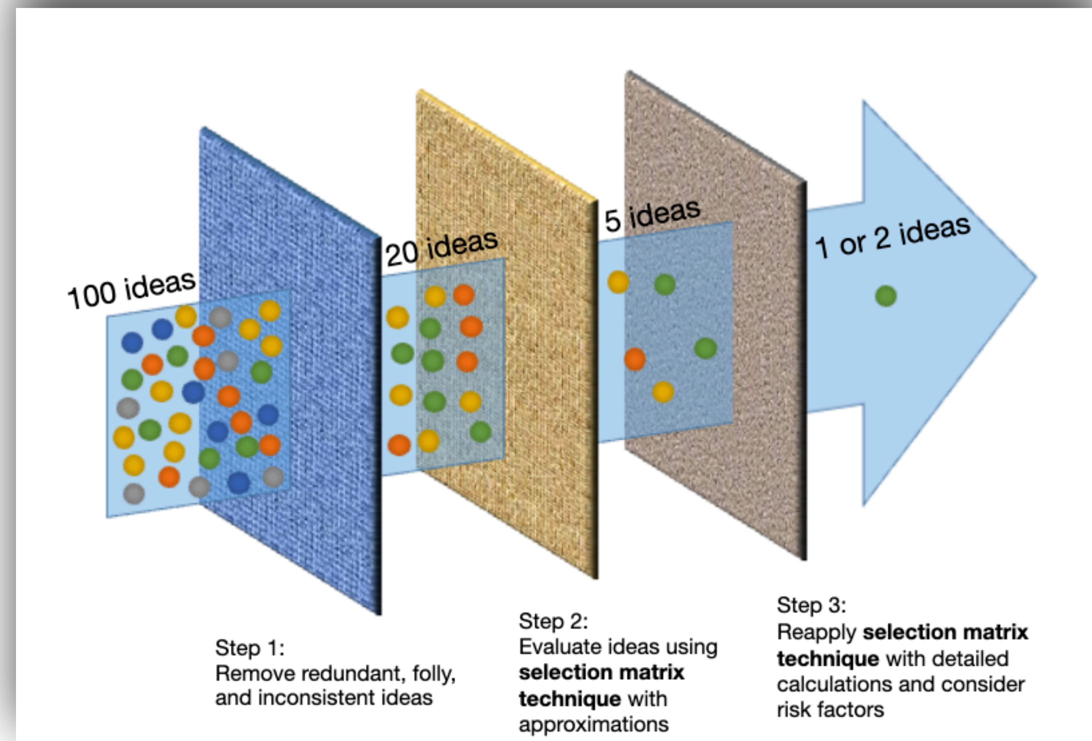
Table 1 ***Risk assessment for the membrane evaporator.***

See detailed discussion on Moodle

Risk	Probability	Consequence	Risk level	Mitigation
1. Difficult to make heat transfer membrane	0.1	0.5	0.05	Use parallel heat exchange technology
2. Difficult to make evaporation membrane	0.3	0.5	0.15	Existing data suggest, at most, required membrane area doubles.
3. Cannot easily manifold the module	0.5	0.2	0.10	Can mitigate with larger steam channel.
4. Evaporation flow is slow	0.5	0.2	0.10	Use larger membrane spacer in steam channel.
5. Cannot sterilize effectively	0.3	0.9	0.27	Chemical cleaning preferred, but requires no dead spots.

Selection: which idea is most promising

Manufacture : How can we make the product? What are its final specifications?



Idea selection complete

Final specifications for product manufacture

- We may have to fill in some missing information about the product specifications – this can lead to further product improvement! For this, we look to specify the following:

    - ***Product structure***
    - ***Central product attributes***
    - ***Any chemical triggers***

When these three steps are complete, we should be in a position to imagine how manufacturing can occur.

Final specifications for product manufacture

Specifying the **product structure** usually involves considering the four items listed below:

Chemical composition

- What is the planned product made of?
- If it is chemically pure, what is its chemical structure?
- If it is a device, how much can its composition be changed without affecting its performance?

Physical geometry

- What product characteristics are fixed?
- Are there fixed macroscopic dimensions? Is there any unusual physics?

Chemical reactions

- Does the product change chemically during use?
- Do additives like acids, bases, and salts affect these changes?

Product thermodynamics

- What is the product's phase?
- Is this phase thermodynamically stable or metastable?
- What is the characteristic size scale in any mixed phases?

Final specifications for product manufacture

Specifying a list of the **central product attributes** can often be organized under three headings:

Structural attributes

- These include the product's physical properties, like its strength and elasticity.
- These attributes are most important for devices.

Equilibrium changes

- Related to changes in product quality.
- Many products, particularly microstructured ones, will show major changes as a consequence of altered temperature, pH, or some other process variable.

Key rate processes

- The most obvious is the rate of any important chemical reaction.
- Less obvious but often important are rates of heat transfer, fluid flow, or diffusion, which are often manipulated by changes in interfacial area.

By making a list of these attributes you should also be able to identify the 1-3 most **central product attributes.**

Final specifications for product manufacture

Specifying any **chemical triggers** which makes the product become active. Essentially, what frees the product from its original thermodynamic bondage (most important for molecules and microstructured products):

Solvents

These dissolve or disperse the product so it becomes useful.

Temperature changes

The most common example is regenerating a product – like an adsorbent – by heating or cooling.

Chemical reactions

The most common occur because of pH changes or hydrolysis.

Other physical changes

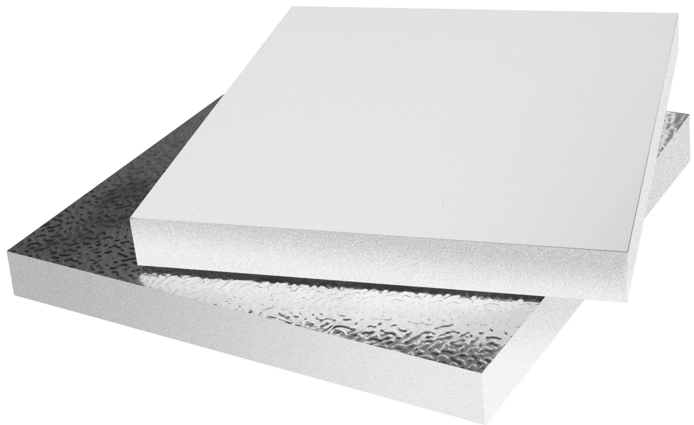
These may include pressure, detergency, and electric field.

Final specifications for product manufacture

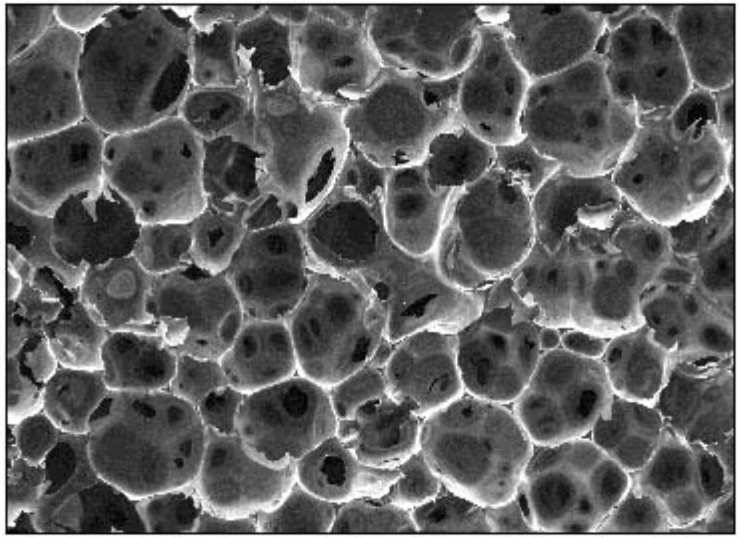
- *Example: Foam insulation without Freon gas*

See detailed discussion on Moodle

We need a better foam to replace polyurethane foam with Freon gas in the bubbles. A careful search for ideas has produced many interesting alternatives. After careful analysis, however, we decide that our best choice is polyurethane foam modified in some way to reduce its thermal conductivity.



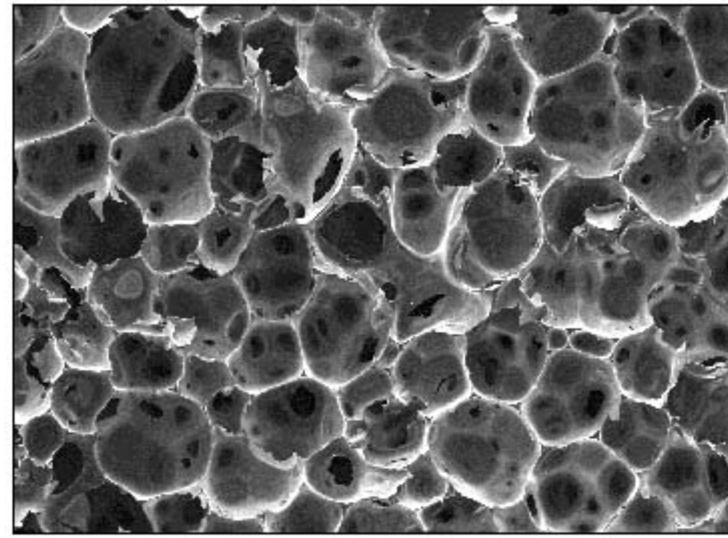
Think about "**product structure**", "**central product attributes**" and "**chemical triggers**" to suggest final product specifications.



Final specifications for product manufacture

• *Example: Foam insulation without Freon gas*

Product structure**.** Defining the structure is easy. We want a polyurethane foam containing 95% gas bubbles. The bubbles should be **small** to avoid free convection: free convection in any larger bubbles will compromise insulation. There are no chemical interactions in the present foam.



The central product attribute**.** The foam is a good internal insulator. This key attribute is directly a result of the thermal conductivity in the foam's gas-filled bubbles. As a result, we can benefit from a review of this transport property.

Some literature search and calculations show that:

For large bubbles:

$$k_{\mathrm{T}} = \frac{0.08}{\sigma^2 \Omega}\sqrt{\frac{T}{\tilde{M}}}$$

For small bubbles:

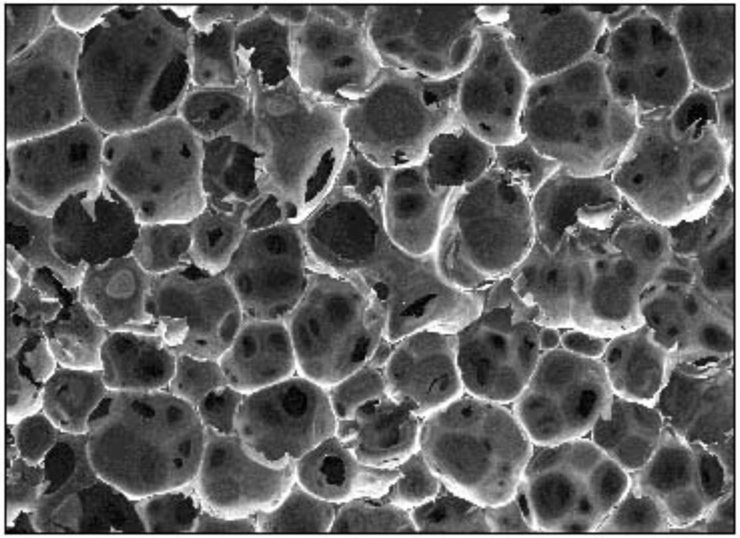
$$k_{\mathrm{T}} = dp\sqrt{\frac{k_{\mathrm{B}}}{2mT}}$$

d is bubble diameter, p is pressure

Final specifications for product manufacture

- *Example: Foam insulation without Freon gas*

Setting final specifications. To complete our product specifications, we must decide what is a large bubble and what is a small bubble. We can find that this difference depends on the Knudsen number *Kn*, the ratio of the mean free path λ and the bubble diameter *d*:



$$\begin{aligned} Kn &= \frac{\lambda}{d} \\ &= \left(\frac{4}{\pi}\right) \frac{k_B T}{p\sigma^2 d} \end{aligned}$$

When *Kn*<<1, we have intermolecular collisions, and hence large bubbles. When *Kn*>>1, we have molecule–wall collisions and hence small bubbles.

We could make the bubbles behave as if they were small by reducing the gas pressure, and hence raising the Knudsen number. The product designers who were involved in making a better foam did just this by a very clever invention and were able to replace the Freon with CO_2. (**Moreover we can use this method to specify the size of bubble and the pressure needed**)

Economic considerations

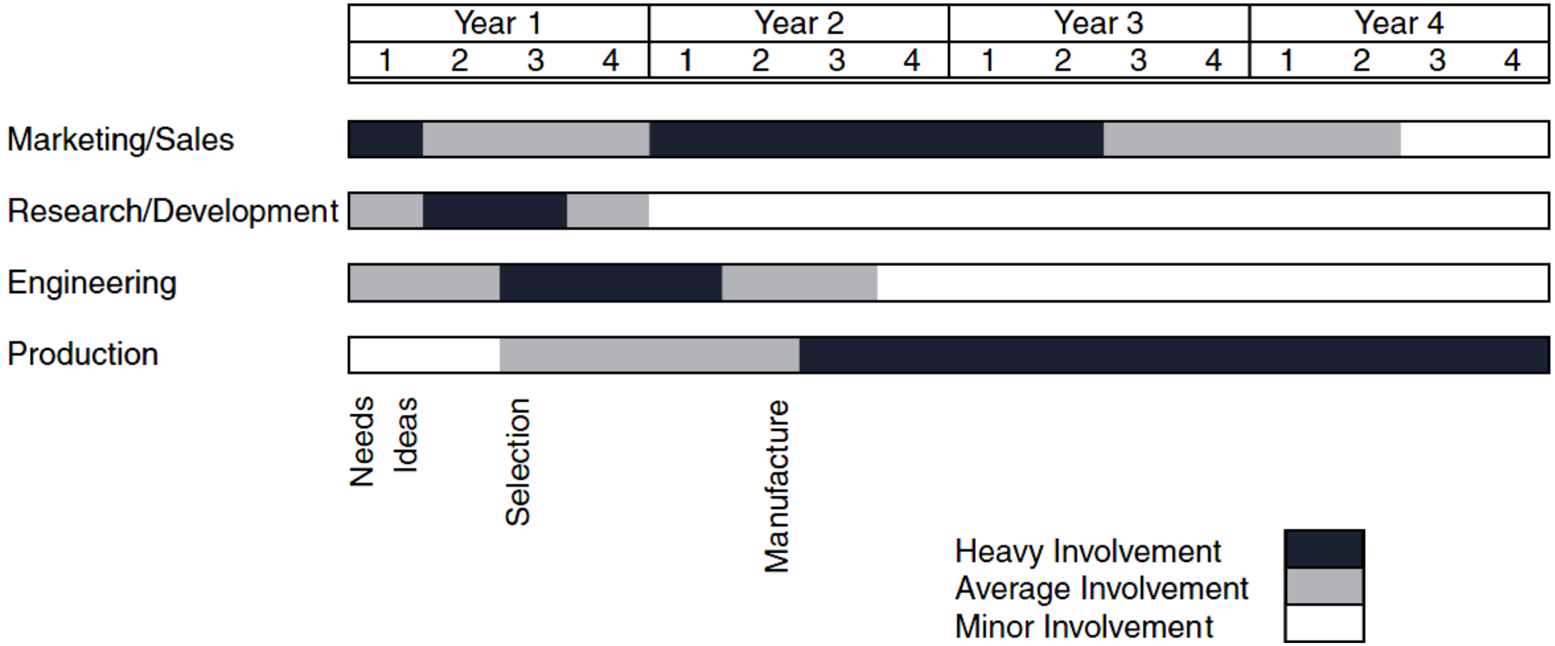
The important factors determining a product's viability are its **potential lifetime** in the market, the **size of that market**, and the **price** the product can command. *There will be considerable uncertainty associated with each of these*.

- Your product design should make some reasonable guesses as to what these factors could be.

We usually assume that products will have a short lifetime. We will aim to turn in a healthy profit in five or at most 10 years; any longer and the variations of the market will make our product too uncertain a proposition to pursue.

Economic considerations are optional for your design project

Economic considerations



Cash flow without the time value of money All values in $\$10^6$. Note the time value to break even is in the third year and the return on investment is 33%.

	Year 1				Year 2				Year 3				Year 4			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Development	–0.69	–0.69	–0.69	–0.69												
Equipment			–1.00	–1.00												
Start-up				–0.20	–0.20											
Production				–1.00	–1.00	–1.00	–1.00	–1.00	–1.00	–1.00	–1.00	–1.00	–1.00	–1.00	–1.00	
Revenue					2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Cash flow	–0.69	–0.69	–1.69	–2.89	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	2.00
Net cash flow	–0.69	–1.38	–3.07	–5.96	–5.16	–4.16	–3.16	–2.16	–1.16	–0.16	0.84	1.84	2.84	3.84	4.84	6.84

Optional for your design project

Life cycle analysis (environmental considerations)

A complete analysis over the lifetime of the product, including construction and decommissioning of the manufacturing facilities, is made against one or more measures of environmental impact, for example energy use or resource consumption.

- Include a full list of environmental stresses, usually including energy use, water consumption, gaseous emissions (NOx, SOx, CO_2), toxic residues, acidification, ozone-depleting agents, etc..

LCA is optional for your design project

The business plan (about 40 pages long)

- The executive summary (see example on Moodle):
  - This written equivalent of the elevator pitch is usually less than two pages long. Because most business plans are not read beyond the executive summary, this is our chance to convince the potential investor. *You will include this in your final report*
- The business idea: (not included in your report)
  - We must describe how the business idea will lead to a sustainable business with significant growth potential. We need to describe the technology underlying the product, and what is novel about it.
- The management team: (not included in your report)
  - We want to demonstrate that the proposed team has the mix of commercial and technical skills required to implement the business plan.
- Intellectual property: (not included in your report)
  - We must review our intellectual property, and any competing claims which may interfere. We describe how the business depends on intellectual property, and what steps have been taken to retain this property.
- Market potential: (not included in your report)
  - We must define the market which our product is seeking to address. We need to estimate the size of the potential market, the expected market share, and the product price.
- Competition: (not included in your report)
  - what competing technology already exists
- Finance: (not included in your report)
  - estimating the costs and income of the project over a number of years

Review of a simple 4-step process for product design

1. **Needs** : Identify what needs the product should satisfy

2. **Ideas** : What different products could satisfy these needs?

3. **Selection** : Which ideas are most promising?

   - Use a selection matrix technique to compare products
   - Use a details from chemical thermodynamics
   - Assess the risks involved with each approach

4. **Manufacture** : How can we make the product? What are its final specifications?

   - Specify product structure
   - Specify central product attributes
   - Specify any chemical triggers
   - Economic and life-cycle considerations (*not included in our project*)

Project timeline

- **Oct 7-14** : Assignment of topics (discussion in class on Oct 7)
- **Oct 28** : Meeting 1 with project coach (**needs & specifications**)
- **Nov 11** : Meeting 2 with project coach (**ideas and initial selection**)
- **Nov 25** : Meeting 3 with project coach (**top idea and key design aspects**)
- **Dec 9** : Final Report due on Moodle by the end of the day
- **Dec 16** : Final oral presentation

Schedule for Homework/Assignments:

Task/Assignment	Percent of final mark
Homework 1 (Due on Moodle September 16)	10% (individual)
Homework 2 (Due on Moodle September 23)	10% (individual)
Homework 3 (Due on Moodle October 7)	10% (individual)
Meeting 1 (Oral presentation by core team and discussion with the project coach)	10% (Group)
Meeting 2 (Oral presentation by core team and discussion with the project coach)	10% (Group)
Meeting 3 (Oral presentation by core team and discussion with the project coach)	10% (Group)
Final report (Due on Moodle December 9)	25% (Group)
Final oral presentation (December 16, MA A1 12)	15% (Group)