Key performance indicators for production - Examples from chemical industry

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2015-04-15

Agenda

- Characteristics of chemical plants; business- and technology-wise
- Which information is readily available from the plants: some examples
- Key performance indicators (KPIs): Examples illustrating the complexity
  - Variable costs
  - ”OEE”

Characteristics of chemical plants

(A view slightly biased by Perstorp experience)

Characteristics of typical Perstorp plants

- Synthesis (reaction) followed by a large number of separation steps
- Reaction is often batch-wise, and separation continuous
- Separation can be a number of sequential distillations, evaporations, crystallizations, filtrations, centrifuges, decanters, etc
- Many intermediate buffers
- High value side streams (byproducts), means many recycle loops
- Plants operate 24/7
- Controlled by computerized control systems

Many types of process units in one plant

- Reactors
  - Continuous, batch, semi-batch, tube
- Heat exchangers
- Distillation columns
- Crystallizers
- Evaporators
- Centrifuges
- Filters
- Decanters
- Dryers
- Boilers

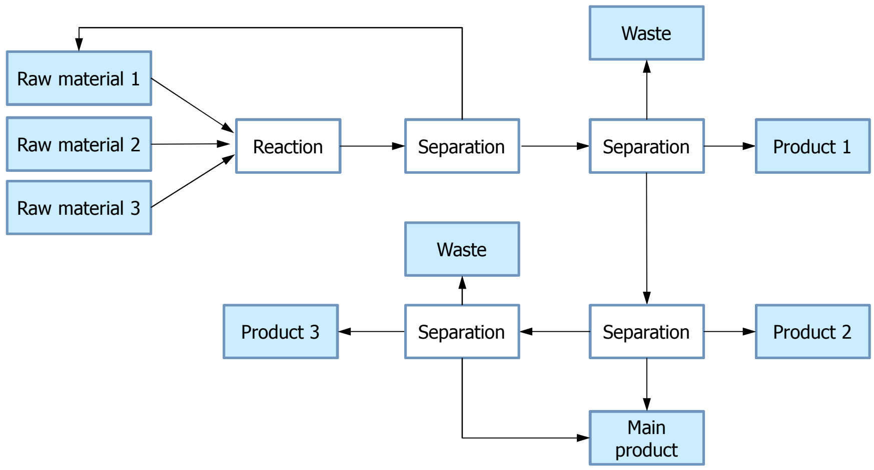
To define sensible key performance indicators (KPIs)
you need fairly deep process knowledge.

Valuable by-products gives complex topology

- A chemical reaction rarely gives one specific output.
- Some of the by-products may be very valuable.
- For this reason the separation part of the plant is often much more complex than the synthesis part (reactors).
  - Separation = distillations, crystallizations, centrifuges, decanters, evaporators...

Topology for plant with multiple separations

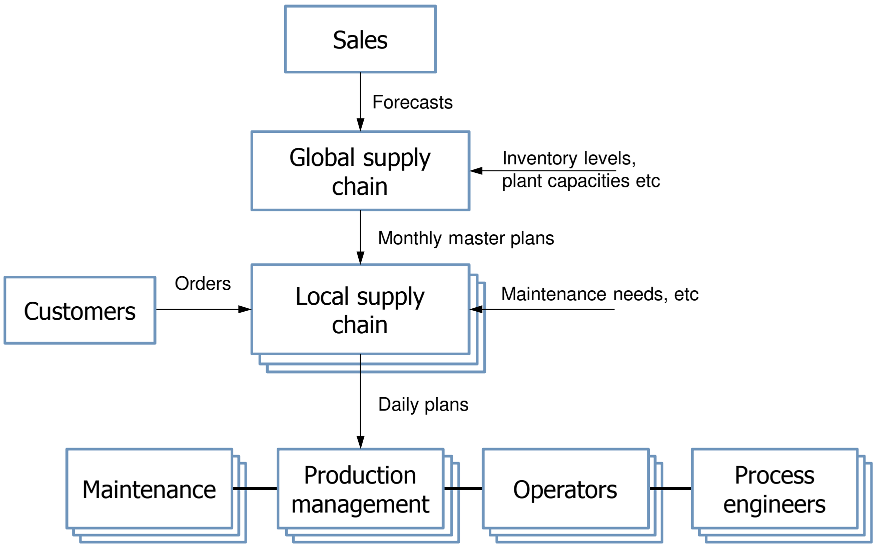
(Loosely based on a true story)



Business aspects

- The market characteristics for different products differ widely
  - Bulk product vs Specialty product
  - Many small customers vs A few large customers
  - Local vs Global products
  - Spot market vs Contracts
  - Make to order vs Make to stock
  - "Postponement" in product specification possible or not possible
  - Raw material internally or externally supplied; Main customer internal or external
- This can make it very hard to answer questions like
  - What is the value of getting extra capacity?
  - How much profit do we lose if we have an unexpected shutdown?

Decision making / work flow in production



Information available from plants

Process historian: Core of all production KPIs

- IP.21 = Process history database (standard software from supplier)
- Makes **plant measurements available to office applications**
- Every production site has its own IP21 server
  - All variables from the control systems are logged; including setpoints, controller modes, on-off-valves, etc.
  - Scan frequency varies from site to site, between 1 and 15 seconds.
- Currently ca 500 users of the client application
- ODBC connections to home made applications
- ~1 GB new data / day

- The control group is owner of the IP21-systems.

In-house developed applications

- We have developed a number of applications based on IP.21 data; see examples on the following slides.

- Main principles:
  - All applications are web based.
  - Users don't have to install a client application
  - Access rights controlled by ActiveDirectory

- Software components in the applications:
  - SQL queries and procedures
  - Reporting services from AspenTech
  - ASP and VB programs
  - HTML and CSS
  - Matlab
  - MS Sharepoint

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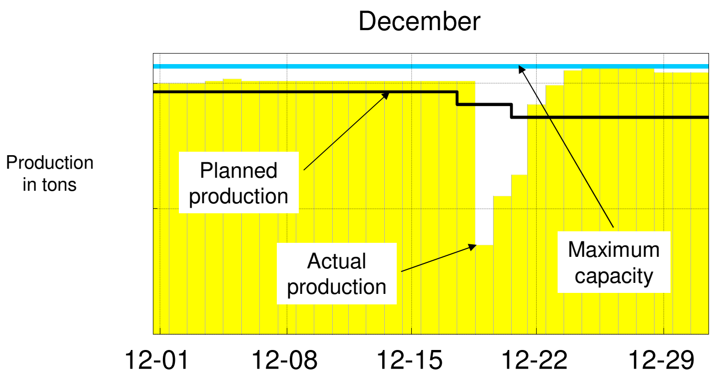
Production portal

- An Intranet website presenting volumes produced for the 35 most important plants in the group, day by day.
- Altogether ~250 home pages automatically updated every morning.
- Production is estimated from process measurements in IP.21; many models are fairly complex.
- 300 users. In a user survey, 20% of the respondents say that the portal has had direct business impact.

Production Portal: Detailed view



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Key performance indicators

1. Variable costs

KPI definitions: depend on usage

- When defining a KPI it is key to think about **how it should be used,** and by whom.
- Financial KPIs are the "bottom line", of course.
  - What were the costs (raw material, energy, salaries etc)
  - What were the contribution margins (sales price – production cost)
  - etc
- However, those KPIs are almost useless for measuring plant performance.
- Now we will discuss why, and how we can define KPIs that are more relevant for plant optimization.

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Different categories of KPIs

- High-level / Financial
  - Examples: Volume produced, Production costs, Inventory turnover
- High-level / Operational
  - Examples: Safety related, Environmental, OTIF
- Technical / Process specific
  - Examples: Quality, Key lab values, Energy usage per unit, Unit availability, Heat transfer coefficient, Distillation reflux rate, Plant utilization rate
- Technical / Generic
  - Examples: Alarm rates, Control loop performance, Valve diagnostics

Challenges

- Find KPIs that separate effects from planning, plant operation and market.
- Find a connection between high and low level KPIs.
  - Then we could "drill down" to find root causes.

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Important KPI: Variable costs

- In process industry, variable costs are often much larger than fixed costs
- Examples of variable costs
  - Raw material
  - Utilities; Typically
    steam, electricity, cooling water, waste water treatment, nitrogen, air,...
  - Transport
  - Packaging
- Often time, costs for raw material and utilities are much larger than other variable costs.
  - From now on we exclude transport and packaging from variable costs.
  - DVC = direct variable costs

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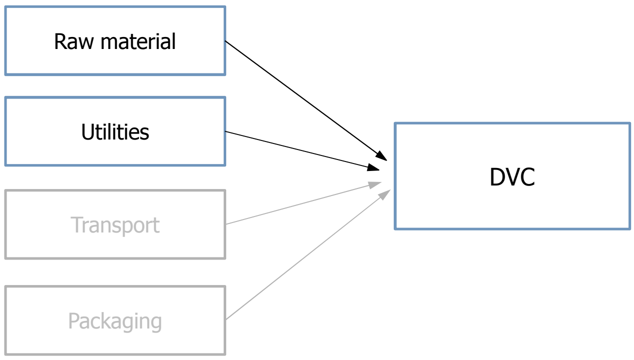
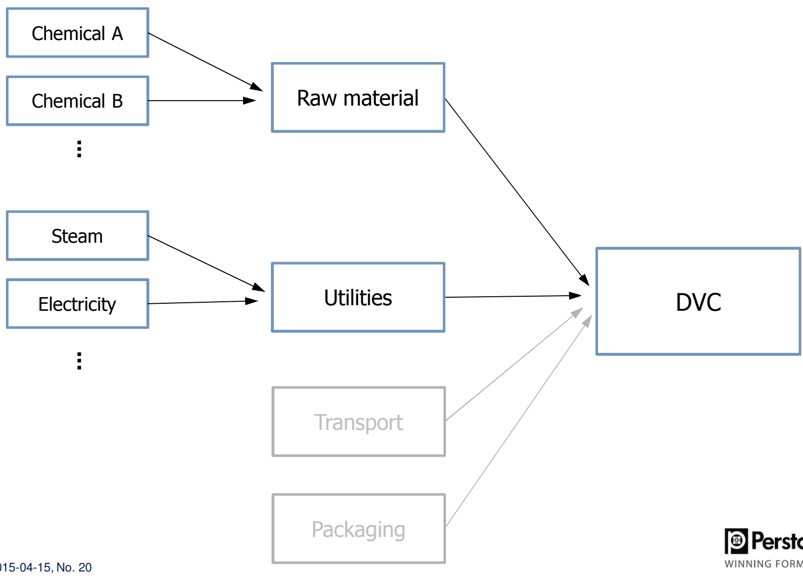
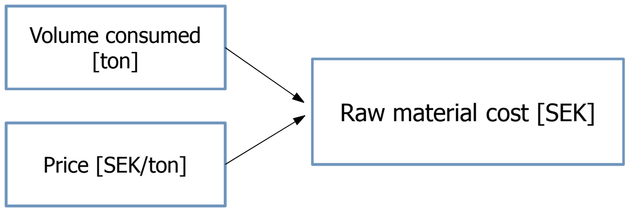
Direct variable costs



Direct variable costs

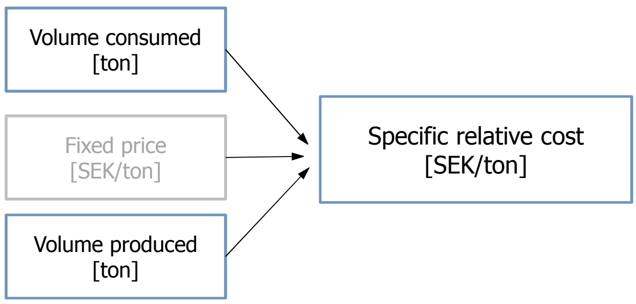


DVC depends on raw material prices



- Raw material prices vary rapidly, with large variations
- If you are working with procurement or supply chain, planning inventories or choosing suppliers, this is important information.
- But if you work with plant optimization, raw material price an external factor which we can't affect.
- To handle that, we can use "Relative" cost, where prices are fixed over a long period of time.
  - E.g. budget prices

"Specific cost" = cost per ton produced



- Example:
  - In January we consumed 1200 tons of methanol to make 2500 tons of product A (obviously there are other raw materials as well)
  - The budget price for MeOH is 4 kSEK/ton
  - The specific relative cost for methanol for the month was then

$$1200*4 / 2500 = 1.92 \text{ kSEK/ton}$$

Typical cost summary

Month: January
Volume produced: 2000 tons

Material	Consumption [ton]	Consumption rate [ton / ton product]	Price [kSEK/ton]	Cost / ton of product [kSEK/ton]
Chemical A	1500	0.75	4.2	3.15
Chemical B	400	0.20	5.5	1.10
Chemical C	500	0.10	6.0	0.60
Steam	2000	1.00	0.2	0.20
...				
Total				4.85

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Is this level of information good enough?

- Depends on who is going to use it.
  - What conclusions can you draw if DVC is high? How should you improve it?
- For most plants, variable costs are dependent on production rate.
  - Normally the production cost, per ton, is lower when running the plant at high speed than at low speed.
  - If DVC is high, in the worst case, we get a "blame game":
    Production management blames planning: "We were forced to run at a low rate."
    Planning blames production management: "Your plant is too inefficient."
- The following few slides explain why DVC per ton may depend on production rate, and indicate how this feature varies between different types of plants.

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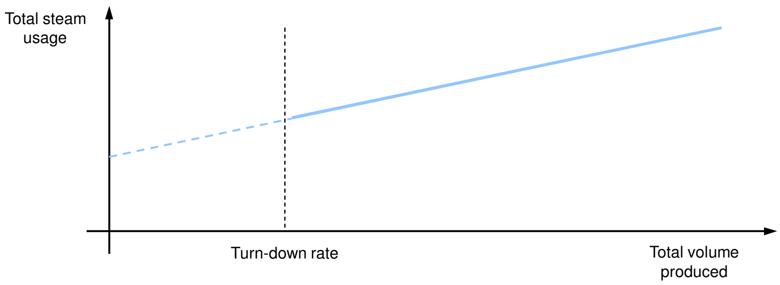
Energy costs: steam and electricity

- In a chemical plant steam costs are often much higher than electrical costs.
- Steam is used e.g. in distillation, evaporation and some reactions.
- Qualitatively, steam usage depends on production rate as shown below.
  - For some equipment, steam usage doesn't depend on production rate
  - There is a "base-load" that is independent on production rate



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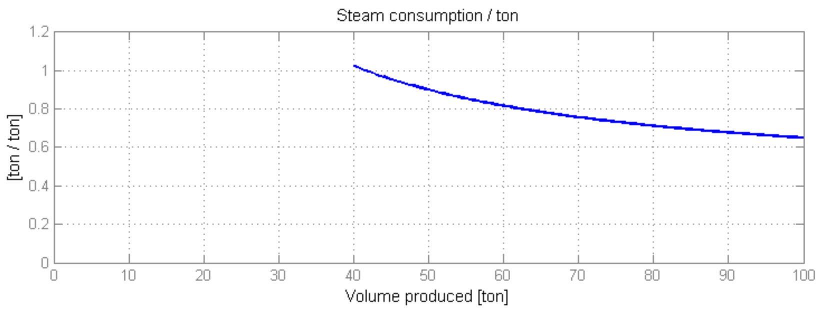
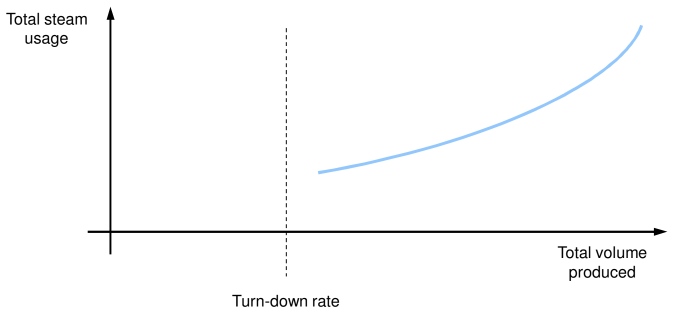
Specific steam consumption vs production rate

- Consequence of the facts on the previous slide:
  - At high rates the steam base load is "shared" between more tons of product



Opposite effect theoretically possible

- Depending on how heat exchangers are used, compared to their design capacity, we may get the opposite effect.
  – Details too complicated to describe here.



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Yield may depend on run rate

- For many plants, the raw material yield depends on production rate.
- This dependence, if it exists, is more complicated.
  – It may be either positive or negative.

- To understand this better we look at how losses of raw material may arise.

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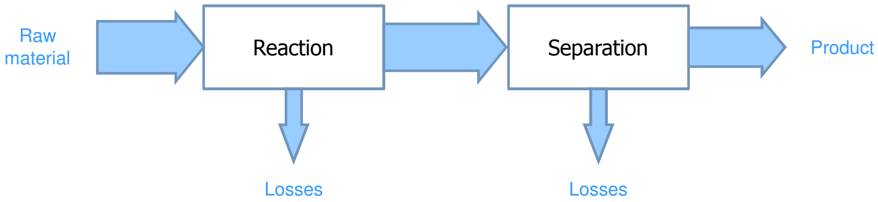
Yield loss characteristics: application dependent



- Reaction process: losses = undesired side-reactions or incomplete conversion
- Separation process, e.g. distillation: losses = imperfect separation
- Both types of yield losses are hard to model.
  - They depend on a large number of parameters in a complicated way.
- Loss rate may depend on production rate
  - But if the reaction is batch wise reaction losses should not depend on rate.

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How can yield depend on production rate?

- For all reaction schemes there is a tree of possible reactions.
- Which ones dominate depends on temperatures and concentrations.
  - If we produce a undesired by-product in an irreversible reaction, then that raw material is lost forever = yield loss
  - If the reaction from raw material to end product is incomplete, the product may contain raw material = yield loss

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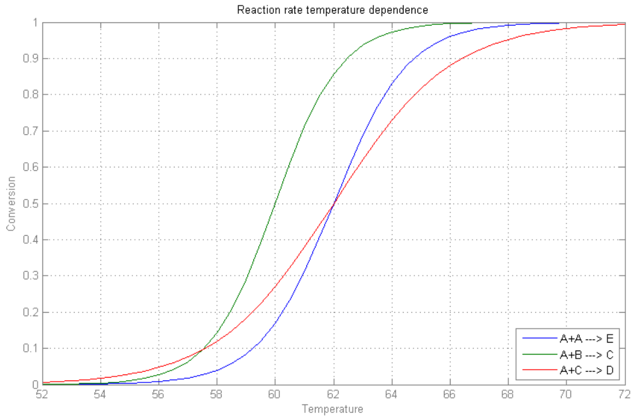
On chemical reactions

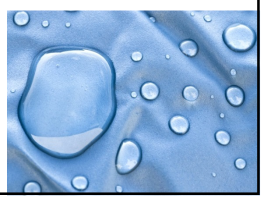
- Typically, several reactions are going on in parallel. Some of them undesired.
- All reactions depend on temperature and concentrations.



cont'd Yield vs Prodn rate

- In a continuous reactor we may have the situation that as we increase throughput, conversion will decrease.
  - "Some of the raw material molecules do not have the time to react to become product."

- Those process characteristics explain how yield may decrease as production rate increases.
- The opposite effect is more common, but more complex.



Minimizing variable cost: not always a good idea

- It is easy to come up with scenarios where minimizing the variable costs does not give maximum total profit.

- Example: If raw material yield decreases as production rate increases then there will be a rate which gives maximum total profit.
  - Producing less than that gives less profit because volume is low
  - Producing more than that gives less profit because margin is low

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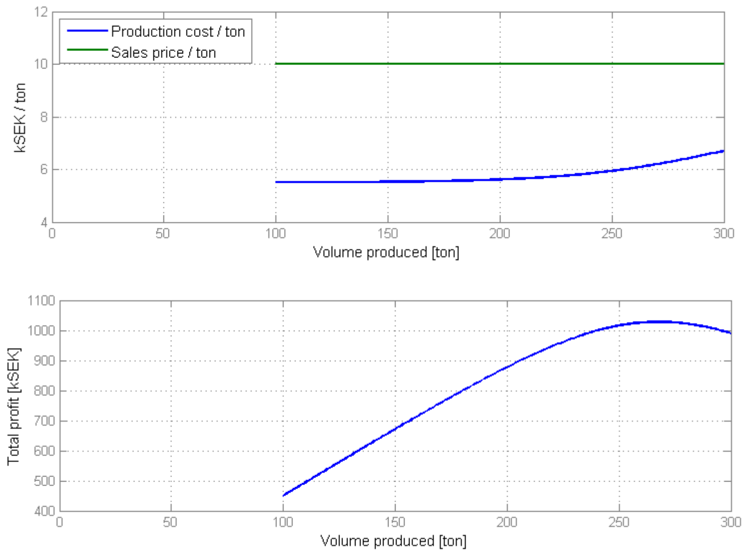
Example: Trade-off between yield and volume



Byproduct optimization vs yield

- It may be that we can control the formation on by-products by manipulating a variable that also affects yield or other cost parameters.
- By running the process in different ways we can get different proportions of by-products.
- Example: 100 tons of raw material we can produce either of the two below
  - Contribution margin product A = 4 kSEK/ton, CM product B = 20 kSEK/ton

Scenario 1

- 92 tons of product A
- 6 tons of product B
- Yield = 98%

Total profit = 92*4 + 6*20 = 488 kSEK

Scenario 2

- 86 tons of product A
- 11 tons of product B
- Yield = 97%

Total profit = 86*4 + 11*20 = 564 kSEK

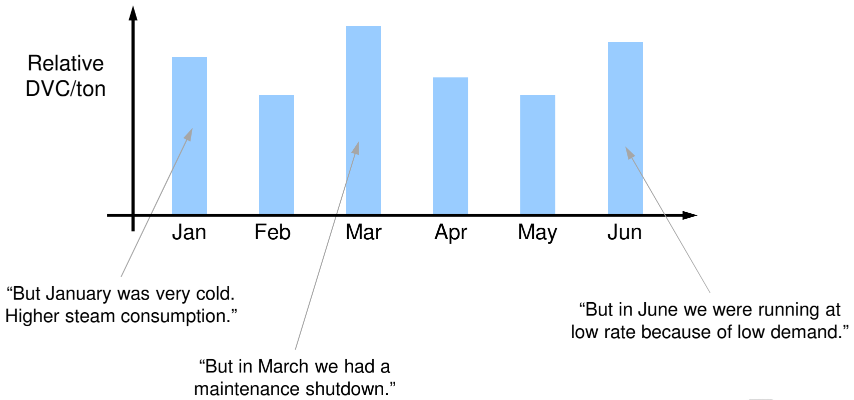
Again:
Minimizing variable costs may lead to suboptimal operation.

Additional complication: start-up costs

- Starting up a plant is often very expensive
  - Loss of raw material + Loss of energy
- It may make more sense to consider DVC/ton as a function of number of shutdowns rather than production rate.
- If market demand is not very high, this leads to and optimization problem:
  - The production cost per ton is higher at low rates
- Example: Assume plant capacity is 100 ton/day and we are asked to produce 2000 tons in January. What is best:
  - Producing 65 tons/day during 31 days?
  - Producing 100 tons/day during 20 days, and have 11 days of shutdown?
- Continuous plants normally have a turn down ratio (as mentioned previously).
  - "Minimum speed"

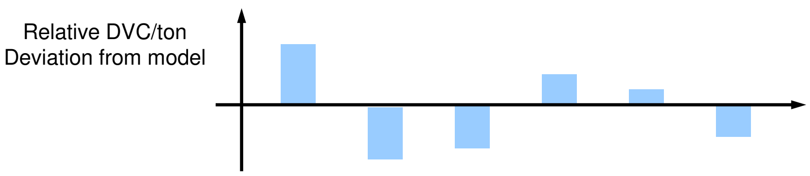
Trending DVC over time: not trivial

- A consequence of these considerations is that it is not easy to find which parameter to trend over time
  - How do we avoid ending up in discussions like this:



Possible solution: deviation from model

- One way to approach this problem: use a model that predicts DVC, and compare with the prediction.
  - The model should not take all known factors into account, only those that are not supposed to be addressed by the user of the KPI
  - E.g. if the user is supposed to improve reliability, then DVC increase due to unplanned shutdowns should not be included in the model.



Example of production related KPI

- Model based steam usage evaluation
- Intended user: operational staff (operators and process engineers)
- Scope: detect excessive steam usage in different units

- The target steam usage for each unit is given by a model.
- The model takes into account all variables that operational staff cannot affect, e.g. production rate and outdoor temperature.
- For every unit, current steam consumption is compared with the consumption predicted by the model.
  - Steam meters show current consumption and target in real time
  - Too high usage results in meter turning yellow or red

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Real-time steam consumption; benchmarking against target

Supports operators and engineers in daily work to minimize energy usage.

Theoretically challenging to define and calculate reasonable targets; regressor collinearity etc
black-box / grey-box modeling. MSc project 2013

Summary on DVC

- Variable costs are affected by yield and energy usage
- They often depend on production rate
- Normally, energy usage per ton of product decreases with production rate
- Start-ups are often very expensive

- There are many theoretical explanations to why the dependency may be positive or negative.
  - In the end you have to study real operational data and verify if the statistical correlations are significant.

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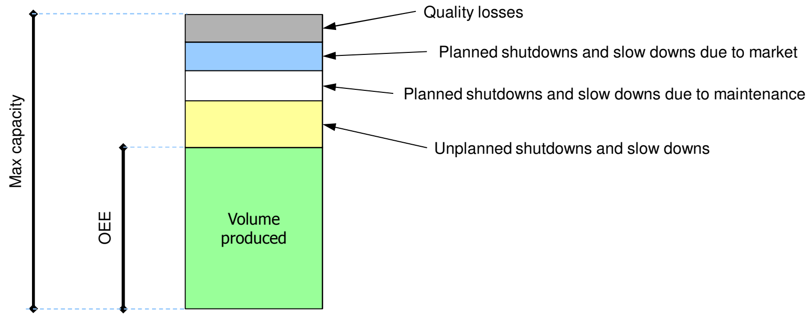
Key performance indicators

2. OEE

OEE = overall equipment efficiency

- A classical KPI that should indicate how efficiently a plant is used, and to some extent the causes of unexploited potential.
- Traditional definition: OEE is a number between 0% and 100%
  - Obtained by subtracting shutdown losses, quality losses and planned unused capacity due to market situation.
  - Unfortunately there are different interpretations of this KPI.



Usage of OEE

- OEE is of course a very coarse measure, but it can help us to see where to focus improvement efforts:

- Improved reliability when running?
- Shorter maintenance shutdowns?
- Improved quality?

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OEE-related KPIs used at Perstorp

- In the production portal described earlier we have
- "Max capacity" is estimated as best ever seven day running average
- "Planned production" manually entered by supply chain
  - Plan can be changed, even retroactively, to cater for external disturbances, e.g. power outages and delays in raw material supply. [Why?]

- Utilization: volume produced as percentage of theoretical max capacity
- Loss versus Plan (LvP): Negative deviation from plan, accumulated
  - Only negative deviations are counted. See next slide.

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Crux: What is an "unplanned" shutdown?

- Two extreme cases:
  - **Regular maintenance shutdown**: planned months or years ahead. Typically lasts for two weeks or more
  - **Immediate, out-of-the-blue**, shutdown: with only minutes or seconds head warning. E.g. power outage, faulty trips, human error

- But many shutdowns are somewhere in between:
  - "The pump sounds strange and needs to be repaired within a week". Check the list of pending maintenance work requiring shutdown, and try to plan the shutdown timing and duration, so as to optimize this.
  - Example: "Fixing the pump only takes 6 hours, but if we have a 12 hour shutdown and fix some other stuff as well, we can postpone the next planned shutdown and get better availability next month".

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Consequence of complex plant topologies

- It is almost impossible to tell only from DCS data what is the cause of a shutdown or reduced production rate.
- If many adjoining units are reduced, it is not necessarily the first one in time that is the root cause.

- Unfortunately, the cause for a slowdown or shutdown is rarely visible in the process data:
  - Leakage
  - Rotating equipment problems, e.g. bearings
  - Human factor
  - Lack of capacity in site wide utilities, such as steam, cooling water, waste water treatment
  - External causes: Disturbances in distribution, supplies

Standards?

ISO TC 184/SC 5 N 1143
Date: 2011-08-31
ISO/WD 22400-2
ISO TC 184/SC 5/WG 9 / **N14**
Secretariat: ANSI

Manufacturing operations management — Key performance indicators — Part 2: Definitions and descriptions of KPIs

- There are production KPI standards down to very specific detail for manufacturing industry. But many of those are hard or impossible to carry over to continuous processing. Examples:
  - A continuous plant has a turn-down rate: it has a lowest possible production rate, typically around 60-70% of maximum
  - Variable cost (SEK/ton) for product depends on production rate
  - Start up time and start up costs may be substantial (MSEK, days)
  - A processing unit is typically not “on” or “off”. It is fed with a continuous valued flow.
  - “Off-spec” is not binary. A product not meeting spec may be acceptable by some customers, or possible to sell at a lower price.

Summary

- Production KPIs must be defined so that it is clear how they should be used, and by whom.
  - Should they be used to optimize long term planning, short term planning, plant settings or for fault detection?
  - Corresponding users: global production planning, local production planning, production management, process engineers
- Frequently it takes deep process understanding to define relevant KPIs.
- The definitions may vary from plant to plant.

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