Guidelines for energy efficient drive trains

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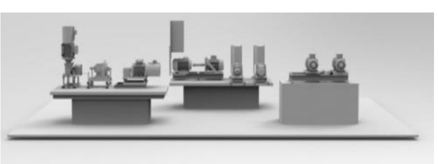
IWT Tetra project nr. 130201



UNIVERSITEIT GENT
CAMPUS KORTRIJK

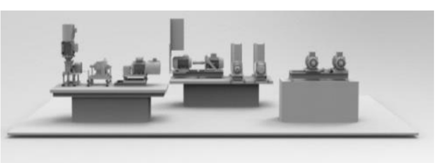
Studienamiddag 17.12.15

Efficiëntieverhoging Elektromechanische Aandrijvingen

IWT

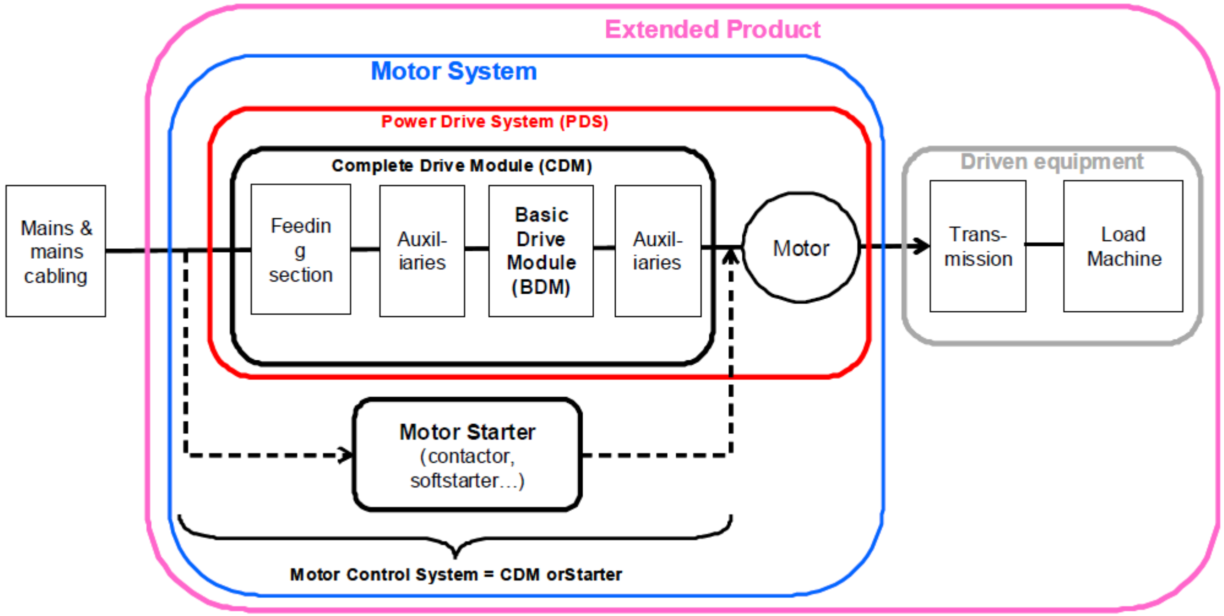
Agenda

- Introduction
- Electrical machines
    - Technology
    - Measurement results
- Transmissions
    - Gearboxes
    - Belts
- Load
    - Fan efficiency
    - Regulation

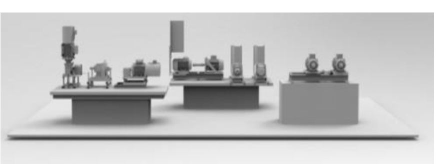


Introduction

- Efficiency of <u>complete</u> drive train is important



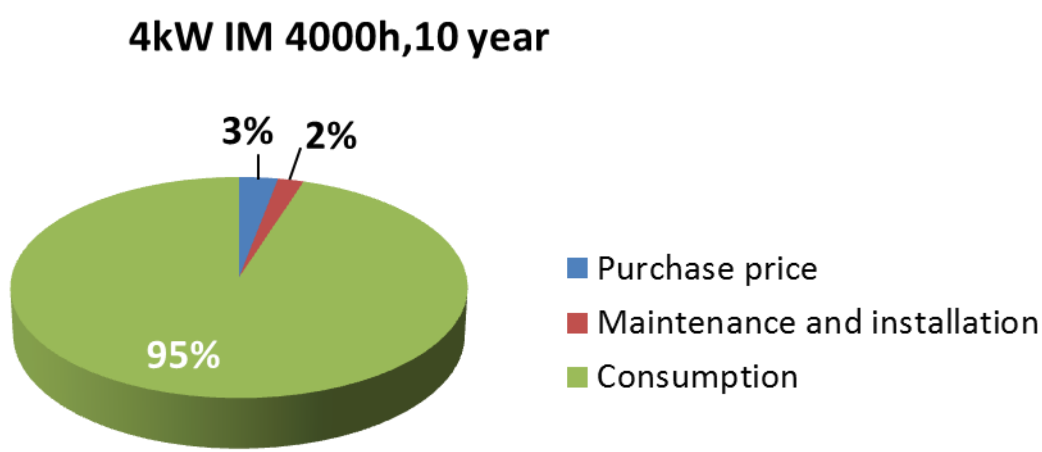
- This presentation: drive, motor and transmission are addressed one by one



Introduction

Why is efficiency improvement important?

- Economical savings→ less consumption = more profit
  - Electrical consumption is largest cost in a drive train



Introduction

Why is efficiency improvement important?

- 20-20-20 goals Europe push industry
- Eco-design directives in Europe aim at 366 TWh annual savings by 2020
  - Electric motors > 40% (135TWh)
  - Industrial fans : 10% (34TWh)
- How much from global electrical consumption is for motors?

Table 1

The first 13 measures (more are planned) = annual savings by 2020 equivalent to more than 12% of the electricity consumption of the EU in 2009

Ecodesign Measure	Adoption	Estimated annual savings by 2020
Standby	December 2008	35 TWh
Simple set top boxes	February 2009	6 TWh
Street & Office Lighting	March 2009	38 TWh
Domestic Lighting	March 2009	39 TWh
External power supplies	April 2009	9 TWh
Electric motors	July 2009	135 TWh
Circulators	July 2009	23TWh
Domestic refrigerators	July 2009	4 TWh
Televisions	July 2009	28 TWh
Domestic dishwashers	November 2010	2 TWh
Domestic washing machines	November 2010	1.5 TWh
Fans	March 2011	34 TWh
Air conditioners and comfort fans	March 2012	11 TWh
Total		**366 TWh**

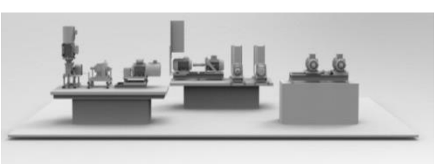
Source : http://ec.europa.eu/enterprise/ecodesign

Introduction

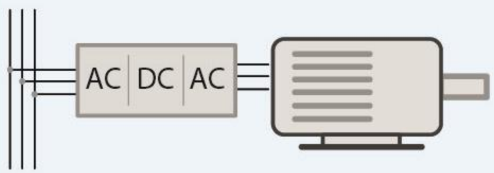
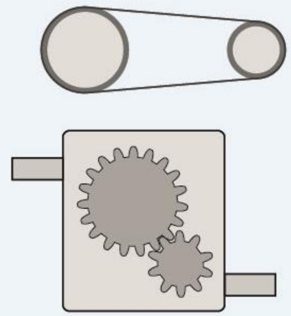
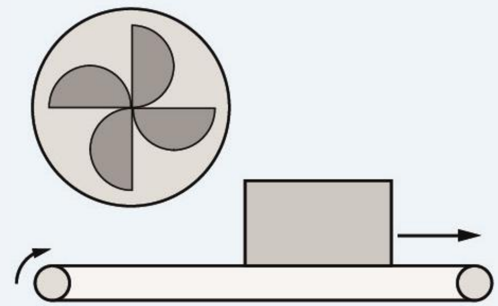
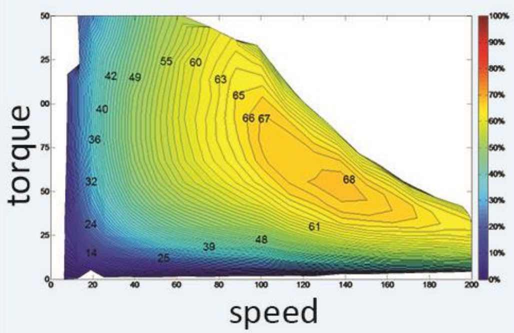
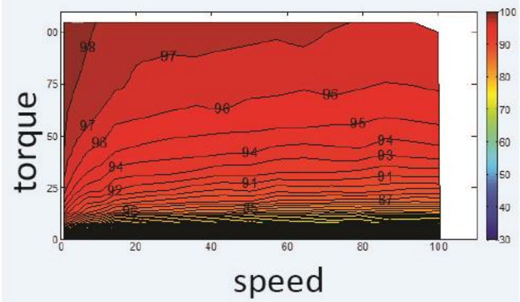
- Standard evolution: focus on total product → system efficiency
  - Circulator pumps
    - EC No 641/2009 & EC No 622/2012
  - Air conditioning and comfort fans
    - EC No 206/2012
  - Industrial fans
    - EC No 327/2011

- Problem statement
  - Need for efficiency information of every part in the drive train
    - Motor and transmission catalogs show limited efficiency values
    - Are the efficiency's reliable?
    - What happens when VSD is used?
    - What when over-dimensioning is necessary?

  - New technologies → how do they perform?



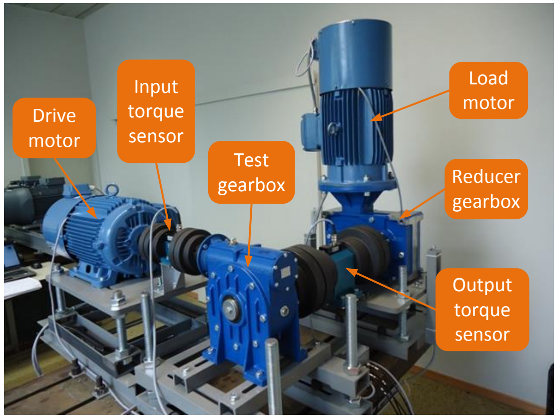
Introduction

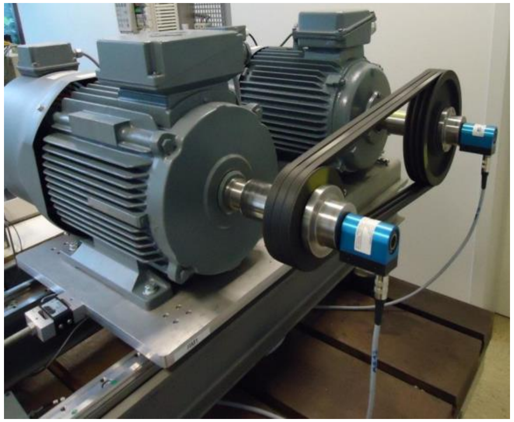
DRIVE & ELECTRIC MOTOR	TRANSMISSION (BELT & GEARBOX)	LOAD
		
2009 - 2011	2012 - 2013	2014 - 2015
		

Introduction

Approach:

- By several research projects all parts of a drive train where investigated
  - Three test benches where designed to test drive trains
    - A lot of efficiency information → iso efficiency maps





  - Practical cases to show efficiency improvements

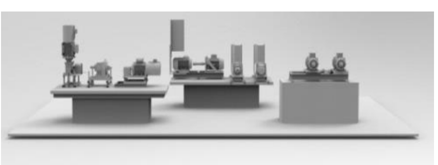
Electrical machines

Electrical machines

Overview - availability high efficiency motors?

- Standard motor in industry: Induction Motor
- Formerly PMM were uses as servo motors, now also as IM replacer version
- New technology: Synchronous reluctance motors
- DC motors: still used in industry, efficiency?

	Induction motor (IM)	Permanent magnet motor (PMM)	Sync. reluctance motor (SynRM)	Direct current machines (DC)
Max efficiency level	IE4	IE4/IE5	IE4	IE2?
Drive necessary?	NO	Mostly	YES	YES

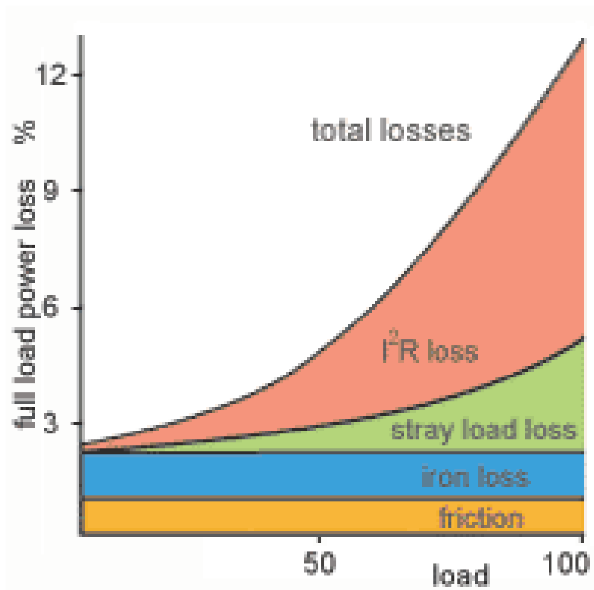


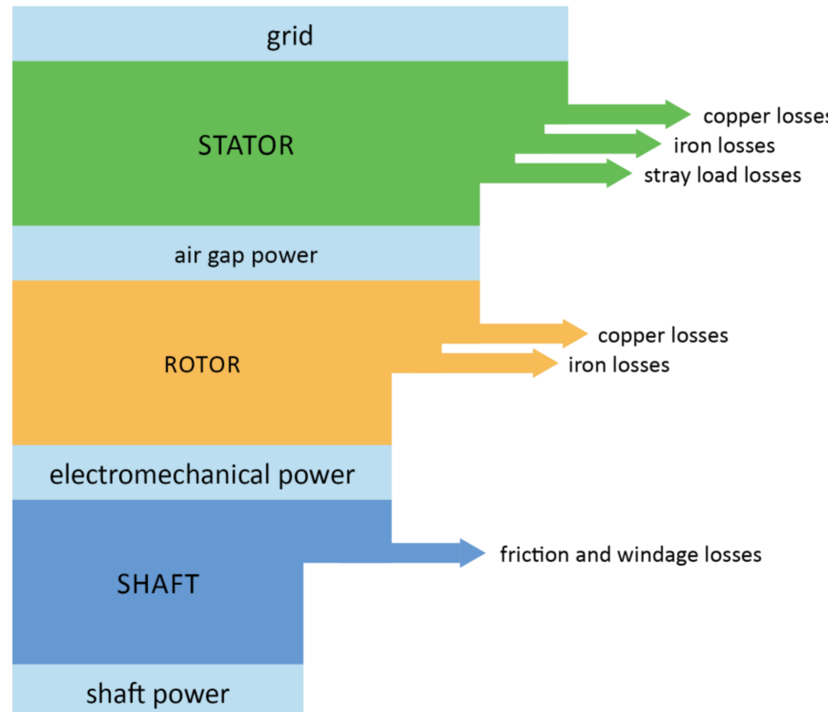
Electrical machines - IM

Technology

- Magnetic rotating field induces current in rotor, which produces torque
- Known and proven technology

Losses

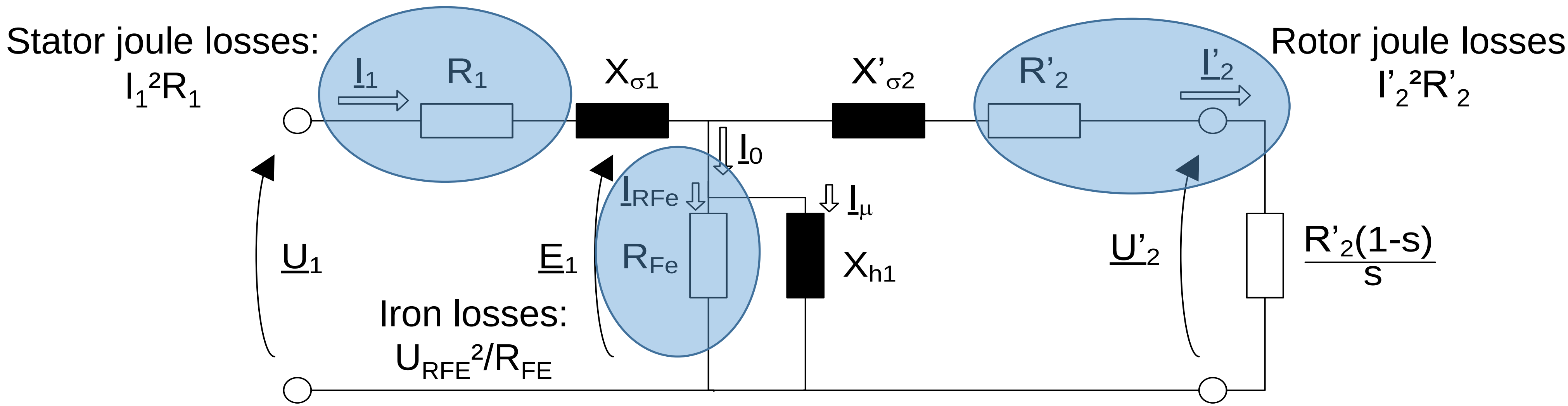




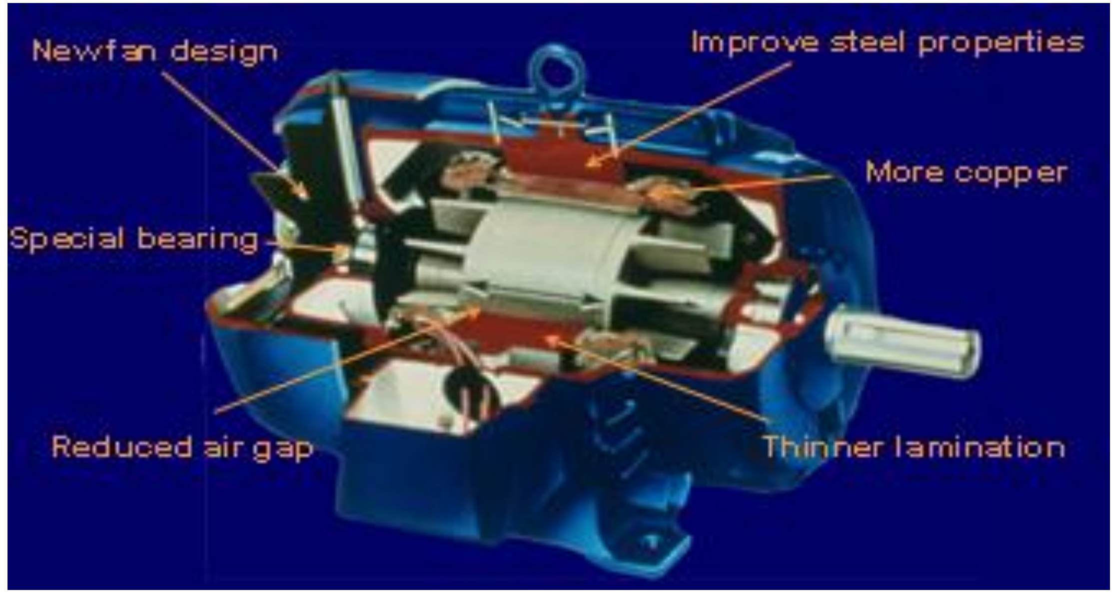
Electrical machines - IM

Efficiency improvements

- Larger cross section windings: R_1 ↘
- Copper rotor instead of aluminium: R_2 ↘
- More and better magnetic material: R_{FE} ↗



Electrical machines - IM

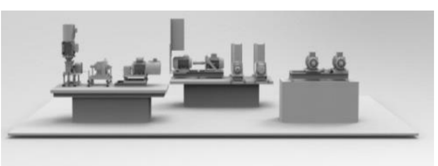


Efficiency improvements

- Smaller air gap
- High efficiency bearings
- Smaller fan
- Overall optimized design

Results

- IM are able to reach IE4 efficiency level
  - Limits reached? Probably yes
- What is effect on other motor specs?



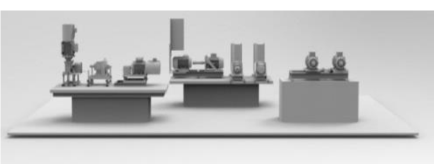
Electrical machines - IM

Impact on motor parameters

- Rated motor speed n_n
  - Reduced rotor cage resistance results in reduced slip
  - DOL:
    - Pumps and ventilators!!
  - VSD:
    - No impact, speed is controlled
- Other frame size?
  - Normally not
- Start current I_{start}
  - DOL
    - Small increase
  - VSD:
    - No problem, is controlled
- Starting torque ?
  - Needs to fulfill standards
  - Not important for VSD operation

4 kW 230/400V, 1500 rpm, 112M		
	IE1	**IE3**
T_n	26,5 Nm	26,4 Nm
n_n	1440 rpm	1450 rpm
I_n	8 A	8 A
I_{start}/I_n	6,2	7
T_{kip}/T_n	210%	230%
T_{start}/T_n	250%	310%
Inertia J	0,0147 kgm²	0,0187 kgm²
Cos φ	0,83	0,81
η	84,5	89,1

250 kW 230/400V, 1500 rpm, 315L		
	IE1	**IE3**
T_n	1603 Nm	1603 Nm
n_n	1490 rpm	1490 rpm
I_n	443 A	433 A
I_{start}/I_n	7.8	8
T_{kip}/T_n	270%	270%
T_{start}/T_n	250%	260%
Inertia J	8,120 kgm²	8,388 kgm²
Cos φ	0,86	0,86
η	94,8	96,6



Electrical machines - IM

Impact on motor parameters

- Rotor inertia J
  - Increases!
  - Increased starting time, Adjust motor protection settings
  - Both DOL and VSD
- Cos φ
  - Lower for high efficiency motor
- Weight
  - Higher efficiency → more material
- Price (related to 11kW)
  - IE2: 85%
  - IE3: 100%
  - IE4: 125%

4 kW 230/400V, 1500 rpm, 112M		
	IE1	IE3
T_n	26,5 Nm	26,4 Nm
n_n	1440 rpm	26,4 Nm
I_n	8 A	8 A
I_{start}/I_n	6,2	7
T_{kip}/T_n	210%	230%
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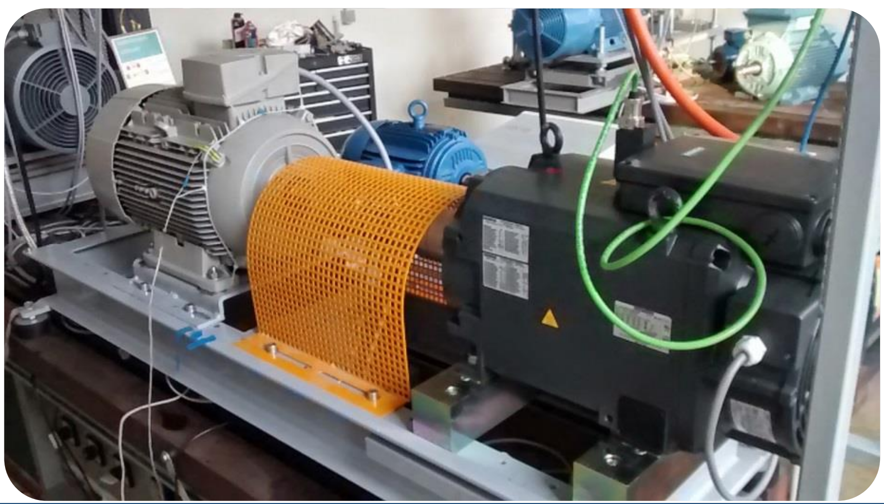
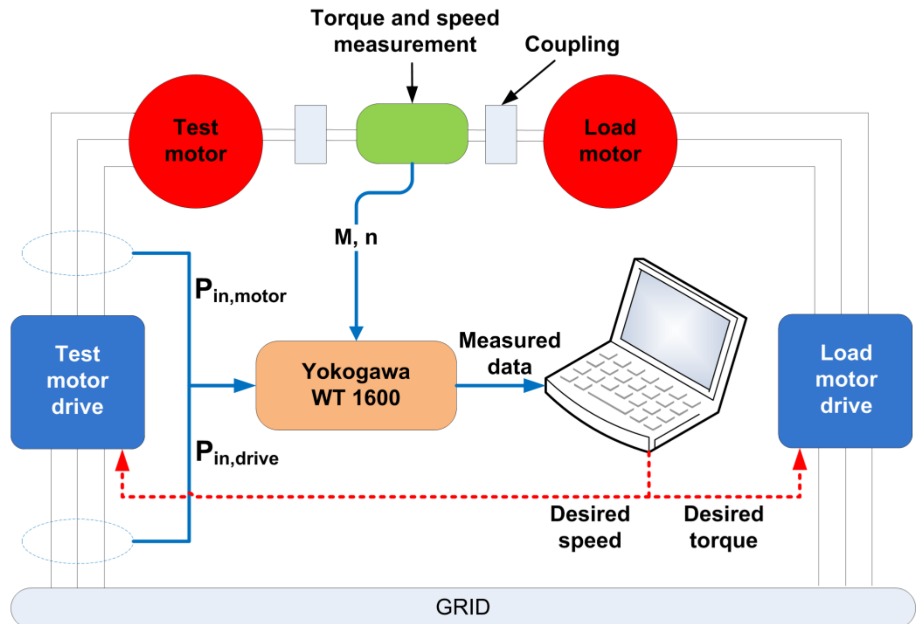
Electrical machines - IM

What happens with efficiency in part load operation?

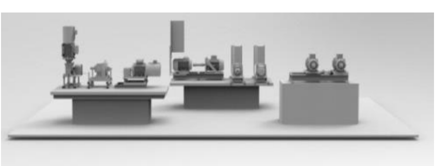
Test bench specs:

- 22kW / 15000rpm
- Total accuracy up to 1%
- Random load profiles



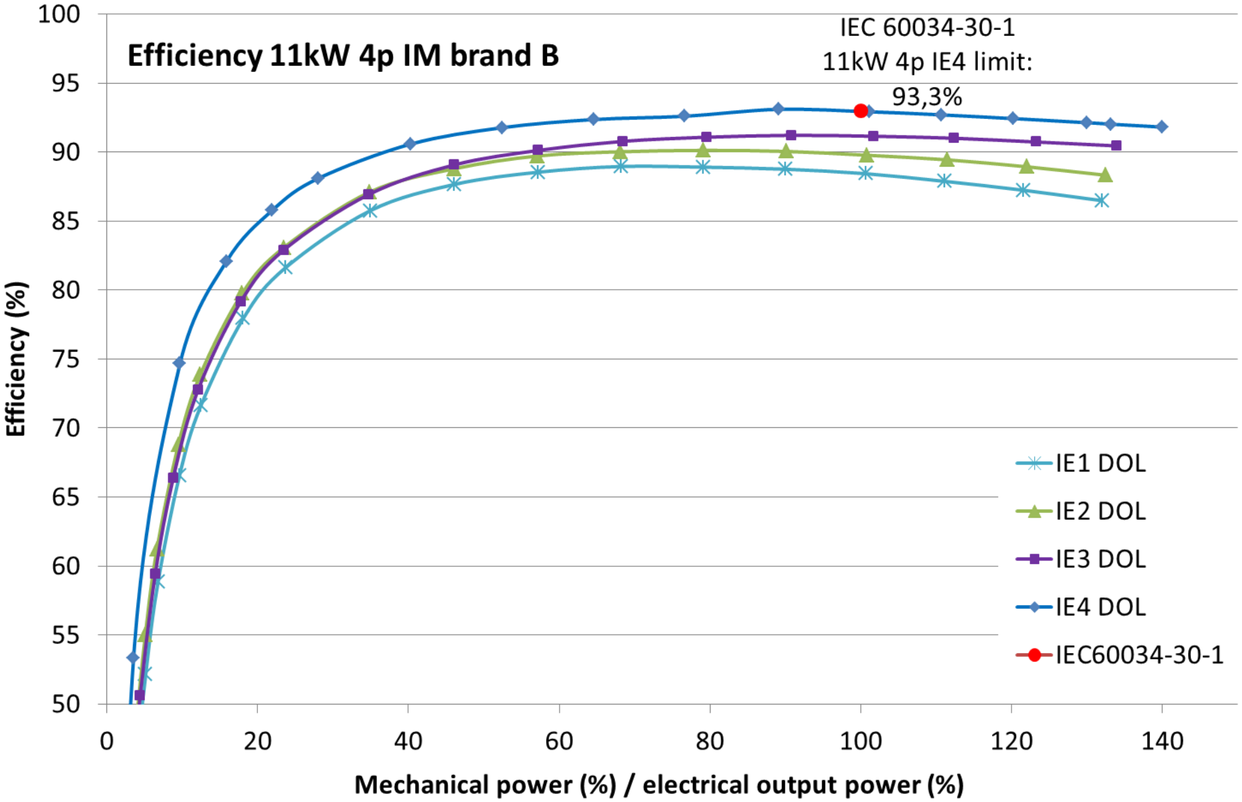


- Measure VSD, Motor and Total efficiency
- Motor and generator tests



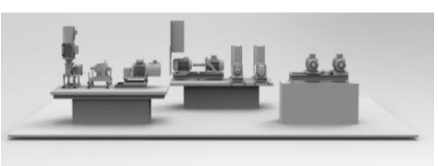
Electrical machines – IM – test results

Impact on motor efficiency



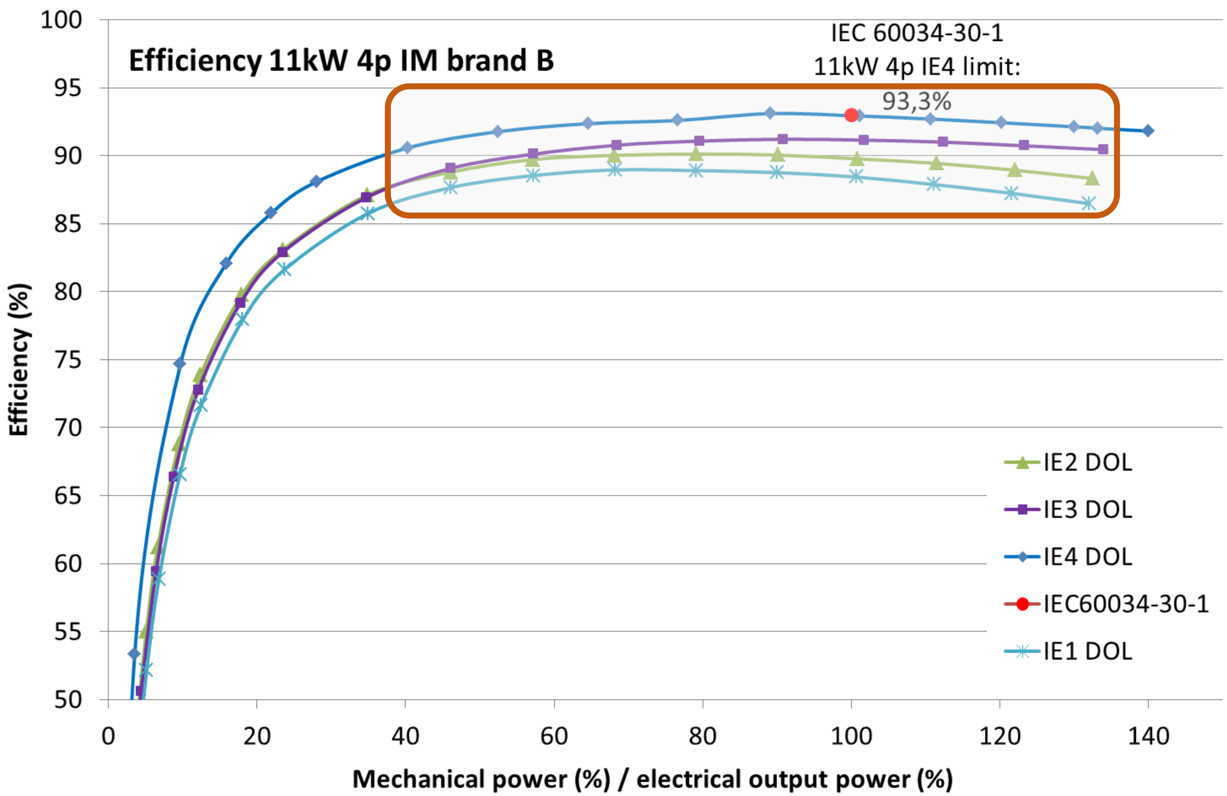
DOL efficiency

- Efficiency at nominal load rises following the IE index
- IE4 efficiency is higher in every torque load point



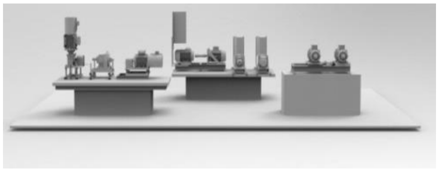
Electrical machines – IM – test results

Impact on motor efficiency



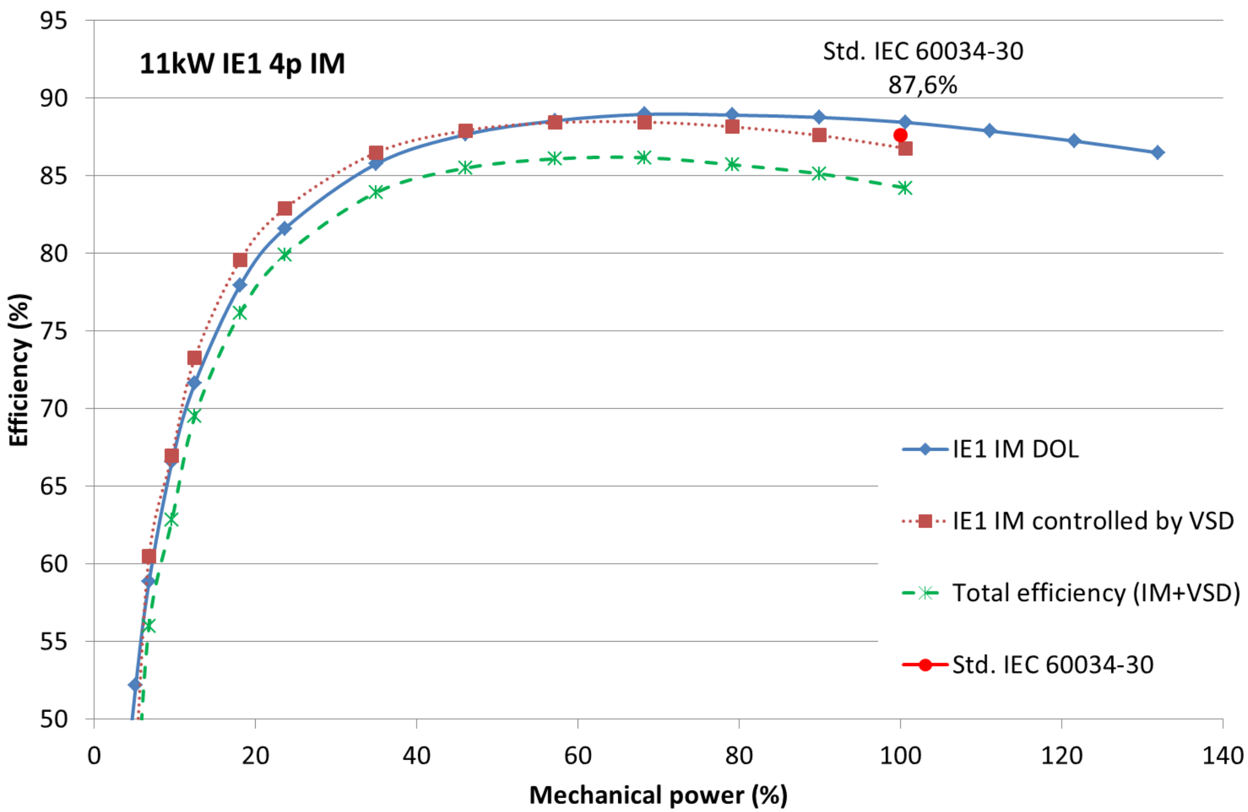
DOL efficiency

- High efficiency from 40% to 120% load
- Wide scope to use motor



Electrical machines – IM – test results

What happens when VSD controls IM?

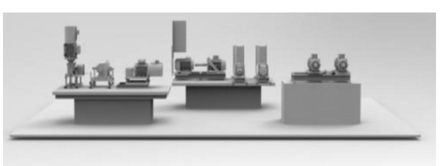


Motor efficiency with VSD

- @ part load
  - equal or higher efficiency
  - due to control strategy
- @ 100% load:
  - lower efficiency
  - due to harmonic currents (derating)

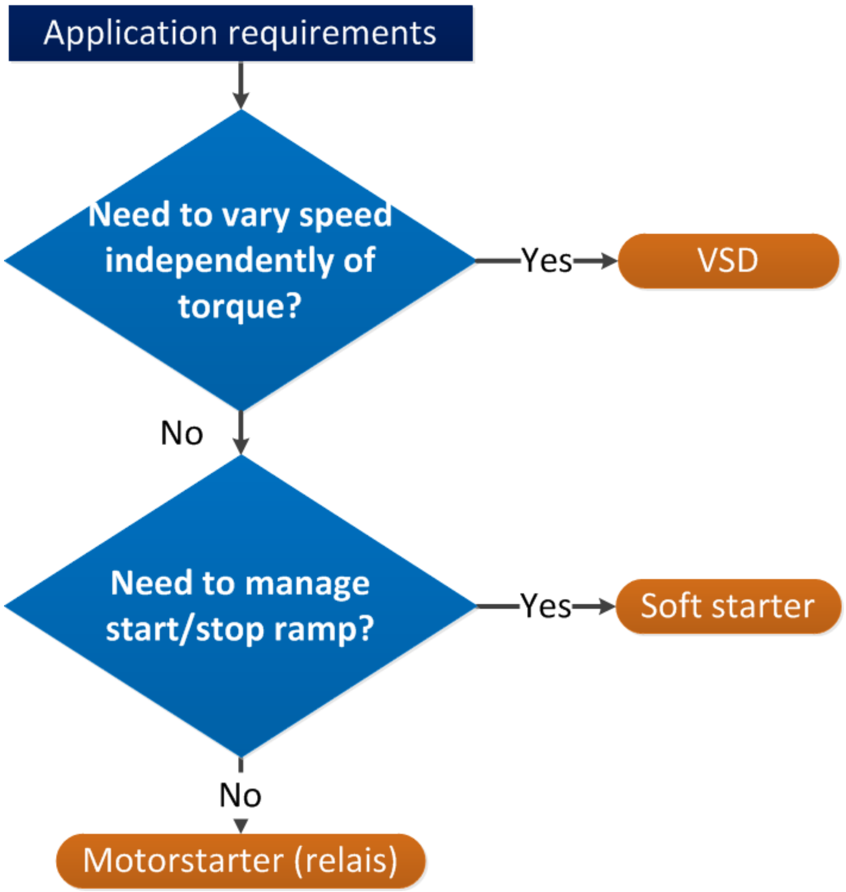
Total efficiency?

- Fact: total efficiency ±3% lower for each load



Electrical machines – IM

General decision flow chart for an energy efficient drive train

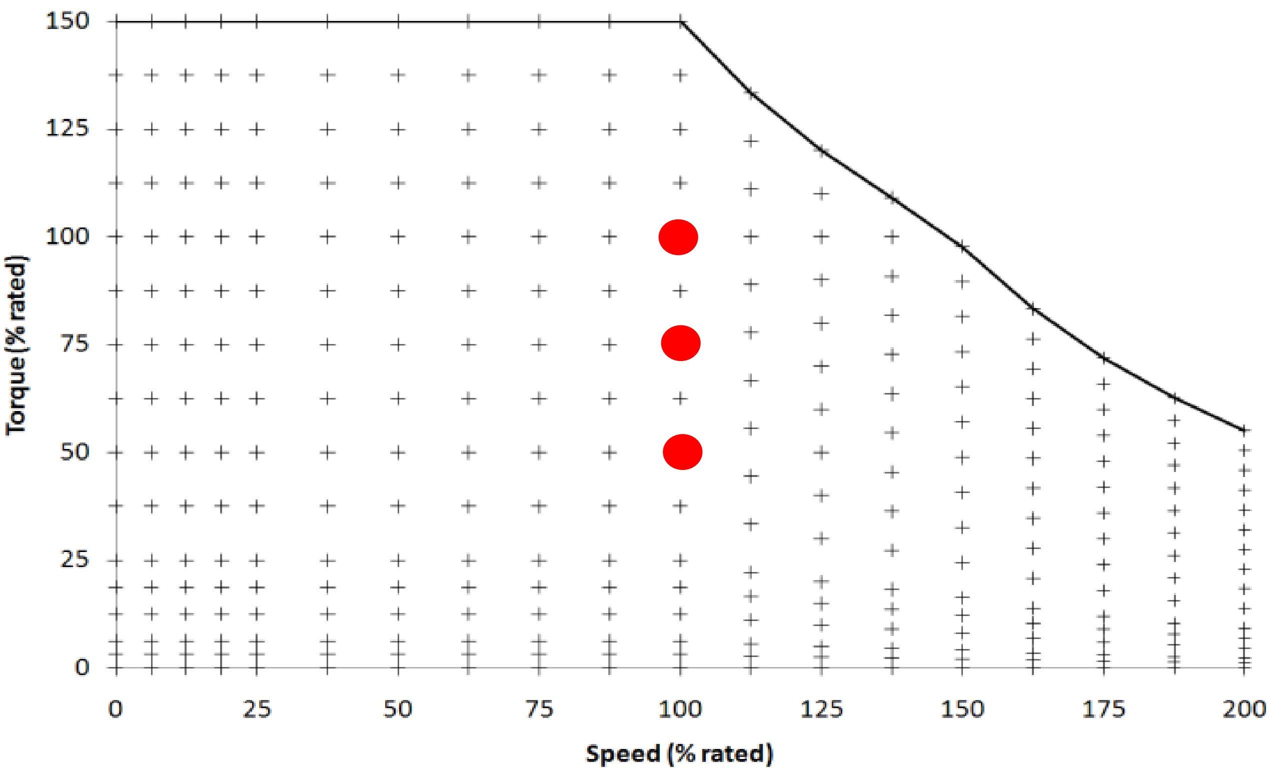


- Assess the need for varying the speed
  - (not the load)
- Avoid oversizing

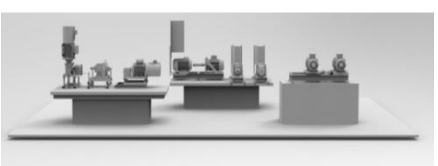
Electrical machines – IM

What happens with efficiency in entire working area?

- In catalogues only efficiency data for DOL machines @ 50, 75 and 100% load



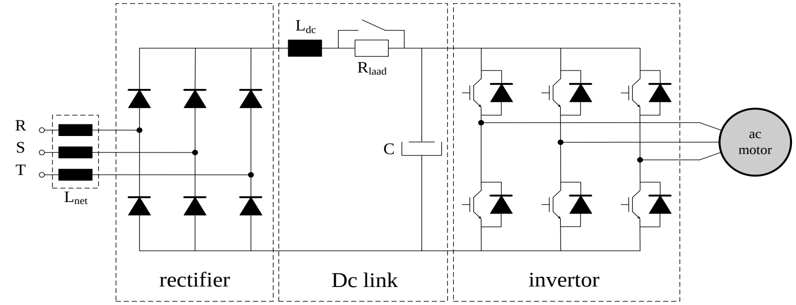
- Measurement matrix to determine efficiency with accuracy up to 1%
- 200% speed
- 150% torque
- Visualization with efficiency maps

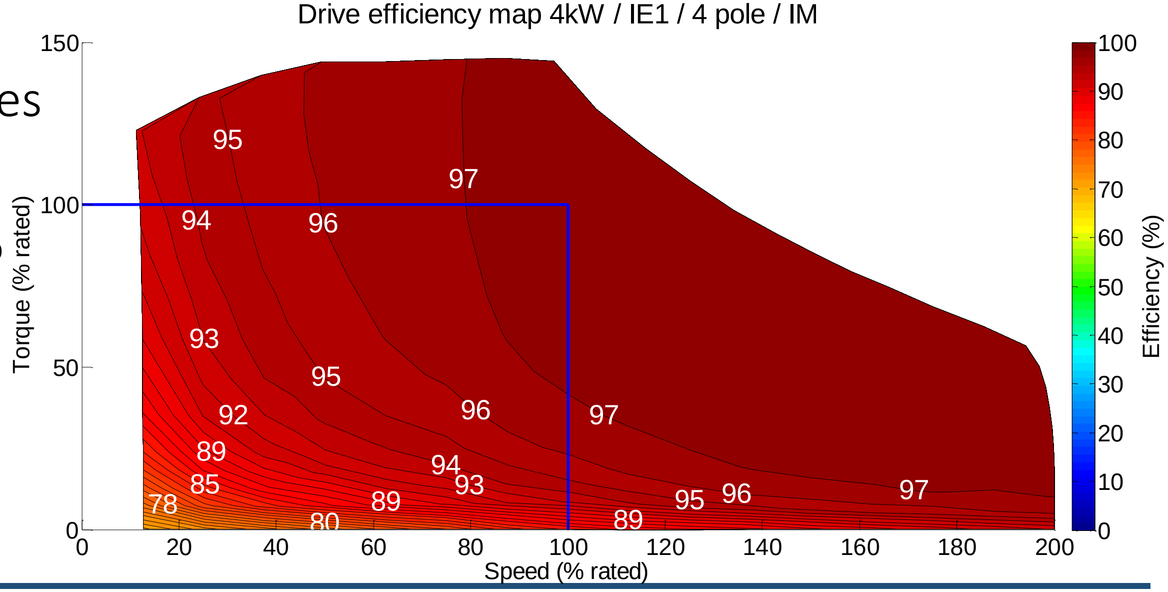


Electrical machines – IM – test results

What happens with VSD efficiency in entire working area?

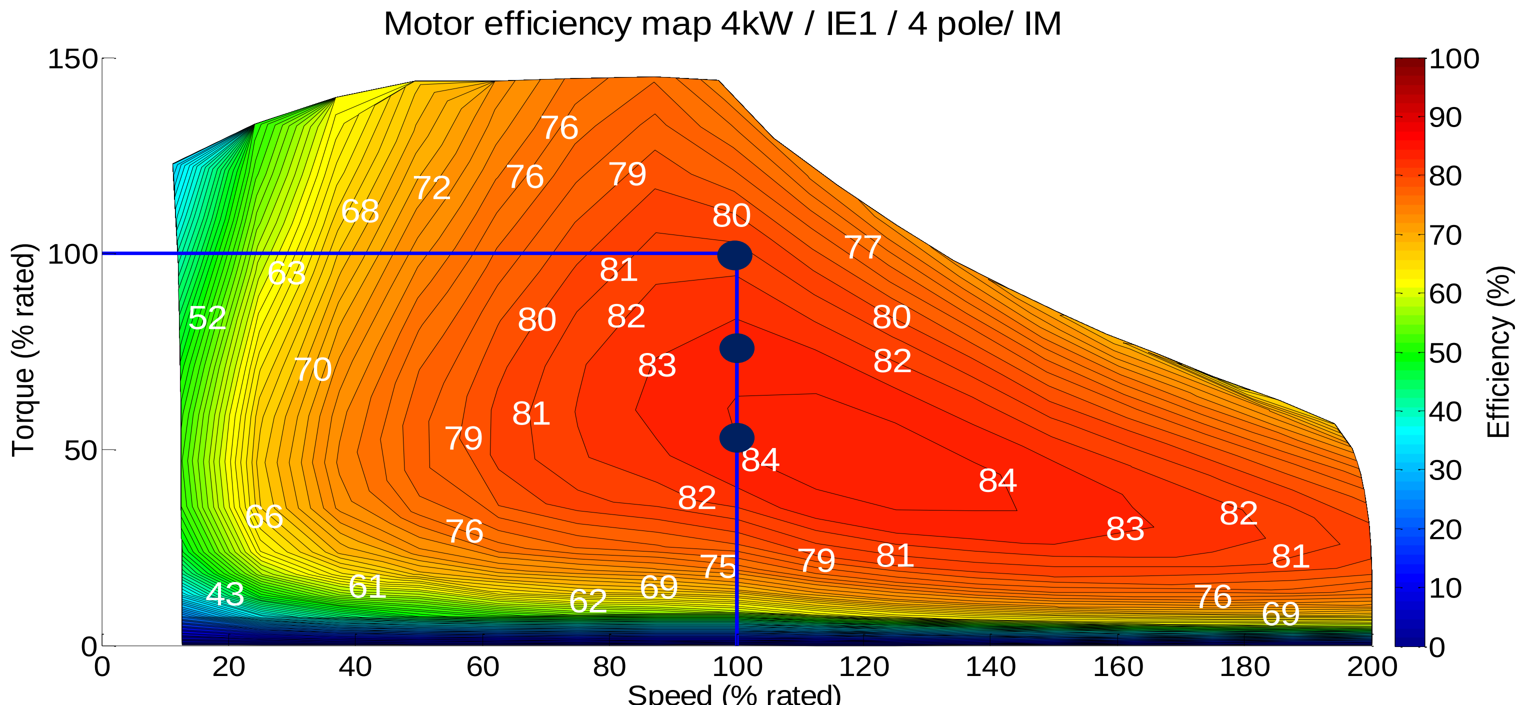
- Variable Speed Drives consists of:
  - Rectifier diodes
  - Dc link capacitor
  - Invertor IGBT’s
- Efficiency values up to 97% à 98%
- Comparable values for all tested drives
  - Within testing range
- 4Q drives efficiency up to 96% à 97%
  - Due to IGBT’s and coils in rectifier





Electrical machines – IM – test results

What happens with motor efficiency in entire working area?

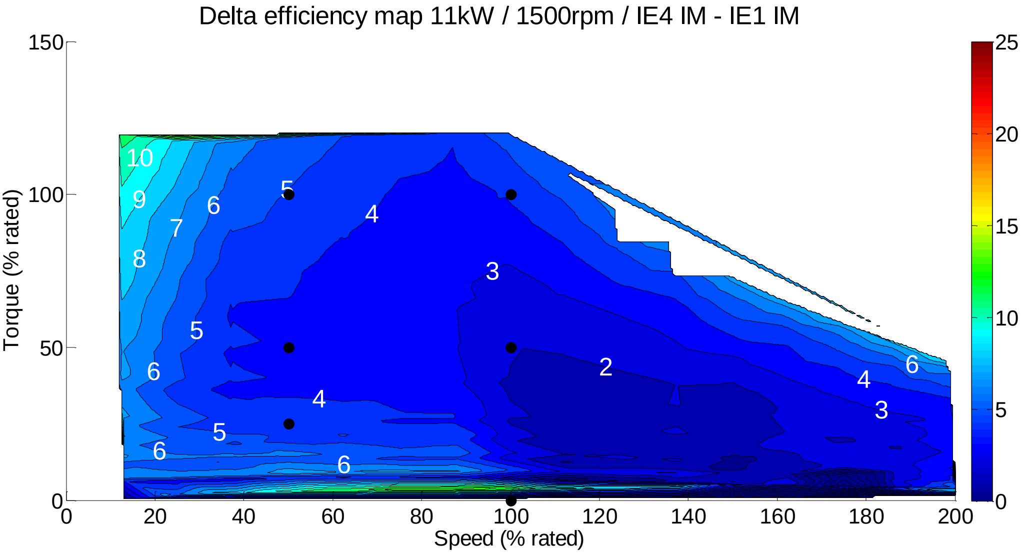


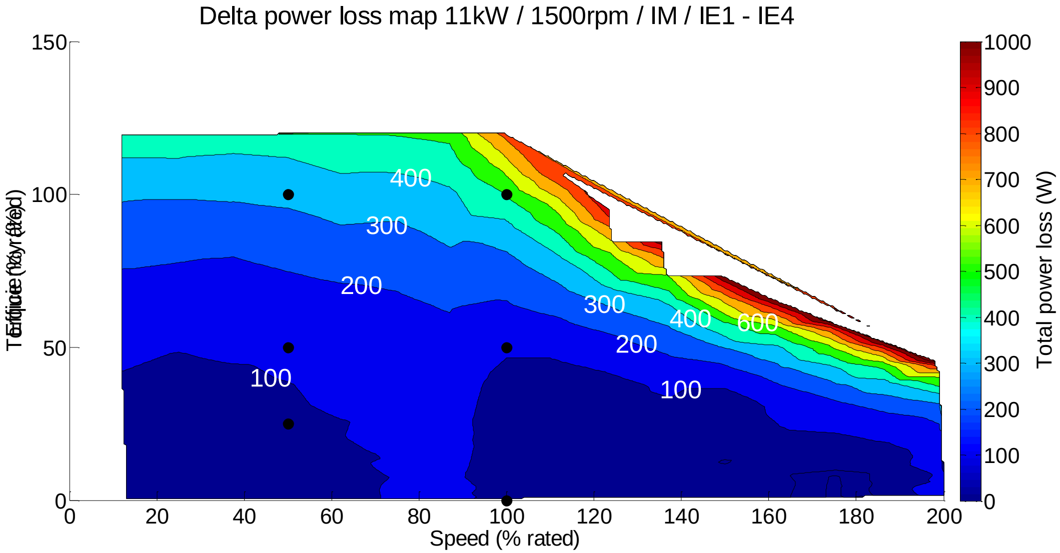
- Efficiency is torque and speed dependent
- Highest efficiency in field weakening area (120% speed, 50-70% load)
  - Typical for all tested induction machines

Electrical machines – IM – test results

What happens with efficiency in entire working area IE1 vs. IE4?

IE1 IM versus IE4 IM



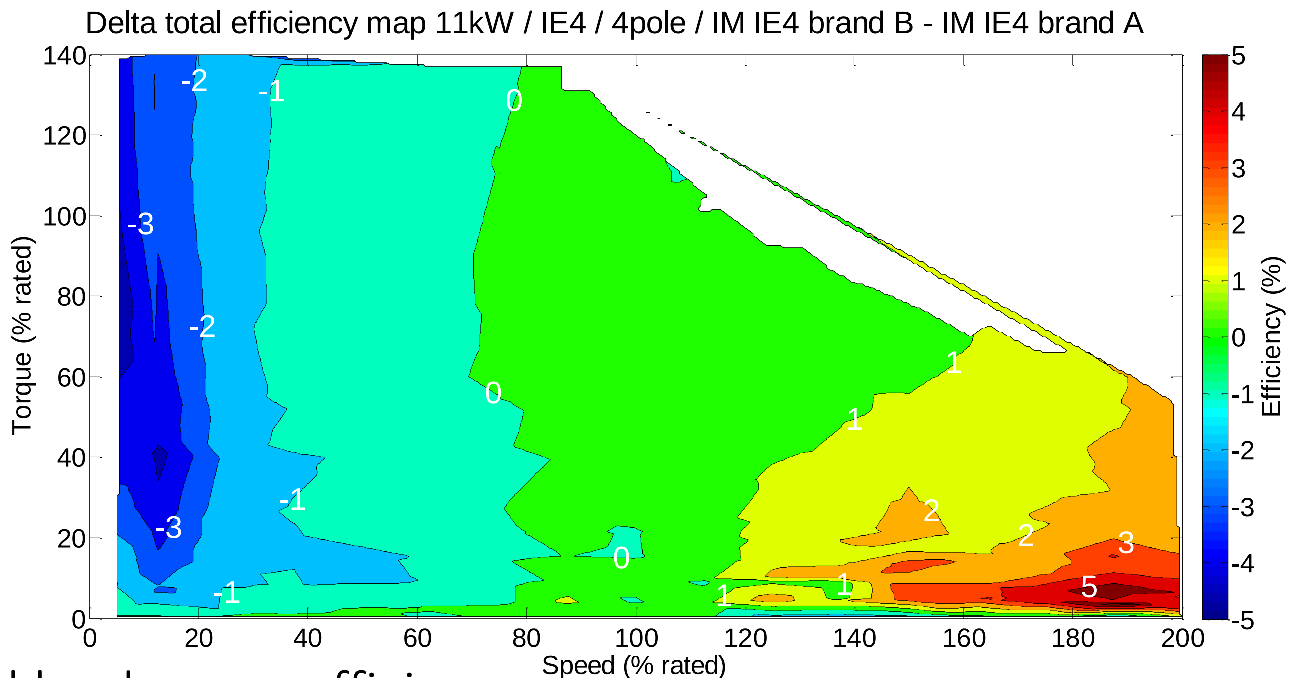


- IE4 IM higher efficiency in entire working area (2% - 10%)
  - Here smaller difference in part load
- @ full load ±500W less losses for IE4 IM
  - Part load: difference in Watt gets smaller

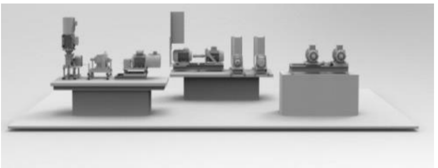
Electrical machines – IM – test results

What happens with efficiency and different brands?

IE4 IM brand B versus brand A



- @nominal load: same efficiency
- Varying efficiency difference in part load → positive and negative!

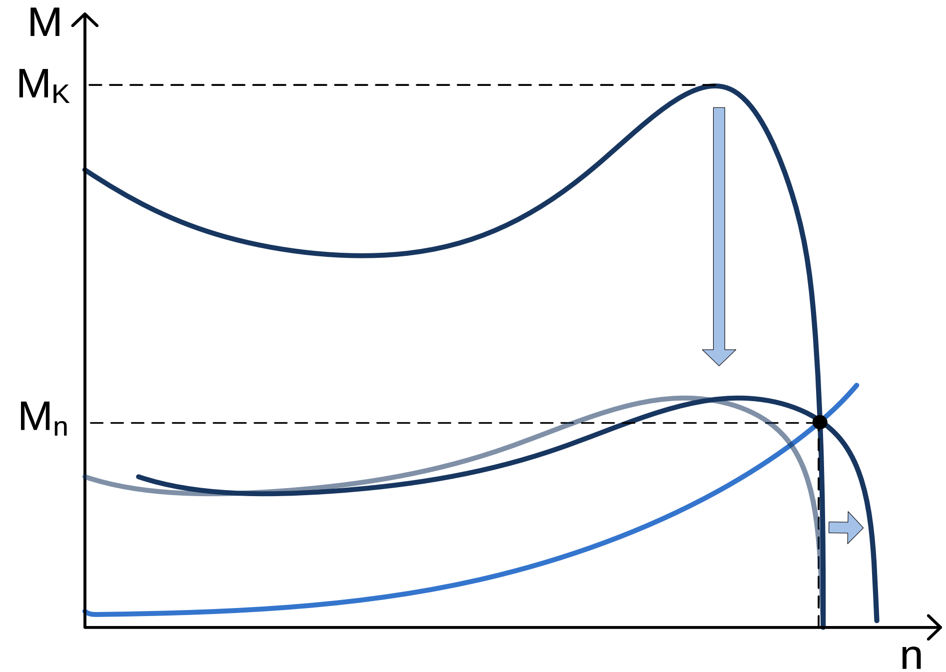


Electrical machines – IM

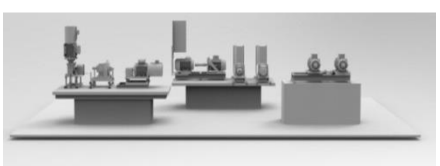
What happens with efficiency when changing VSD parameters?

Flux optimization

- Normally: U/f relation kept constant
    - Purpose: nominal torque in entire working area
- Flux optimization: lowering U
    - Advantage: U drops = less iron and joule losses
    - Disadvantage : no dynamical torque response (200 à 300ms)
- Standard parameter setting in nowadays VSD's

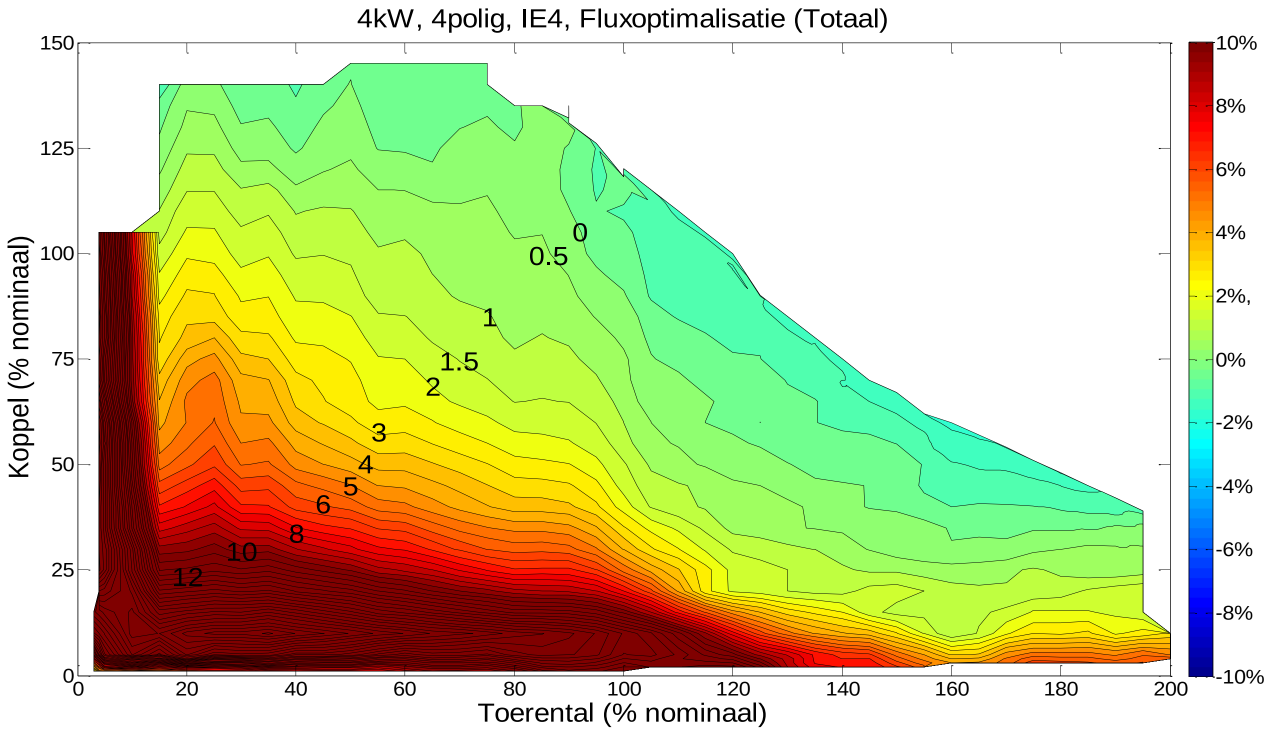


$$T_{max} \sim \frac{U}{f} \sim \phi$$



Electrical machines – IM – test results

What happens with efficiency when changing VSD parameters?



Nominal torque

- No difference
- Logical, because here nominal torque needed so nominal voltage needed

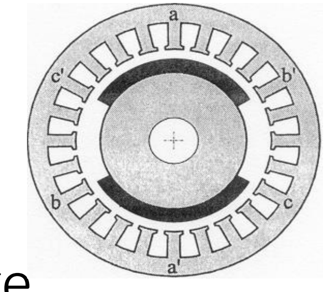
Part load

- Efficiency rise up to 15%
- Difference in Watt smaller

Remark

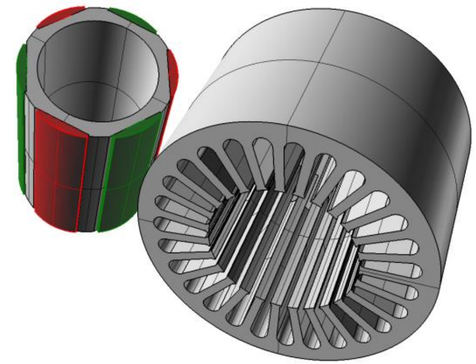
- Efficiency gain dependent of drive control strategy
- Do not use with large load variations

Electrical machines – PMM



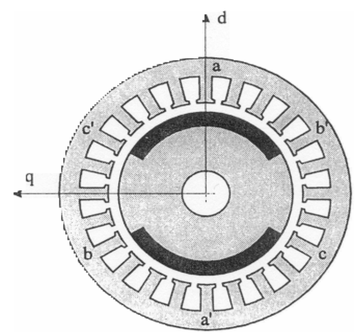
Technology

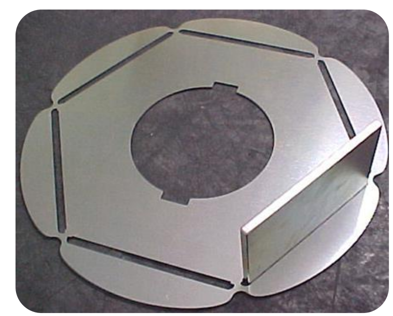
- High density rare earth magnets on rotor take care of magnetization
- Surface mounted or interior magnets
- Not only as 'servo performance' motor but also as IM replacer



Losses

- No rotor currents
- Reduced stator currents
- Reduced iron losses
- Less cooling required





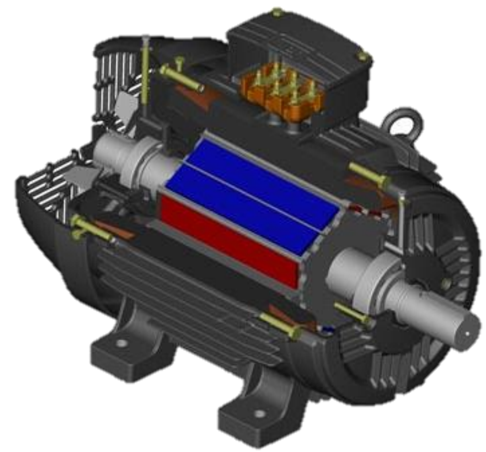
Electrical machines – PMM

Advantages

- Low losses → high efficiency up to IE4 and IE5 level
- Sometimes smaller size

Disadvantages

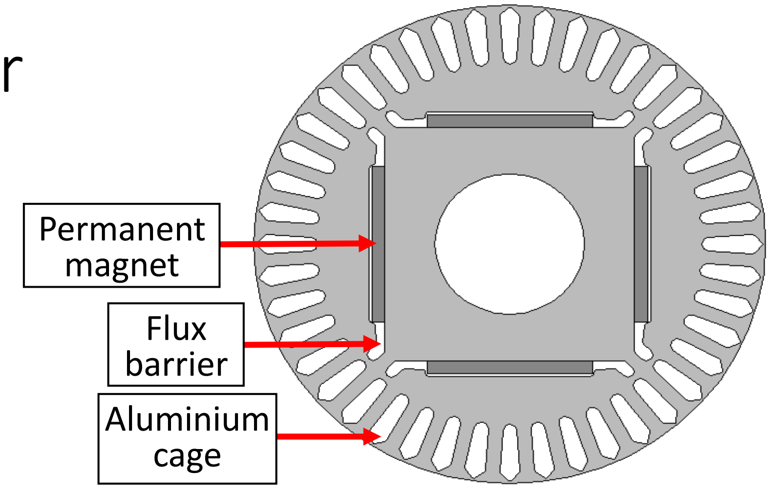
- Expensive magnets
- Customized maintenance
- Over temperature → demagnetization
- Drive required (solution: LSPM)



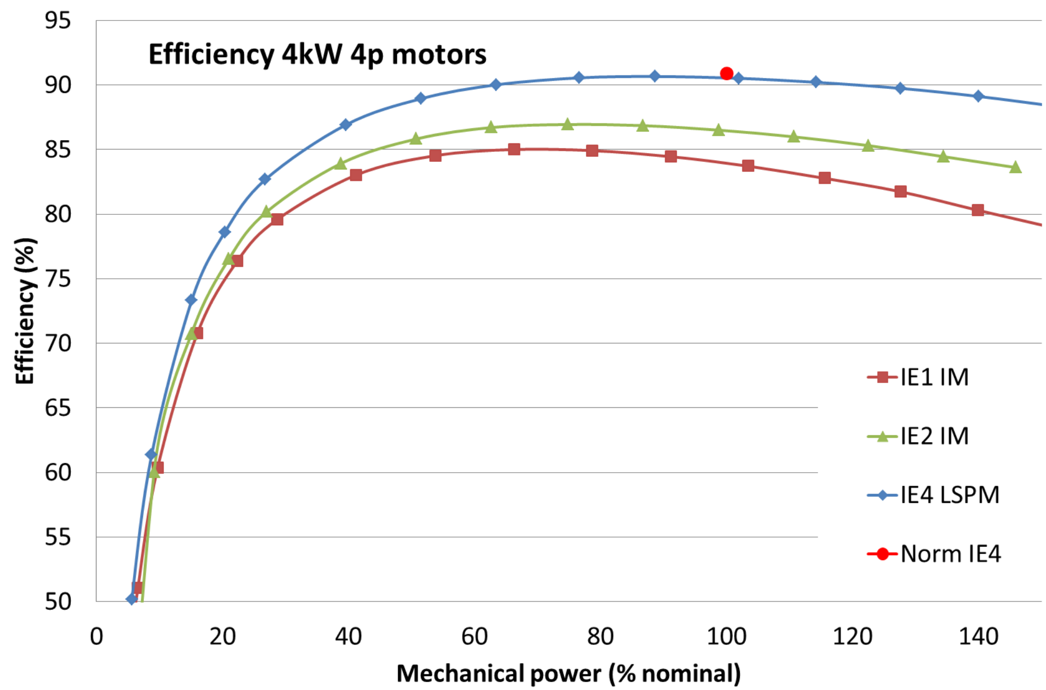
Electrical machines – LSPMM – test results

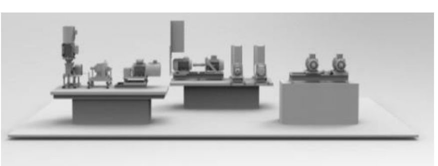
Line Start Permanent Magnet motor

- Combination of IM and PMM
- Starts as IM → then PMM
- IE4 efficiency level



- Be careful when replacing!
  - LSPMM runs at synchronous speed
  - How much rises the power of a fan application when the speed rises from 1442rpm to 1500rpm (+4%)?



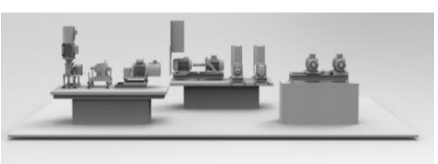


Electrical machines – PMM

Impact on motor parameters

		IE4 IM br. B	IE4 PMM br. B	IE5 PMM br. B
Frame		160M	132S	160M
Weight	[kg]	143	82	117
Inertia	[kgm²]	0,154	0,054	
T_{nom}	[Nm]	71,3	70,1	71,4
I_{nom}	[A]	21,0	18,5	18,7
n_{nom}	[rpm]	1475	1500	1500
Efficiency 100% T	[%]	93,3	93,6	94,8
cos Φ 100%		0,81	0,94	0,95
Price vs. IE3 IM	[%]	125	165	?

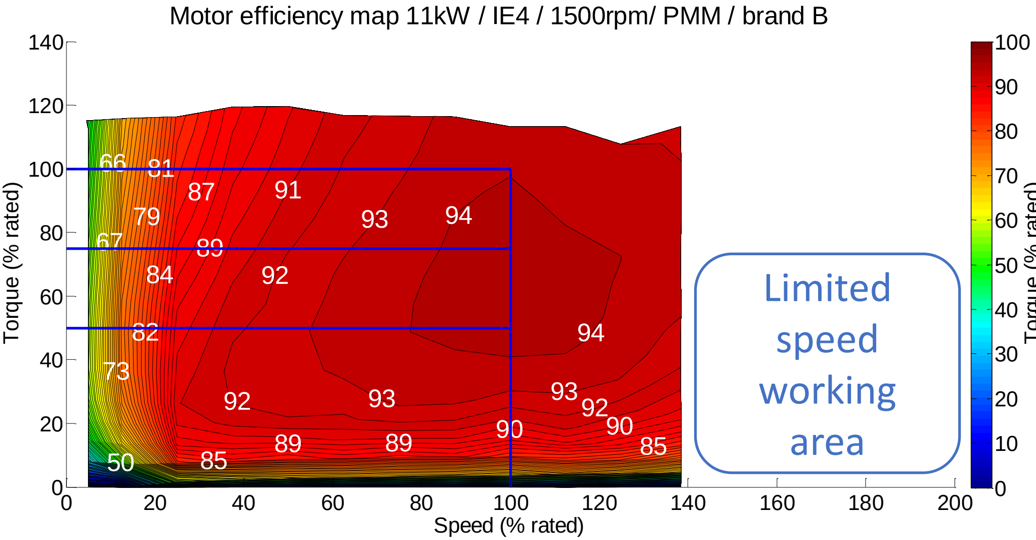
- PMM vs. IE4 IM
  - Smaller size
  - Lower weight: -43%
  - Lower rotor inertia: -65%
  - Higher cos Φ → PMM requires VSD
    - cos Φ input VSD → 1
  - PMM motor expensive
- IE5 PMM vs. IE4 IM
  - Same size
  - Lower weight: -18%
  - PMM requires VSD
  - IE5 price!
- IE5 PMM vs. IE4 PMM
  - Bigger size
  - Higher weight: +30%
  - Efficiency +1,2%
  - IE5 price!

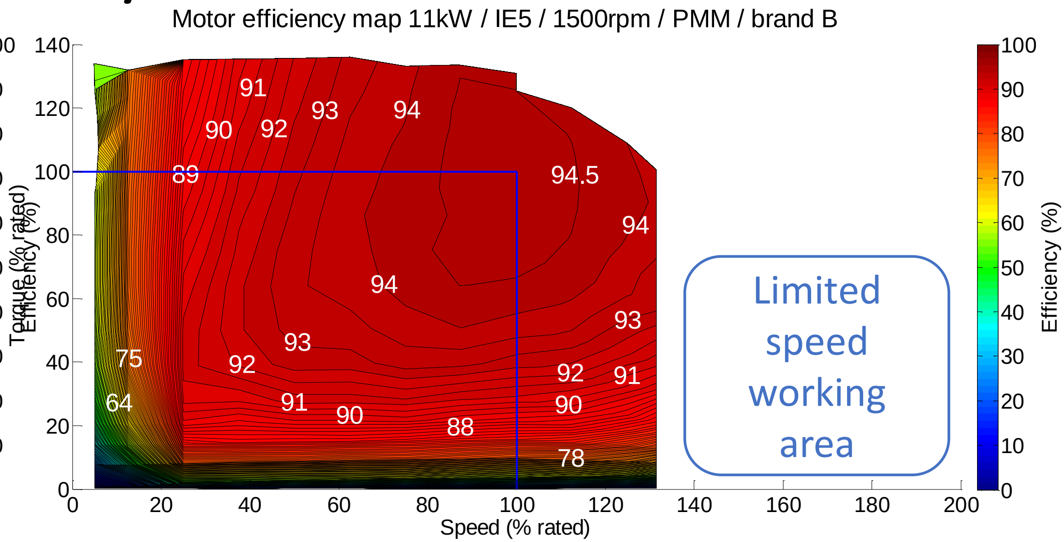


Electrical machines – PMM – test results

What happens with efficiency in entire working area?

IE4 and IE5 PMM motor efficiency





- Nominal efficiency = 93,9% = $\Delta\eta_{cat}$
- Best efficiency point: 94,5%

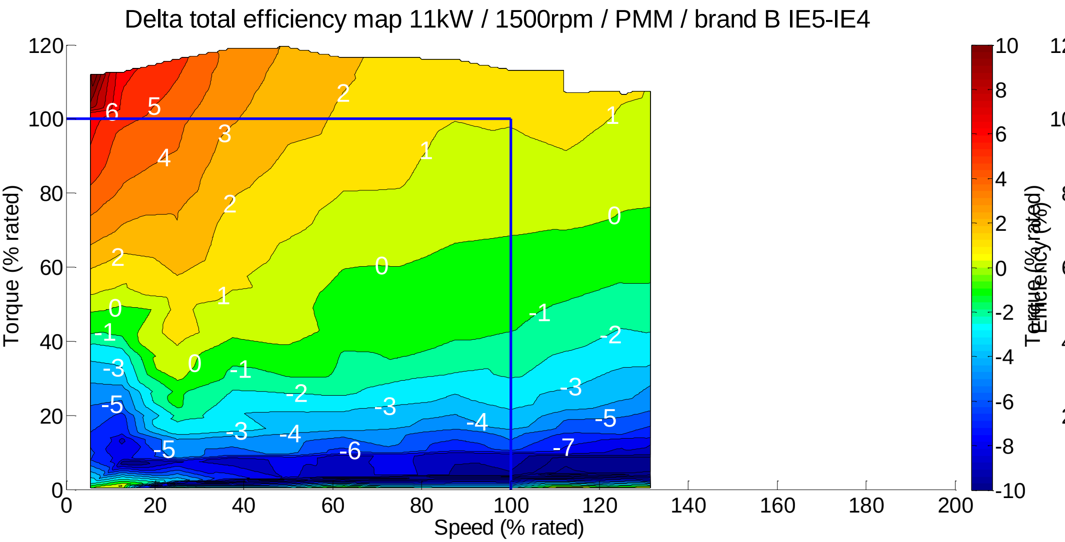
- Nominal efficiency = 94,8% = $\Delta\eta_{cat}$
- 100% torque = best efficiency point!

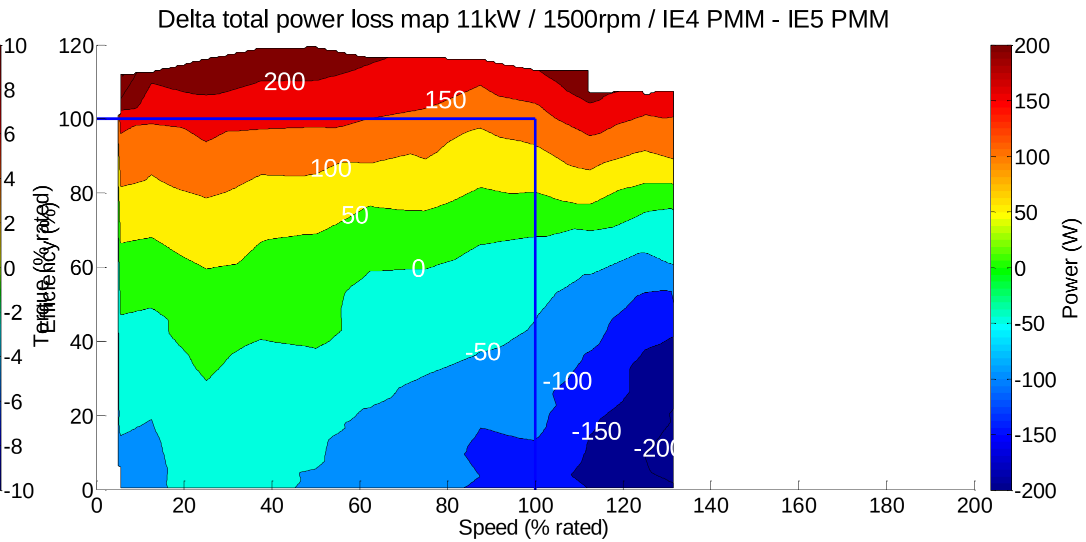
- Limited speed range due to induced voltage of permanent magnet rotor11

Electrical machines – PMM – test results

What happens with efficiency in entire working area?

IE5 PMM vs. IE4 PMM



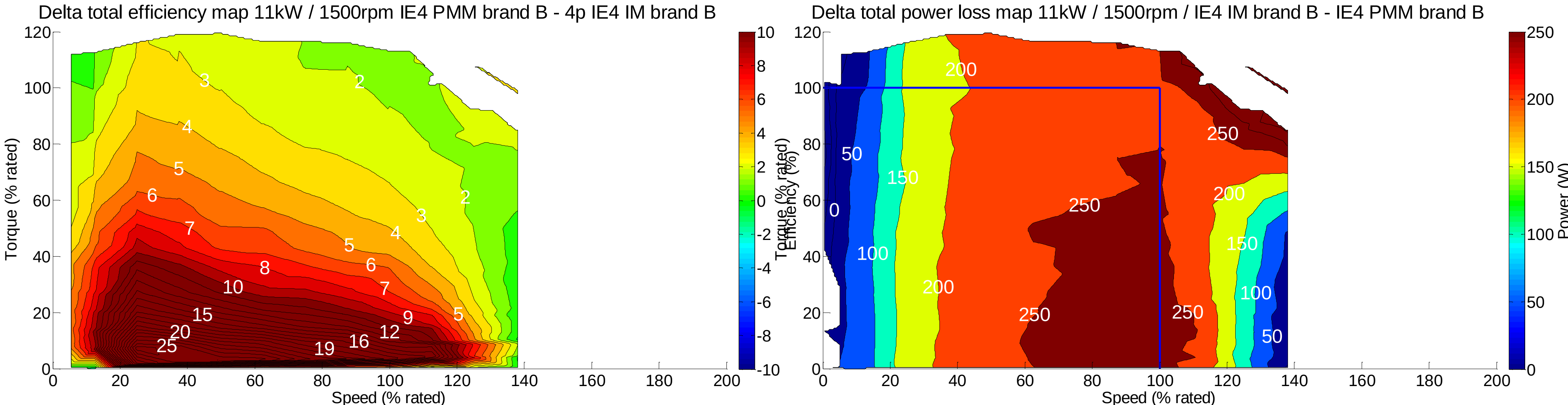


- @ nominal load → efficiency IE5: +1% → 125W less loss
- @low speed, high torque: IE5 efficiency ↗
- Beneath 50% torque: IE5 efficiency ↘
- No uniform conclusion on efficiency

Electrical machines – PMM – test results

What happens with efficiency in entire working area?

IE4 PMM versus IE4 IM

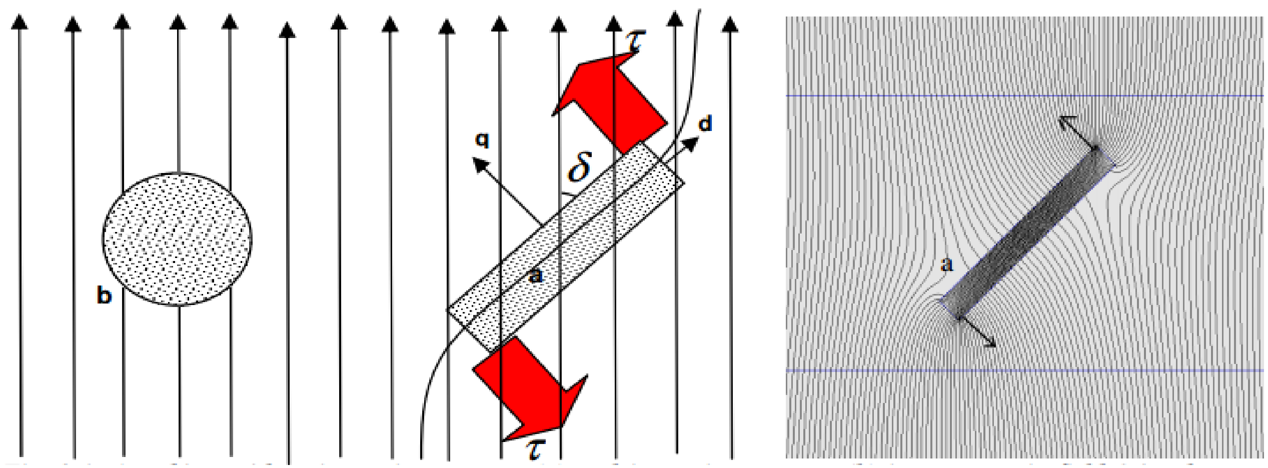


- @ nominal load → PMM efficiency: +2%
  - 200W less losses
- @ part load: much higher PMM efficiency → up to 25%
  - difference in losses stays constant: ±200W

Electrical machines – SynRM

Technology

- Basic operating principle:
  - Reluctance concept together with a rotating sinusoidal magnetomotive force → torque production



- Not new!
  - First switched reluctance motor in the 1800s by W.H. Taylor
  - First synchronous reluctance motor in 1923 by Kostko

Electrical machines – SynRM

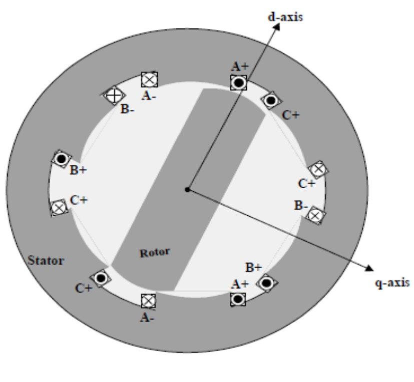
Technology

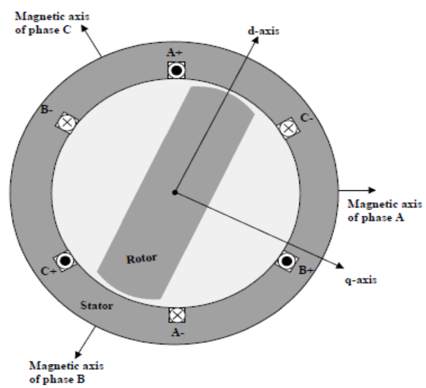
- Difference SRM and SynRM

Switched:

- Salient poles on stator and rotor
- Multiple concentrated stator windings → Complex drive strategy

SRM

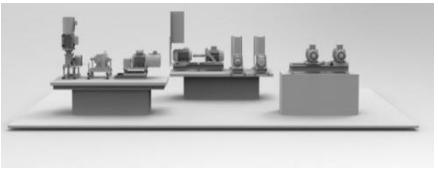




SynRM

Synchronous:

- Salient rotor poles, smooth stator and distributed poles
- Standard IM sinusoidal distributed windings in stator → 'basic' drive strategy

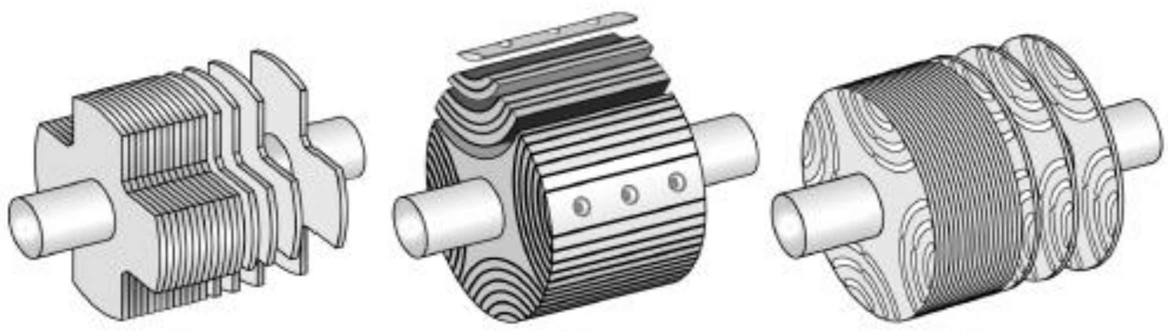


Electrical machines – SynRM

Technology

- Difference with IM → rotor
- Construction: Only electrical steel laminations
    - Good magnetic properties
- Target: High inductance ratio (=salient ratio)
- SynRM rotor designs: SP, ALA or TLA (a,b or c)

$$T_{em} = \frac{3\,p}{\omega}\left[\frac{X_q - X_d}{2} . I^2 . \sin 2\beta\right]$$



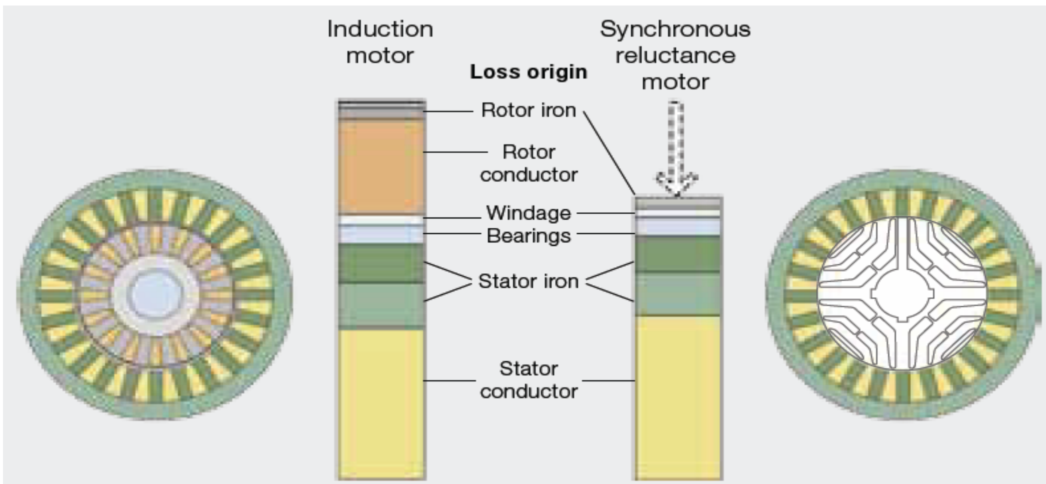
(a) (b) (c)

- Target: large difference in q- and d-axes magnetic reluctance
    - How? → air, magnetic isolation, flux air barriers

Electrical machines – SynRM

Losses:

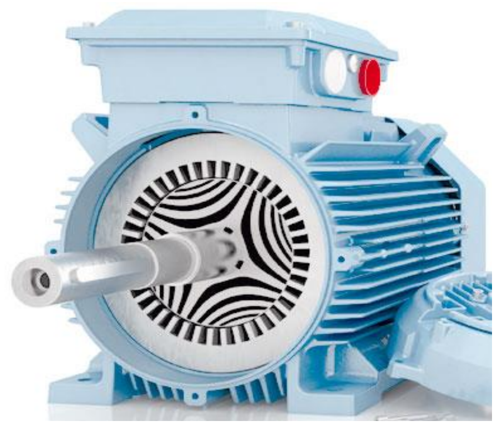
- No rotor bars → no rotor joule losses
- Magnetization current of SynRM higher (flux barriers)→ higher stator joule losses



Electrical machines – SynRM

Advantages

- No magnets → cheaper, no demagnetization at high temperature
- Easy rotor speed detection due to high inductance ratio
  - Simple control algorithm, especially at low and zero speed
- IE4 efficiency
- Air gaps/barriers in rotor → Lower rotor inertia



Disadvantage

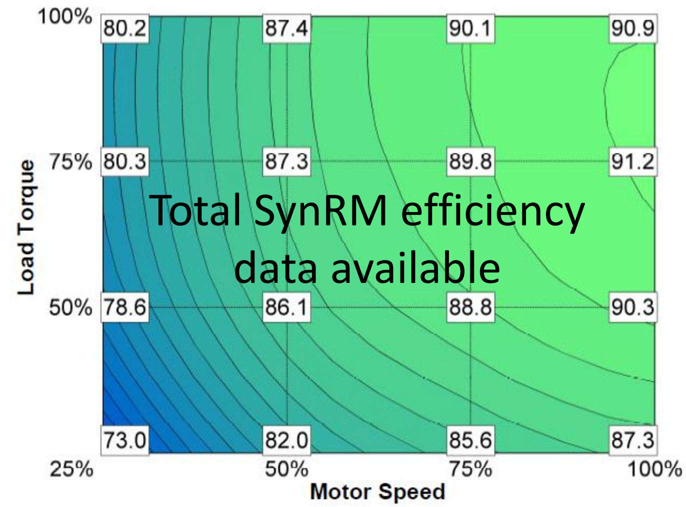
- Drive necessary → line start in future
- Price is higher than IM → no mass production yet

Electrical machines – SynRM

Specs comparison with IE4 IM and IE4 PMM

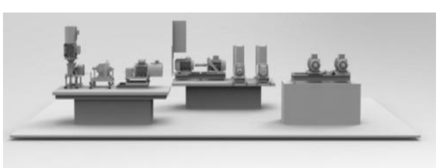
		IE4 IM br. B	IE4 PMM br. B	SynRM br. D
Frame		160M	132S	160
Weight	[kg]	143	82	160
Inertia	[kgm²]	0,154	0,054	0,0702
T_{nom}	[Nm]	71,3	70,1	70
I_{nom}	[A]	21,0	18,5	24,9
n_{nom}	[rpm]	1475	1500	1500
Efficiency 100% T	[%]	93,3	93,6	93,3 (90,9)
cos Φ 100%		0,81	0,94	/
Price vs. IE3 IM	[%]	125	165	140

- 93,3% = motor efficiency (driven by converter)
- 90,9% = package efficiency (motor + converter)



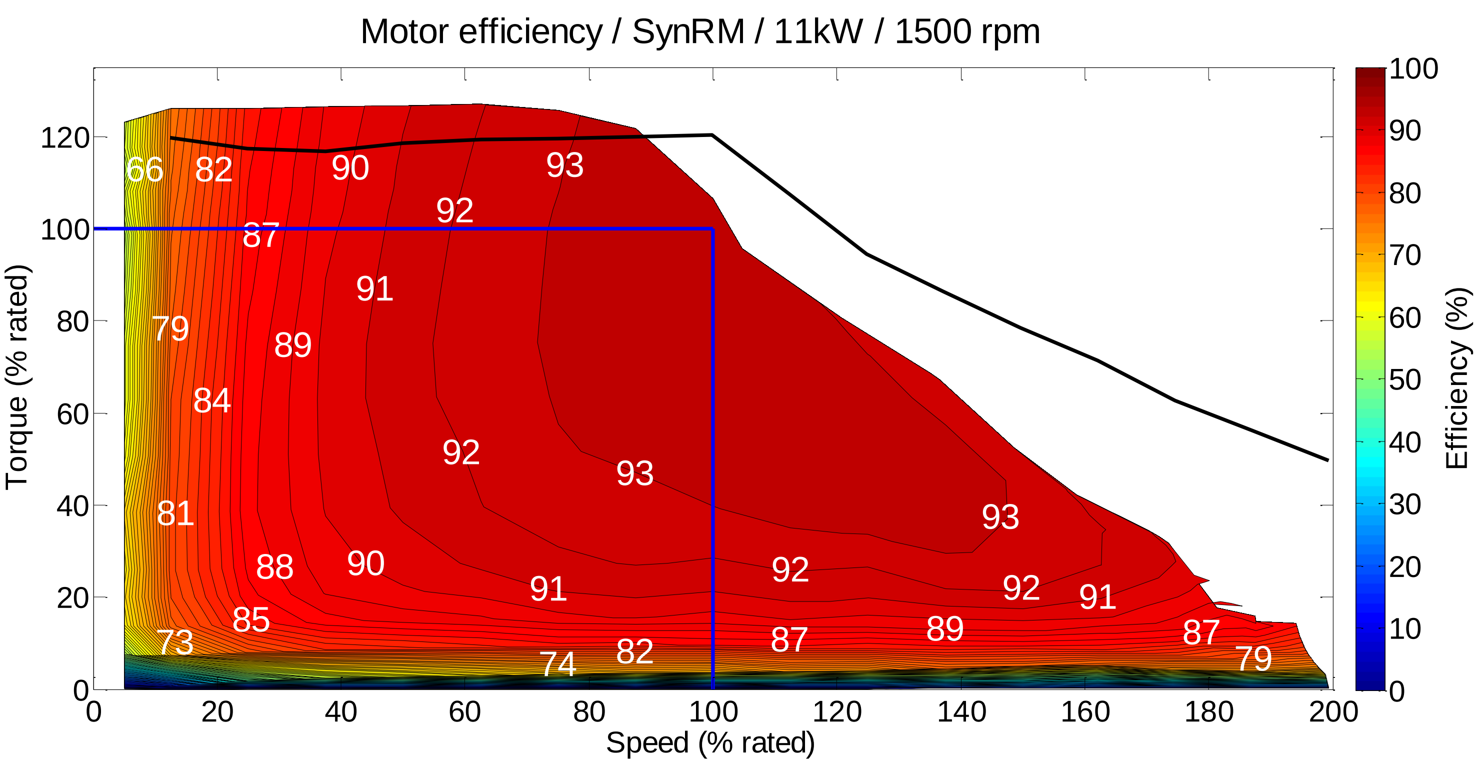
SynRM

- Higher weight → brand dependent
- Lower inertia than IM
- Larger nominal current
    - Magnetization current!
- Less expensive than PMM



Electrical machines – SynRM – test results

What happens with efficiency in entire working area?



@100% load:

- Efficiency = 93,5%
  = catalog value

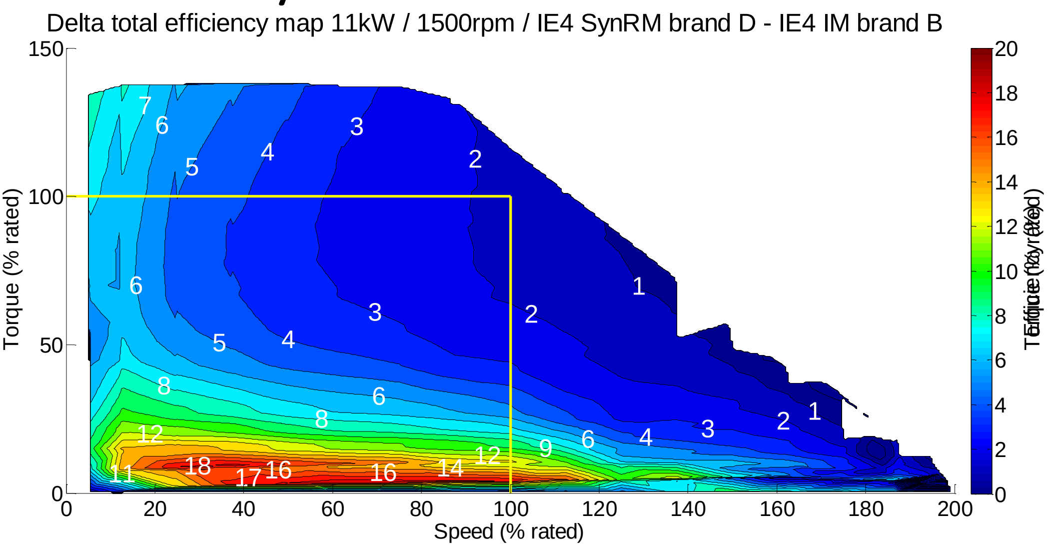
Black line = working area IM

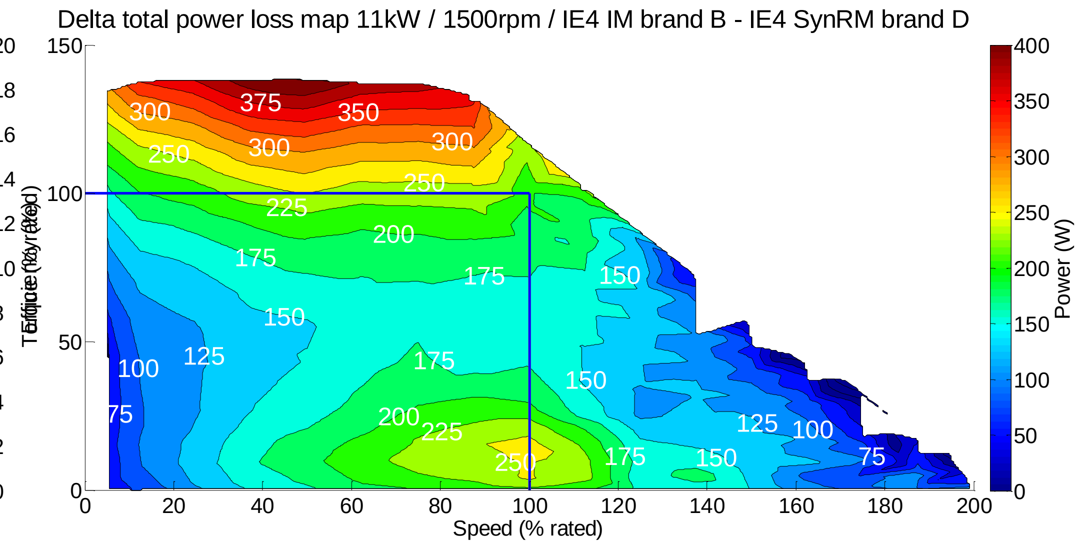
- VSD current is limiting factor
- SynRM has a higher stator current for same shaft power → VSD should have higher power range

Electrical machines – SynRM – test results

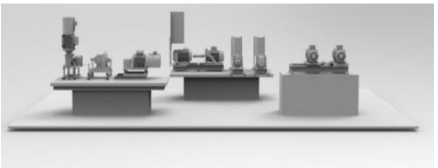
What happens with efficiency in entire working area?

IE4 SynRM versus IE4 IM





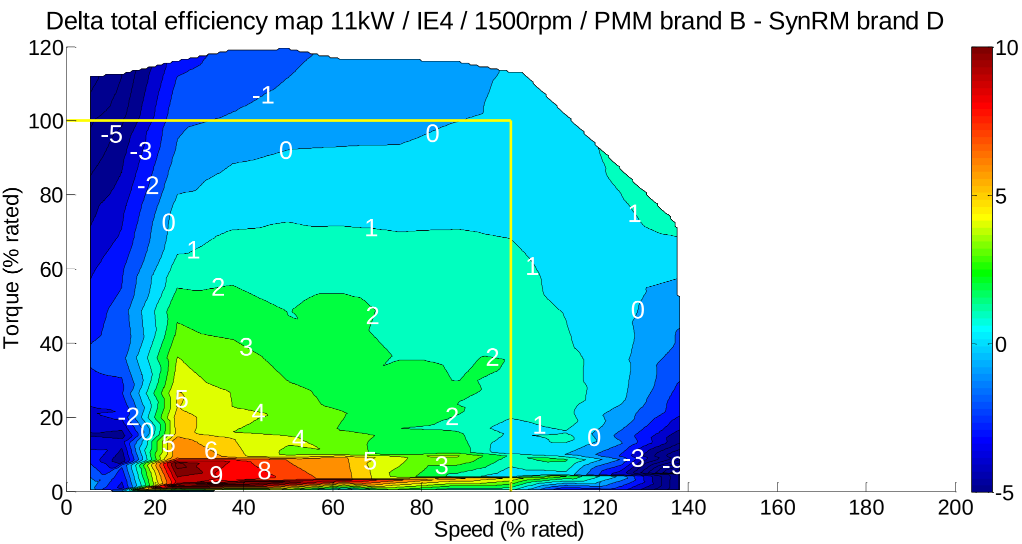
- SynRM highest efficiency, +2% at nominal load
  - 200W less losses
- Bigger efficiency difference in part load
  - What about actual losses in Watt? → difference in Watt varies

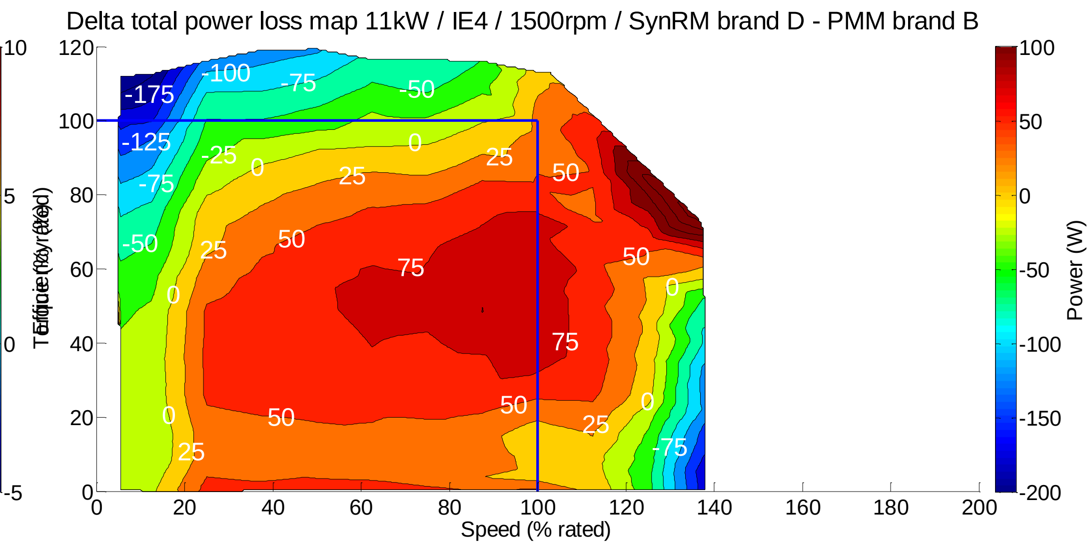


Electrical machines – SynRM – test results

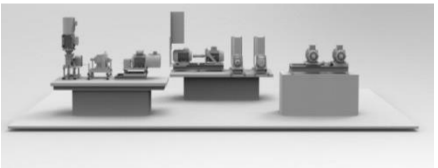
What happens with efficiency in entire working area?

- **IE4 SynRM versus IE4 PMM**



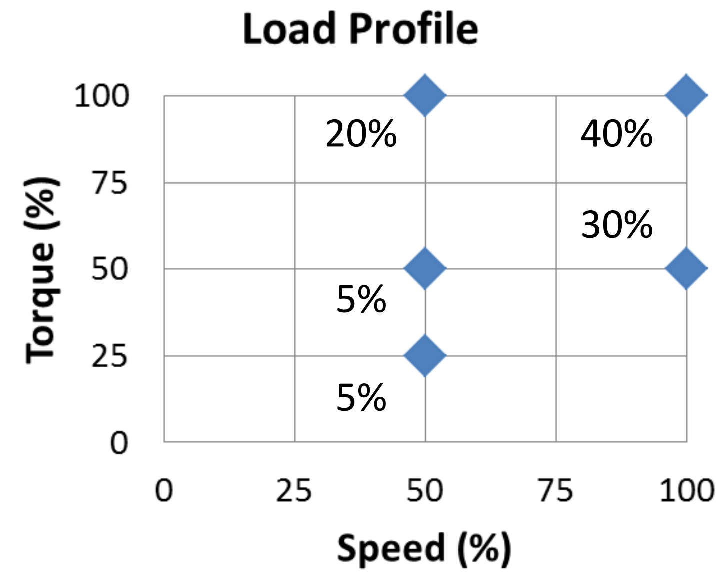


- @ nominal load → equal efficiency
- @part torque load: PMM efficiency ↗ (±50W less losses)
- @part speed load: PMM efficiency ↘



Electrical machines – Economical

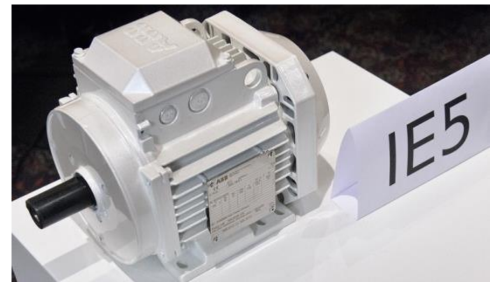
- Yearly consumption calculated via efficiency maps and load profile
  - Operating hours: 5000h
  - Energy cost: 0,11 €/kWh

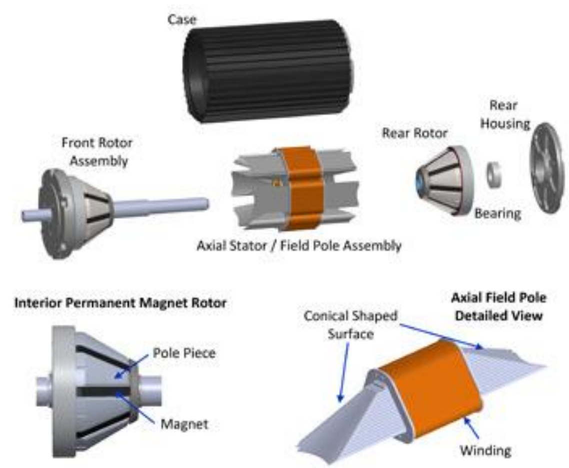


11kW drive train with load profile 1	IM IE2	IM IE4	SynRM IE4	PMM IE5
Yearly consumption cost	4641€	4480€	4403€	4311€
Difference relative to IE2 IM on 15 years	Ref.	2421€	3576€	4950€
Drive train cost	1200€	1410€	1500€	1650€
Payback on 15 years for new drive train	Ref.	1,3 year	1,3 year	1,4 year

Electrical machines – future

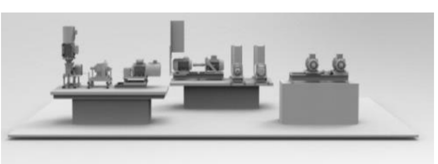
- Next generation Synchronous Reluctance motors
  - SynRM + (cost efficient) ferrite magnets
  - Ferrite magnets = Losses -20% vs. IE4 SynRM = IE5 SynRM
- Direct On line SynRM
  - SynRM + induction cage for starting (similar to LSPMM)
  - IE5 level
- Other high efficiency motor designs
  - Axial motor design with permanent magnets
  - IE5 level





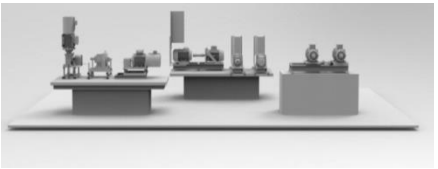
Electrical machines – future

- More technologies reach IE4 and IE5 level
  - But no high efficiency rises: 11kW IE4 → IE5 → +1,2%
    - 11kW IE1→IE4: 66% more material for 6% less losses!
    - Is the research cost justifiable versus the profits?
  - Limits almost reached
- Importance Extended Product approach
  - Other parts of the drive train could yield more profit
  - Also standards and directives move in that way



Conclusions electrical machines

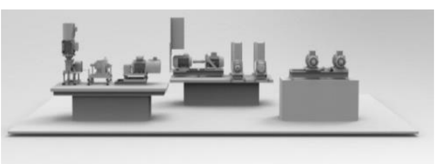
- Direct On Line
  - IM up to IE4 efficiency
  - Efficiency highest from 40% to 120% load
  - IE4 LSPMM only competitor for DOL operation for now
- VSD supply
  - Efficiency drops ±3% when VSD is used
  - Remember decision flow chart to select energy efficient drive train
- Efficiency IE4 Induction Motors
  - Nominal load: high efficiency according to IE class
  - Part load: varying differences, positive and negative
  - IE4 IM against each other
    - @ full load: equal efficiency, @part load: differences
  - Price: IE4 ±25% more expensive than IE3 IM



Conclusions electrical machines

- Efficiency IE4 PM Motors
  - Lighter and smaller compared to IM and SynRM
  - High efficiency in entire working area
    - Versus IM: high part load efficiency
  - Limited speed range
  - Expensive: 65% more expensive than IE3 IM

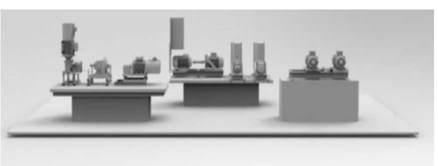
- Efficiency IE5 PM Motor
  - Efficiency higher at 100% load
    - but not always higher in entire working range
  - Expensive: minimum 65% more expensive than IE3 IM



Conclusions electrical machines

- Synchronous Reluctance Motors
  - High efficiency in entire working area
    - Versus IM: high part load efficiency
    - Versus IE4 PMM: slightly lower part load efficiency
  - Price
    - 40% more expensive than IE3 IM
    - 15% cheaper than IE4 PMM
- Economical
  - PB is short for new drive trains
  - TCO important: consumption is largest cost of a drive train
- Future
  - More technologies reach IE4/IE5 level
- Limits in motor efficiency reached?
  - Importance Extended Product approach

Transmissions



Theoretical efficiency

- Efficiency per gear pair found in literature:

Spur and helical gear

94%-99%

Bevel (helical) gear

93%-99%

Worm gear

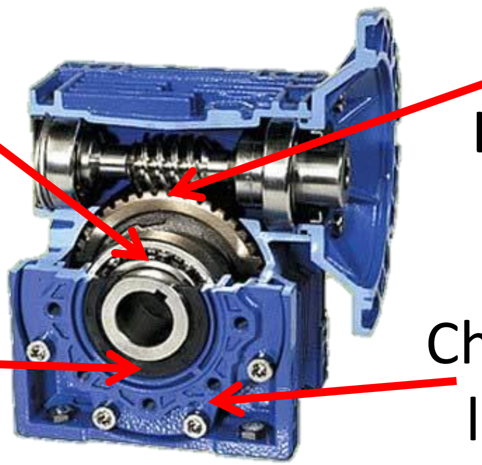
20%-90%

Spiroid gear

40%-90%

Hypoid gear

50%-95%



- Gearbox efficiency is a combination of losses
  - Not much research knowledge in literature

Catalog efficiency

- Few info about gearbox efficiency values in catalogs

> The efficiency of helical, parallel shaft and helical-bevel gear units varies with the number of gear stages, between 96% (3-stage), 97% (2-stage) and 98% (1-stage).

Source: Gear manufacturer catalog

  - NO information about: Part load, ratio and power dependency
  - Only exception: worm gears

- No info concerning measurement conditions

  - Catalog info: "Efficiency is reached at nominal operating temperature."
    → But no temperature is given!

- No standardization to measure gearbox efficiency

→ Consequence: Efficiency values not comparable

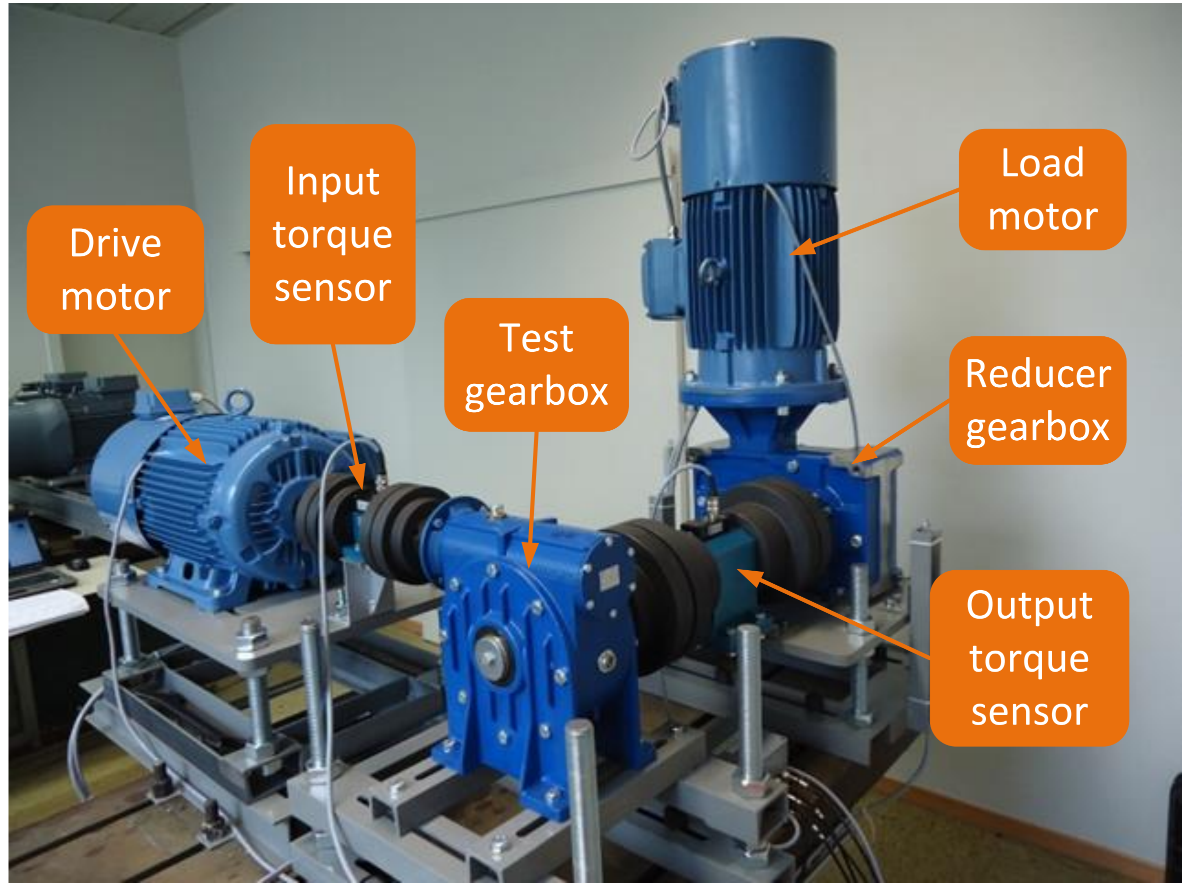
Gearbox test rig – Measurement principle

- Efficiency determination:

$$\eta_{gearbox} = \frac{P_{out}}{P_{in}} = \frac{M_{out}\ x\ \omega_{out}}{M_{in}\ x\ \omega_{in}}$$

$$\boxed{\begin{array}{c}\text{ratio i = cte.}\\ \text{(mech. fixed)}\end{array}} \quad = \frac{M_{out}}{M_{in}\ x\ i}$$

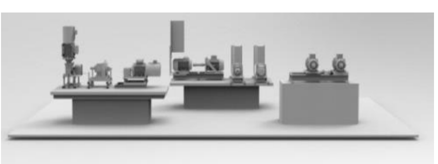
- Direct method: Back-to-back electrical with reducer gearbox



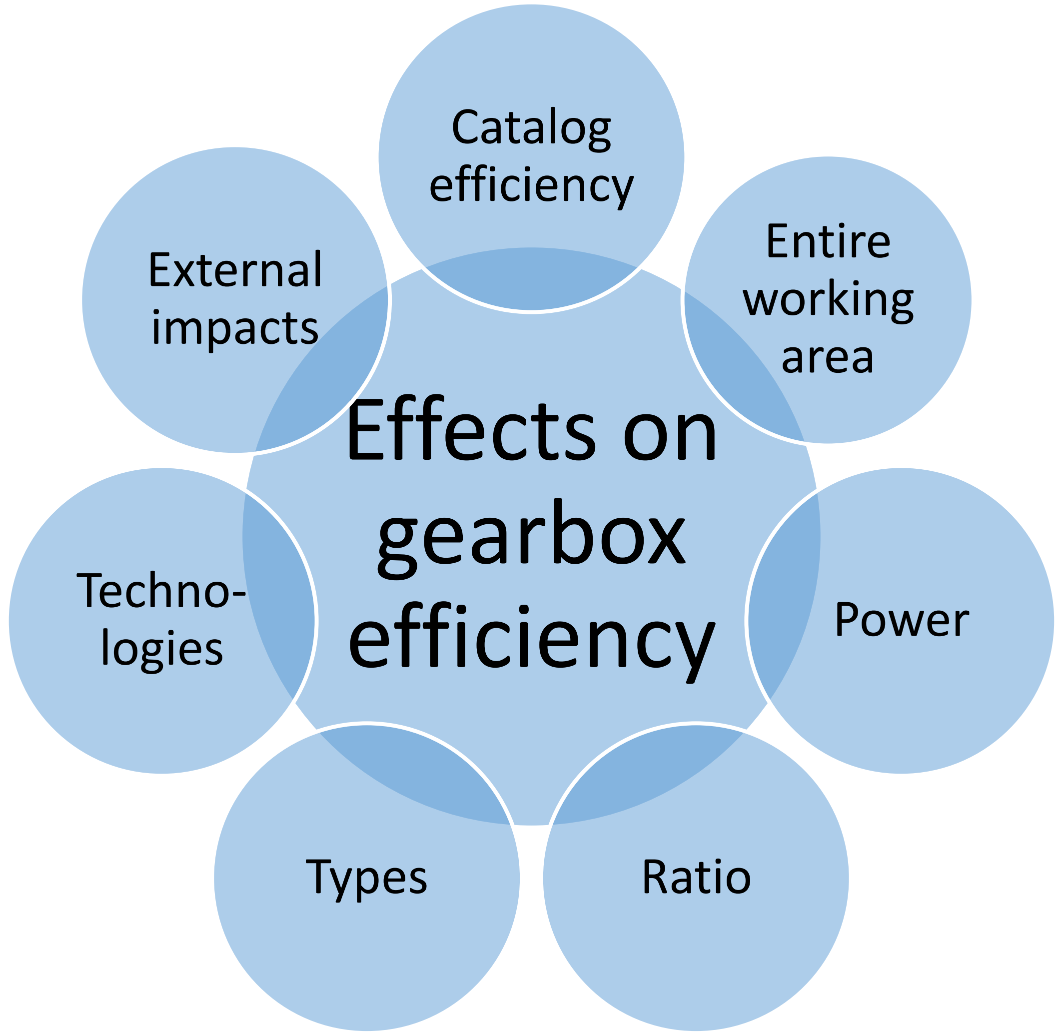
Tested gears - Overview

	Brand A	Brand B	Brand C	Brand C	Brand C	Brand D	Brand D	Brand E	Brand E	Brand E	Brand F	Brand F	Brand F
Type	Right angled	Right angled	Right angled	Right angled	Right angled	Right angled	Right angled	Right angled	Right angled	Straight	Right angled	Right angled	Right angled
Technology	Worm	Helical bevel	Helical bevel	Helical worm	Helical spirod	Helical bevel	Helical worm	Helical bevel	Helical worm	helical	Helical worm	Helical worm	Helical worm
Stages	1	2	3	2	2	3	2	3	2	2	2	2	2
Ratio	80	77.76	72,54	71,75	74,98	72,21	77	11,41	11,67	10,93	87,65	68,44	30,26
Torque (Nm)	450	505	186	167	180	190	180	434	373	390	285	270	260
Power (kW)	0,82	0,95	0,37	0,35	0,36	0,39	0,34	5,58	4,7	5,23	0,69	0,82	1,51
Catalog efficiency	62%	95%	96%	62%	±90%	95%	78%	94%	90%	96%	69%	71%	83%

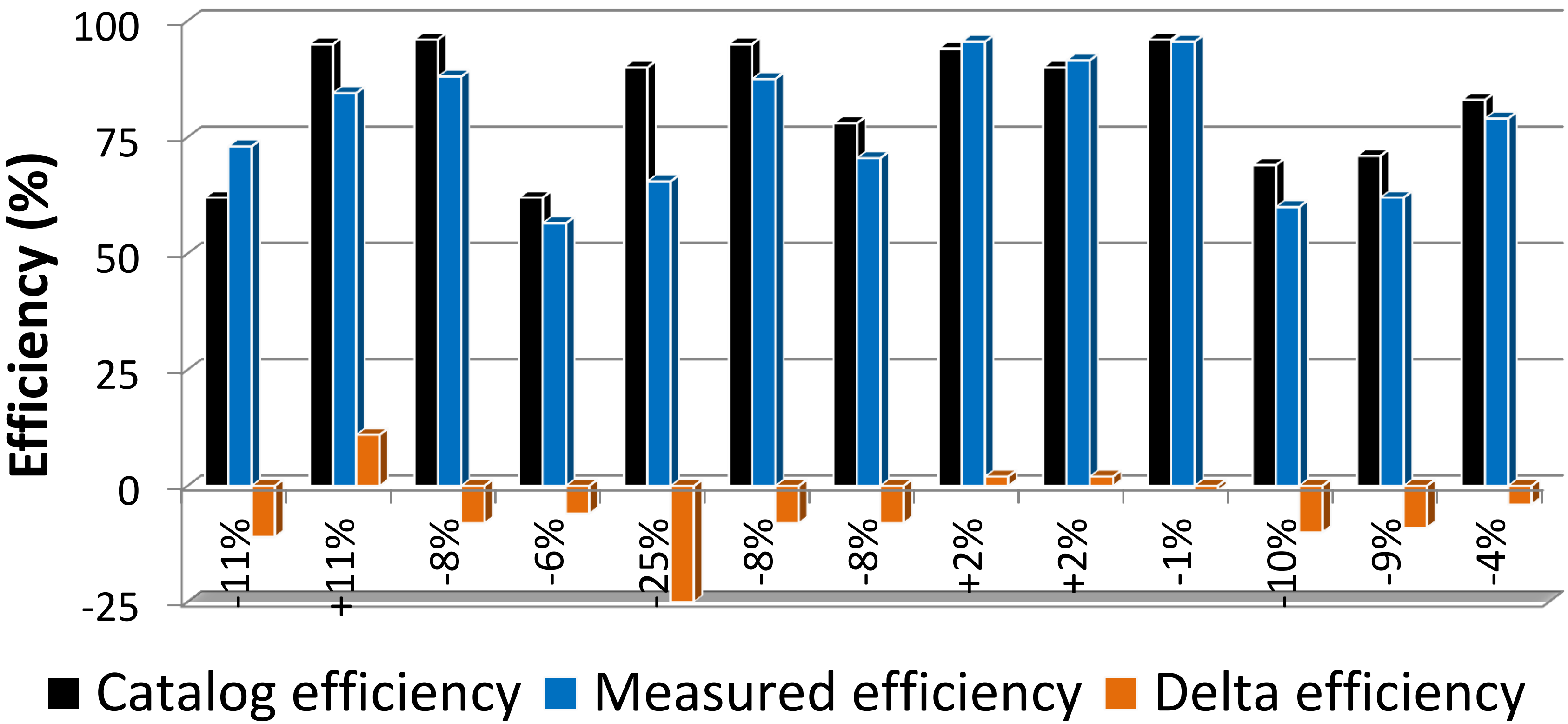
- Several comparisons: Technology; brand; ratio; power
- The highlights are discussed



Tested gears – Relevant questions

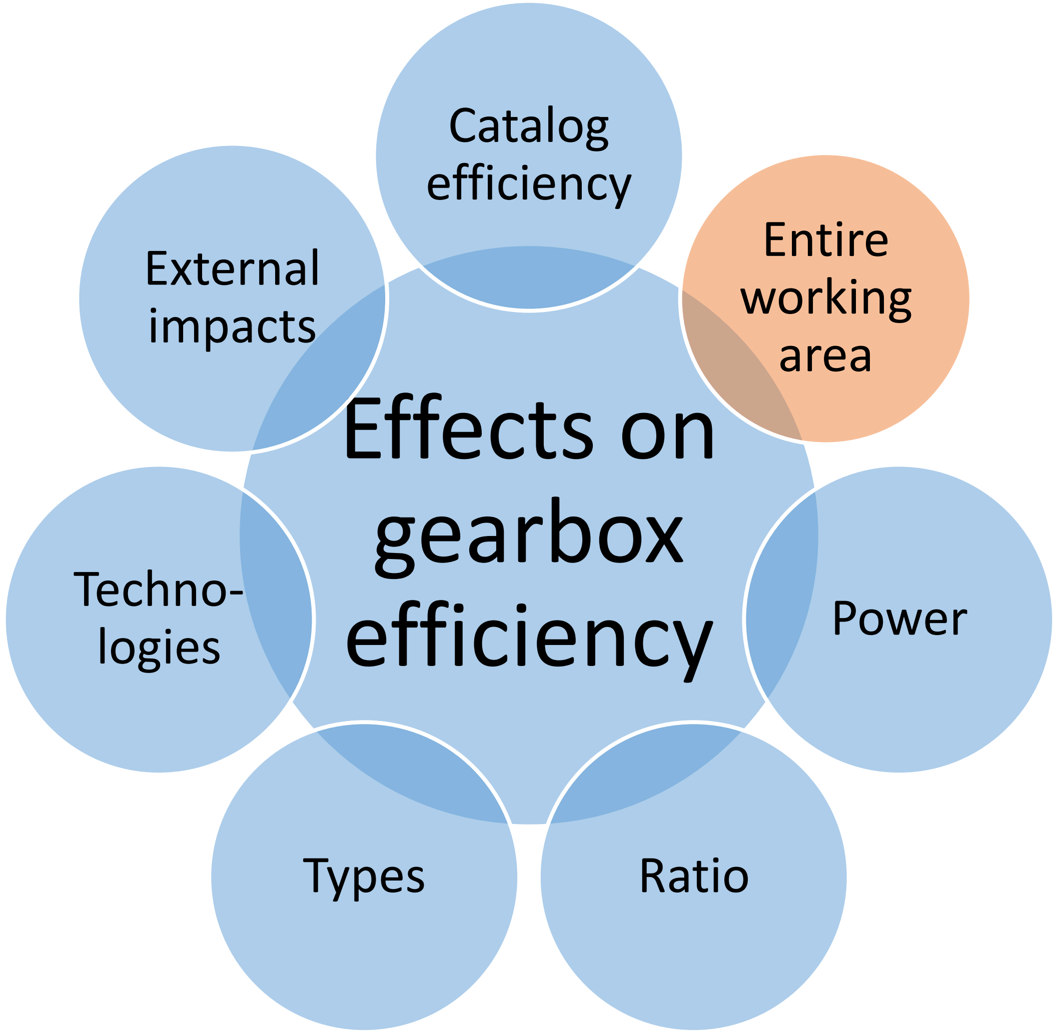


Results – Catalog vs. actual efficiency

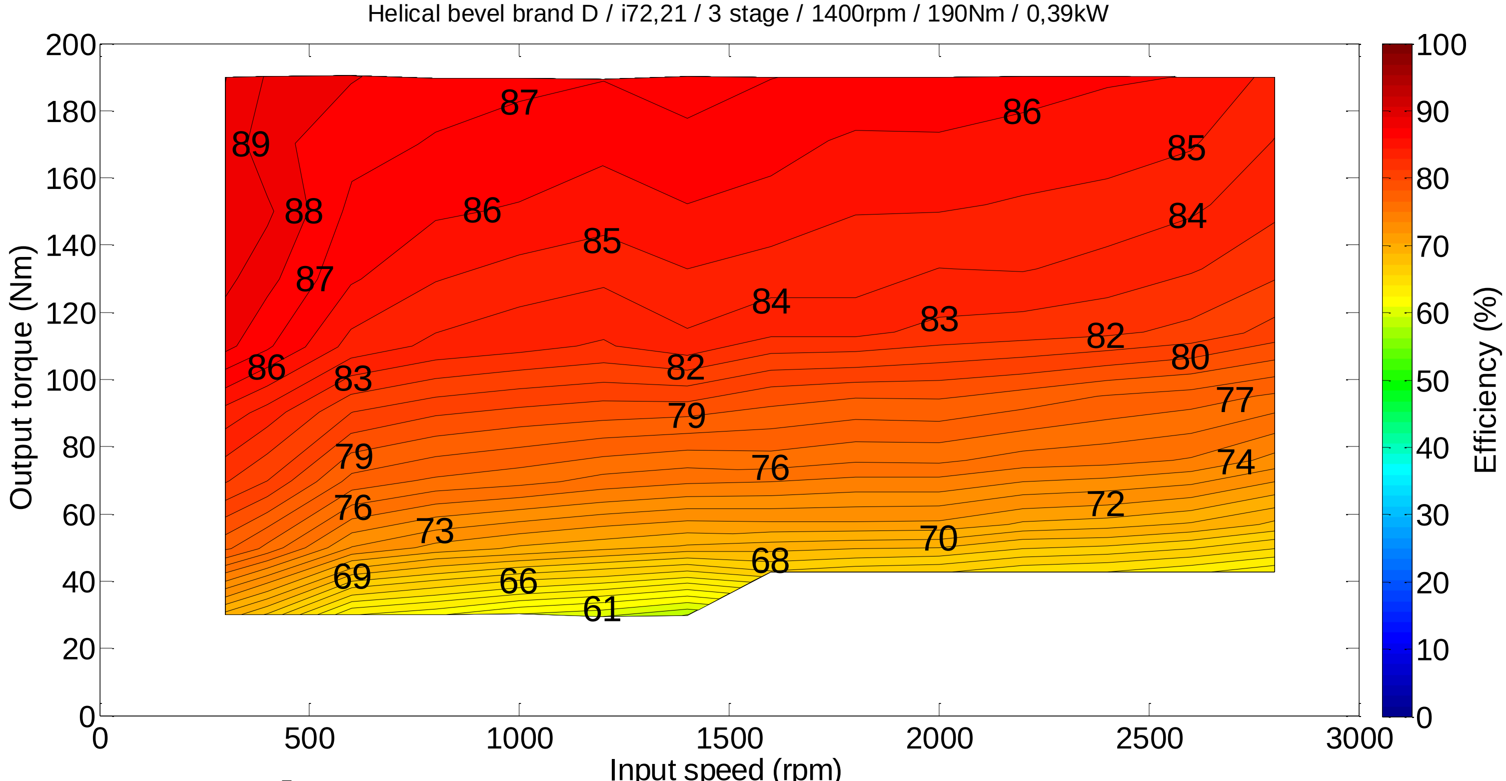


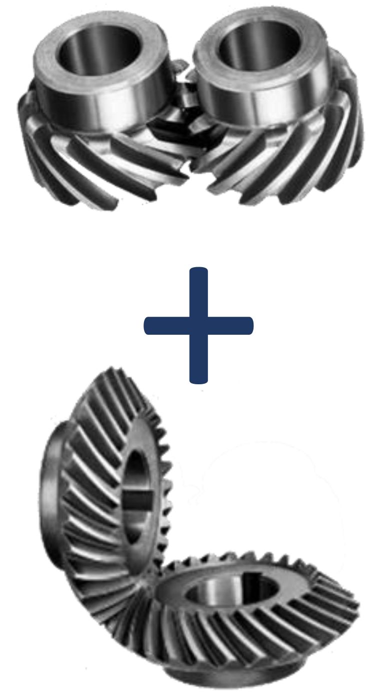
- Efficiency at nominal load and speed
- Catalog and measured efficiency value are <u>**not equal**</u>

Tested gears – Relevant questions



Results – Efficiency in entire working area



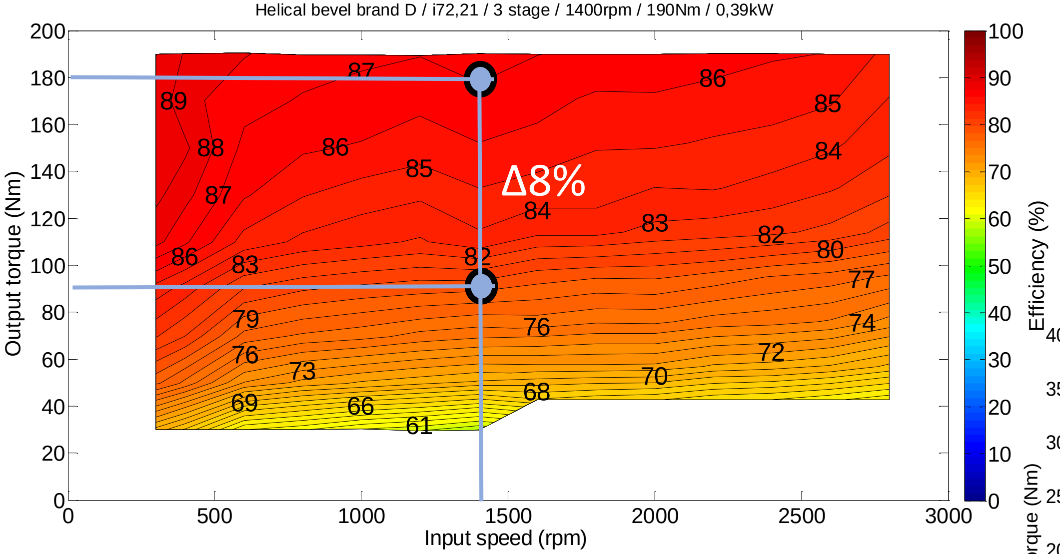


- η_{max} → nominal torque
- Torque ↓ then η ↓
- Speed variation → η=

Most tested gearboxes have similar efficiency maps

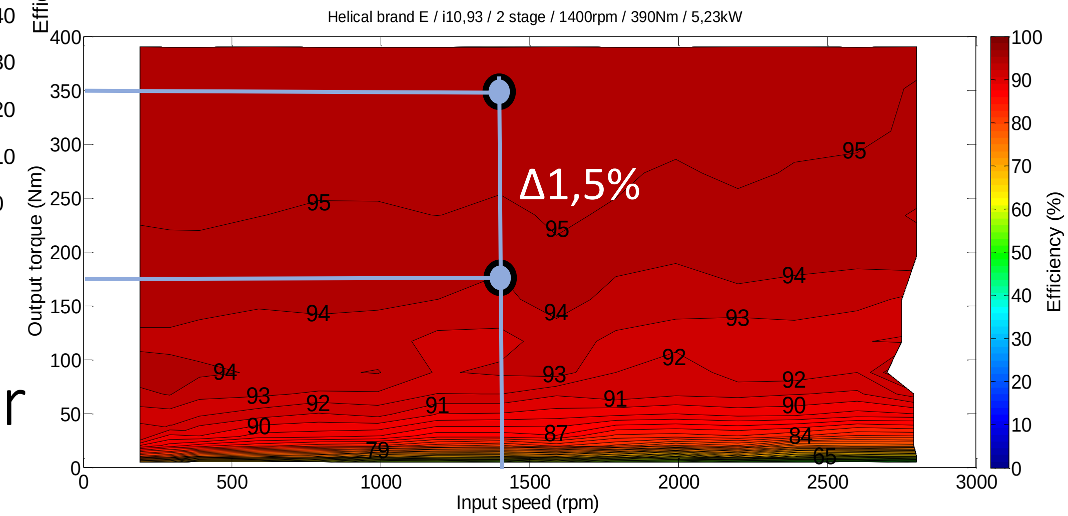
Results – Efficiency in entire working area

0,4kW; i = 72

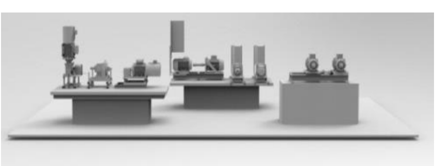


- Efficiency equal in larger area for higher power and smaller ratio

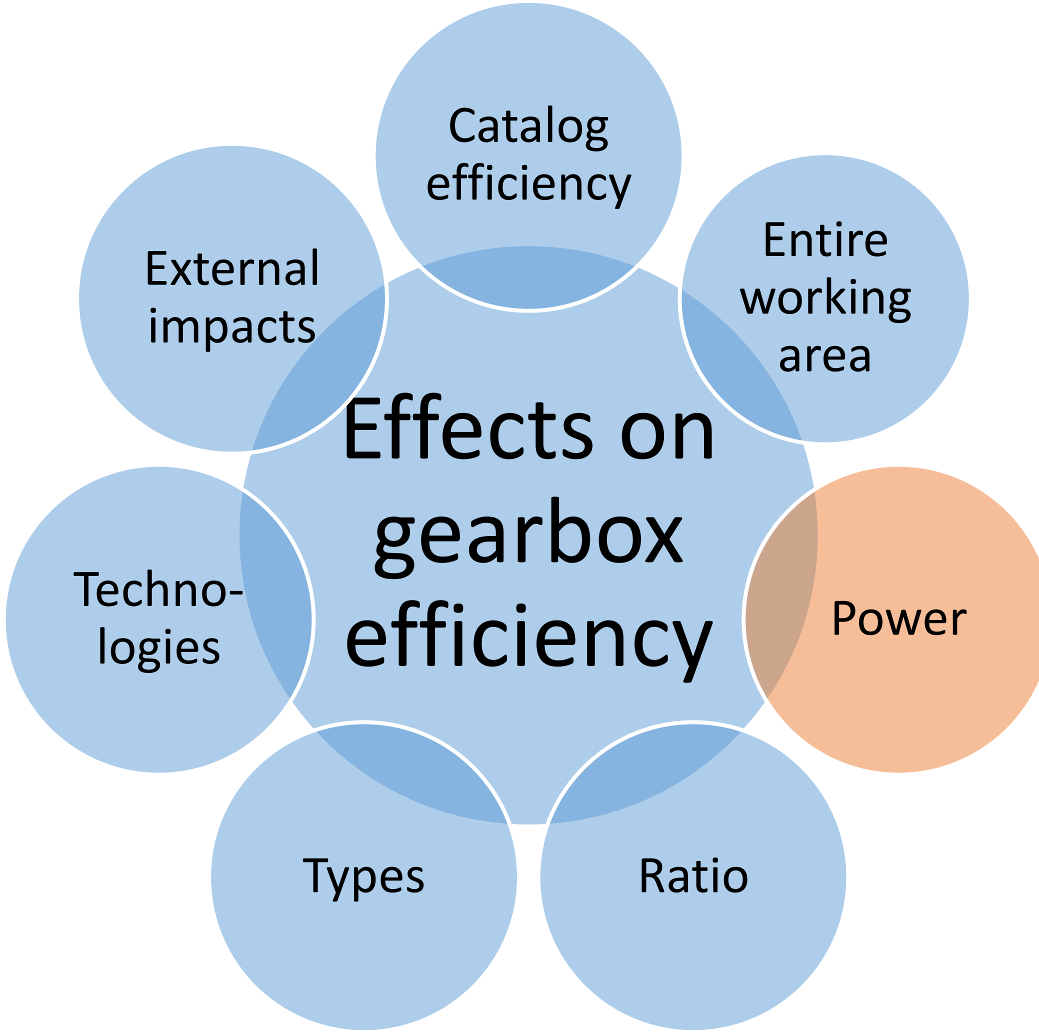
5kW; i = 11



- Part load → efficiency is lower
  - Δη smaller for high power and small ratio



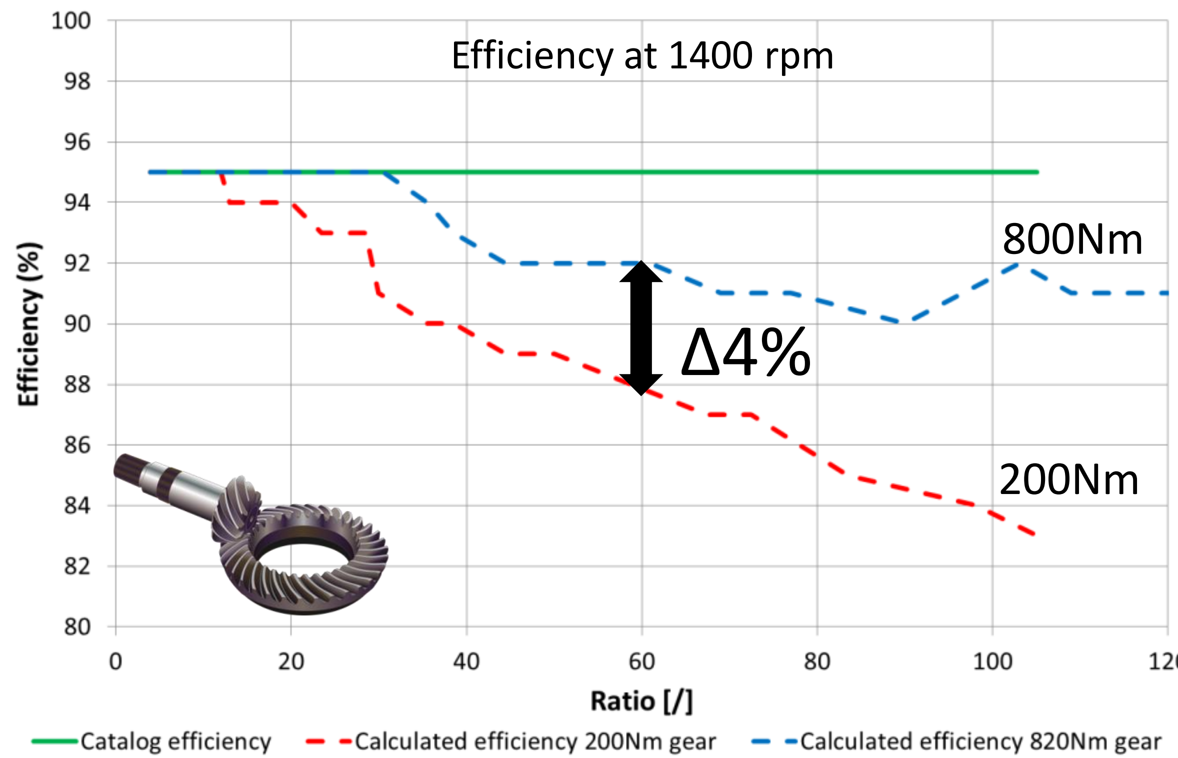
Tested gears – Relevant questions



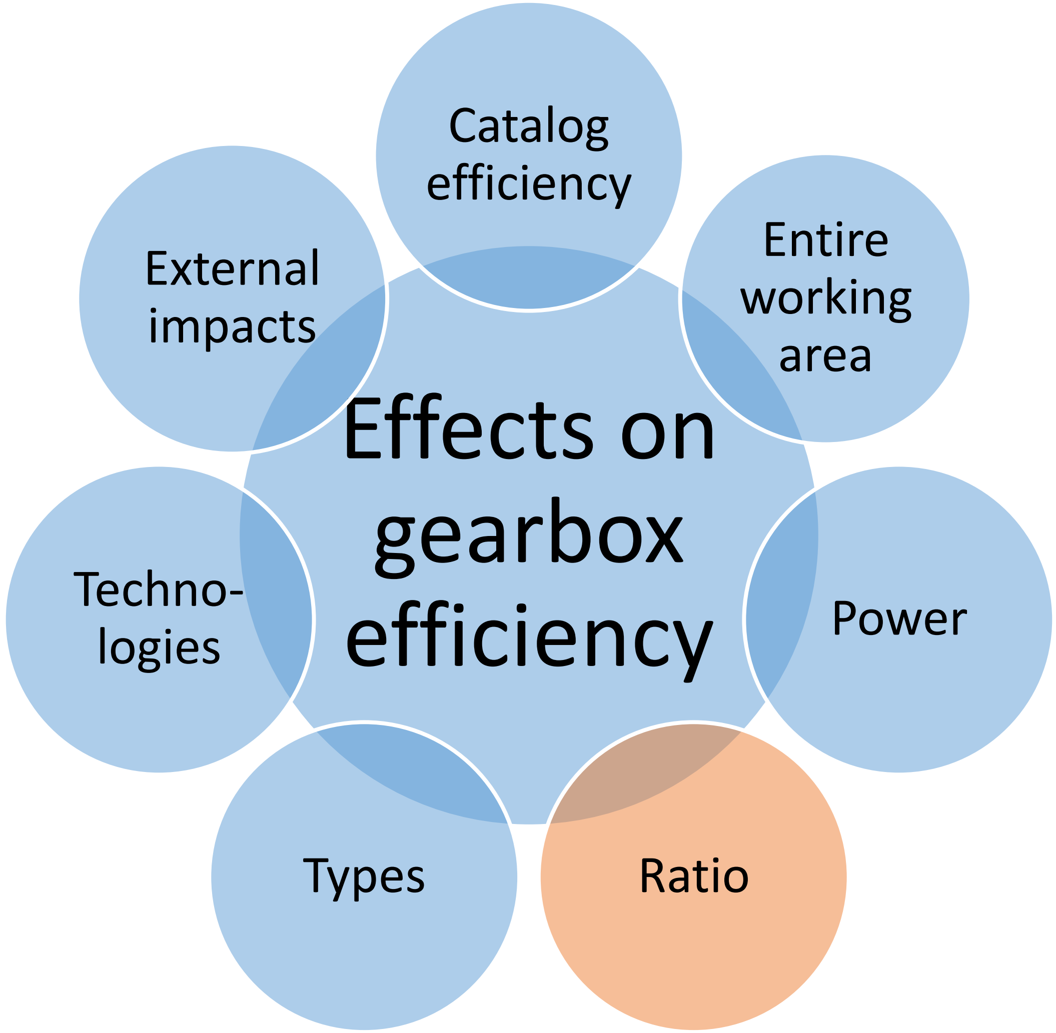
Results – Power dependency

Observations:

- Power or torque is determined by application/load
- Measurements show power dependent efficiency variation



Tested gears – Relevant questions

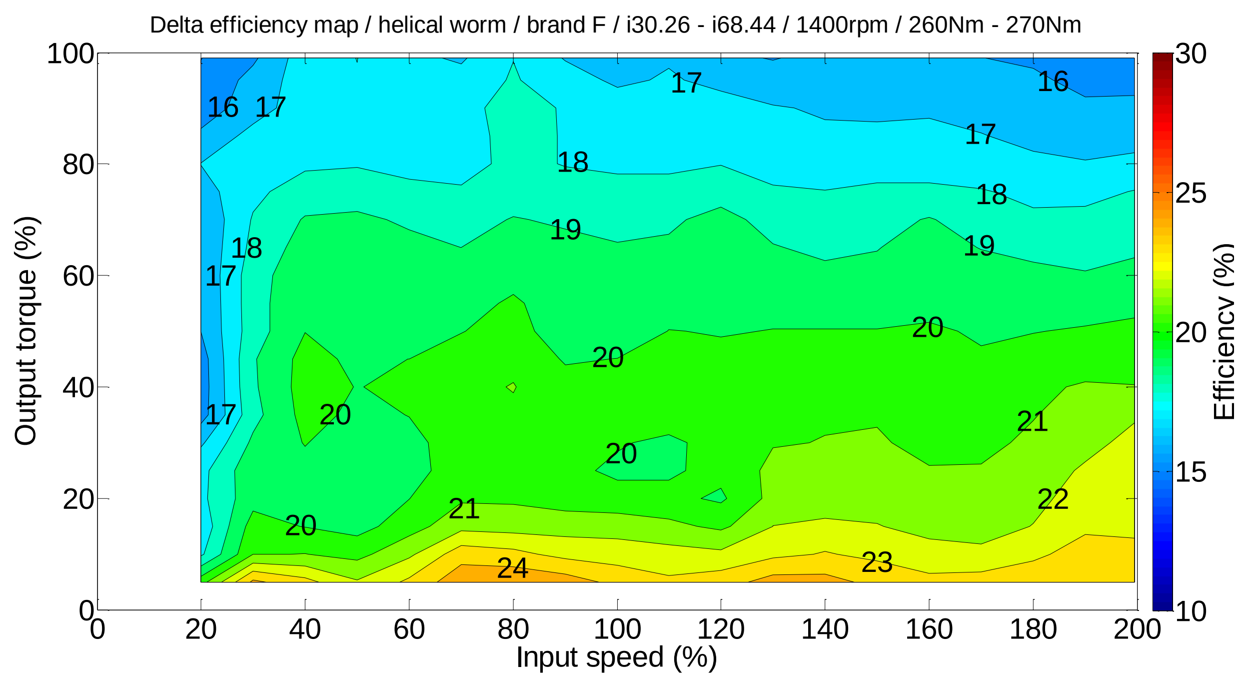


Results – Ratio dependency

Measurements: comparison 2 similar gears with ≠ ratio

	Brand F	Brand F
Technology	Helical worm	Helical worm
Stages	2	2
Ratio	68,44	30,26
Torque (Nm)	270	260
Catalog efficiency	71%	83%

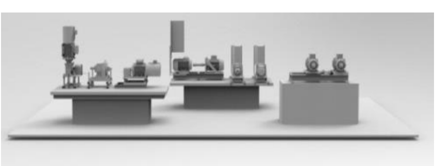
i: 30,26 vs. 68,44



High ratio → lower η

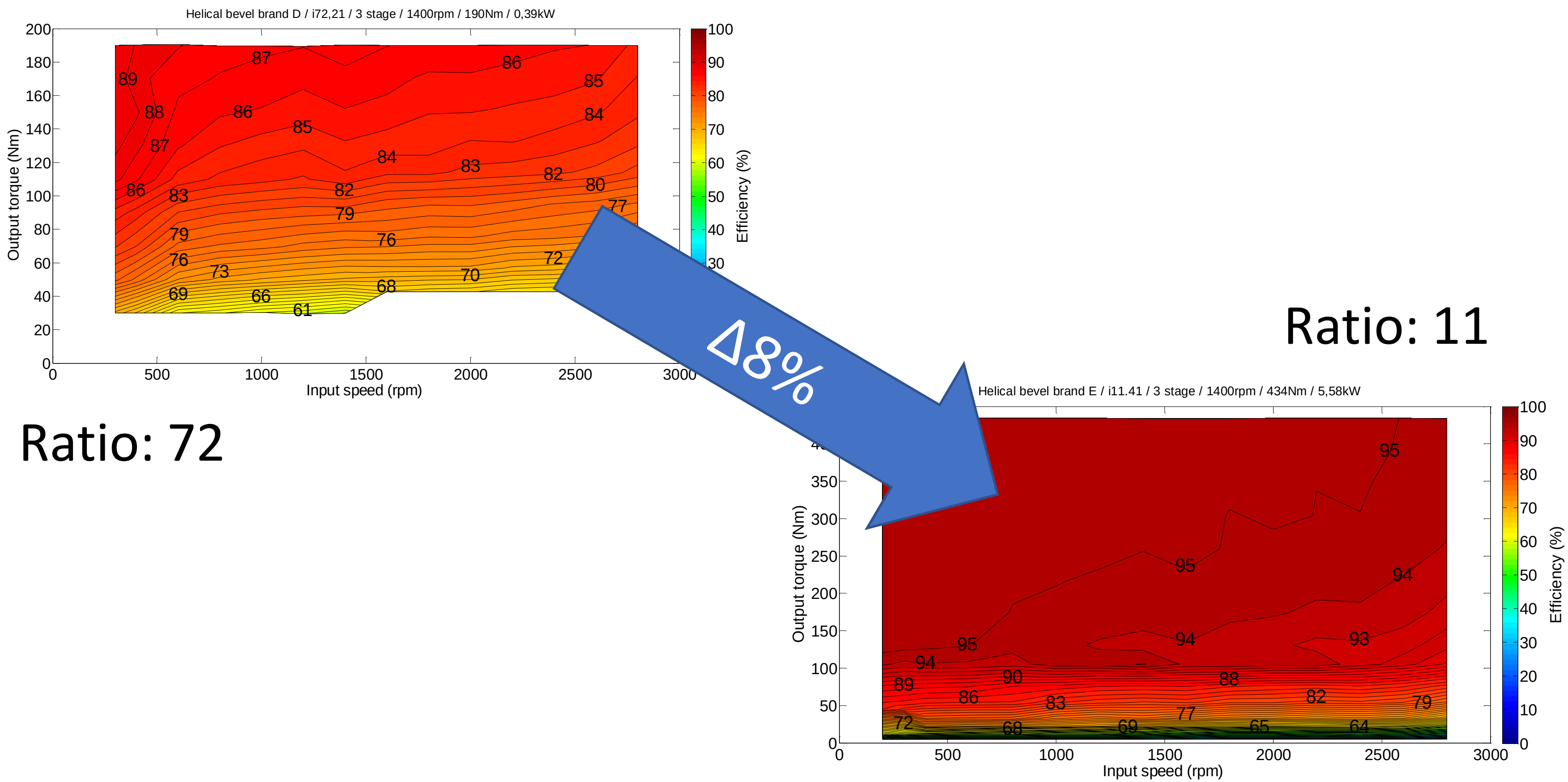
Catalog:

- worm gears → catalog confirms
- helical (bevel) gears → no ratio dependency in catalog?



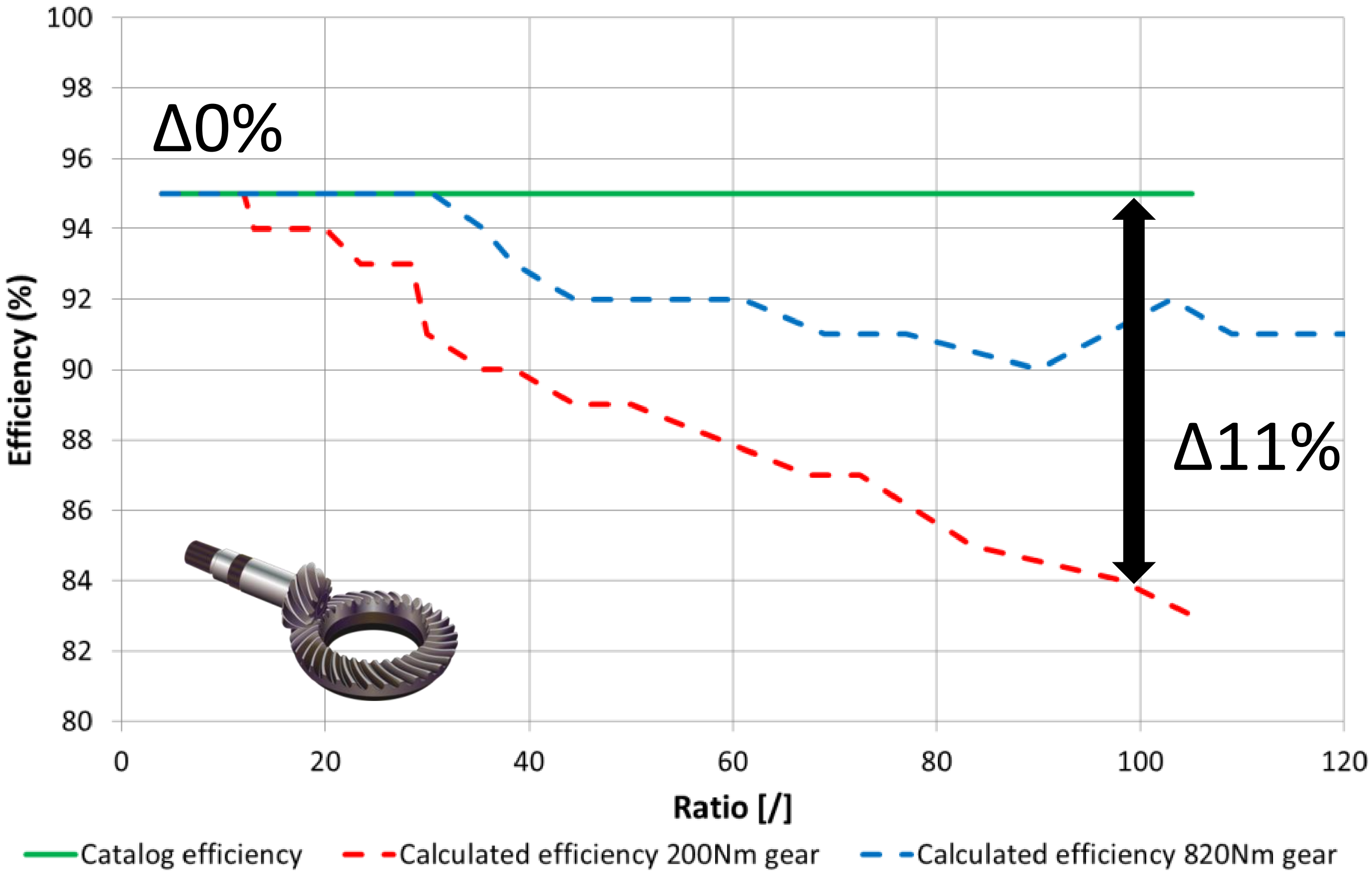
Results – Ratio dependency

Helical (bevel) gear measurements:



Results – Ratio dependency

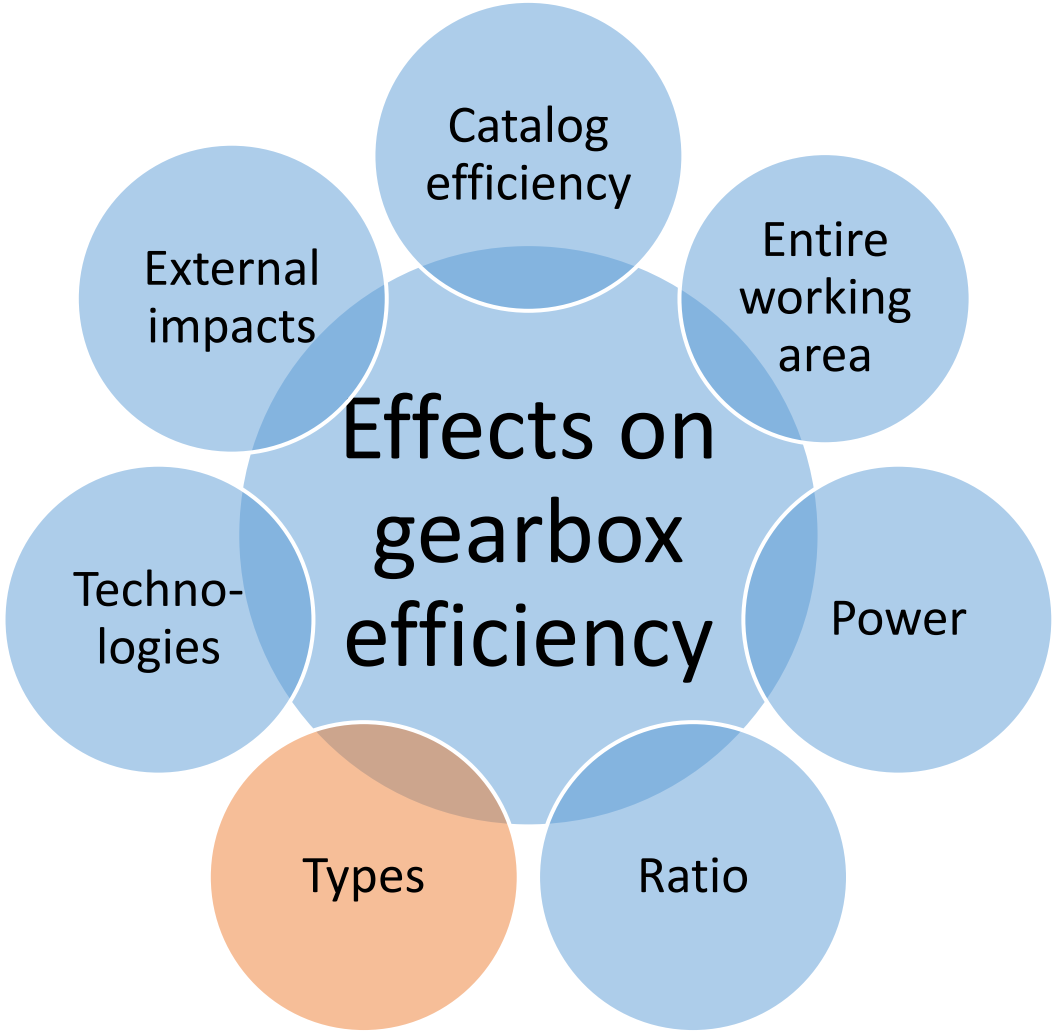
Helical (bevel) gear: internal manufacturer info



Ratio ↗: η ↘

Power ↗ : smaller Δ

Tested gears – Relevant questions



Results – Type dependency

Observations:

- Depending on space availability: Straight ↔ Right-angled
- Efficiency difference?

Measurements:

	Brand E	Brand E	Brand E
Type	Right angled	Right angled	Straight
Technology	Helical bevel	Helical worm	helical
Stages	3	2	2
Ratio	11,41	11,67	10,93
Torque (Nm)	434	373	390
Power (kW)	5,58	4,7	5,23
Catalog efficiency	94%	90%	96%

Results – Type dependency

- Straight vs. right-angled

Type	Right angled	Straight	Right angled
Technology	Helical bevel	Helical	Helical worm
Catalog efficiency	94%	96%	90%
Measured efficiency	95,5%	95,5%	91,5%
Price (%)			

(100% = average price)

- No large difference in measured efficiency

Results – Type dependency

- Straight vs. right-angled

Type	Right angled	Straight	Right angled
Technology	Helical bevel	Helical	Helical worm
Catalog efficiency	94%	96%	90%
Measured efficiency	95,5%	95,5%	91,5%
Price (%)	147	54	98

(100% = average price)

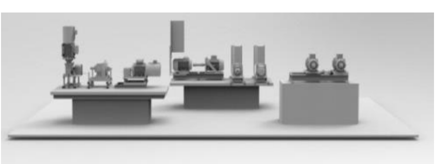
- No large difference in measured efficiency

BUT

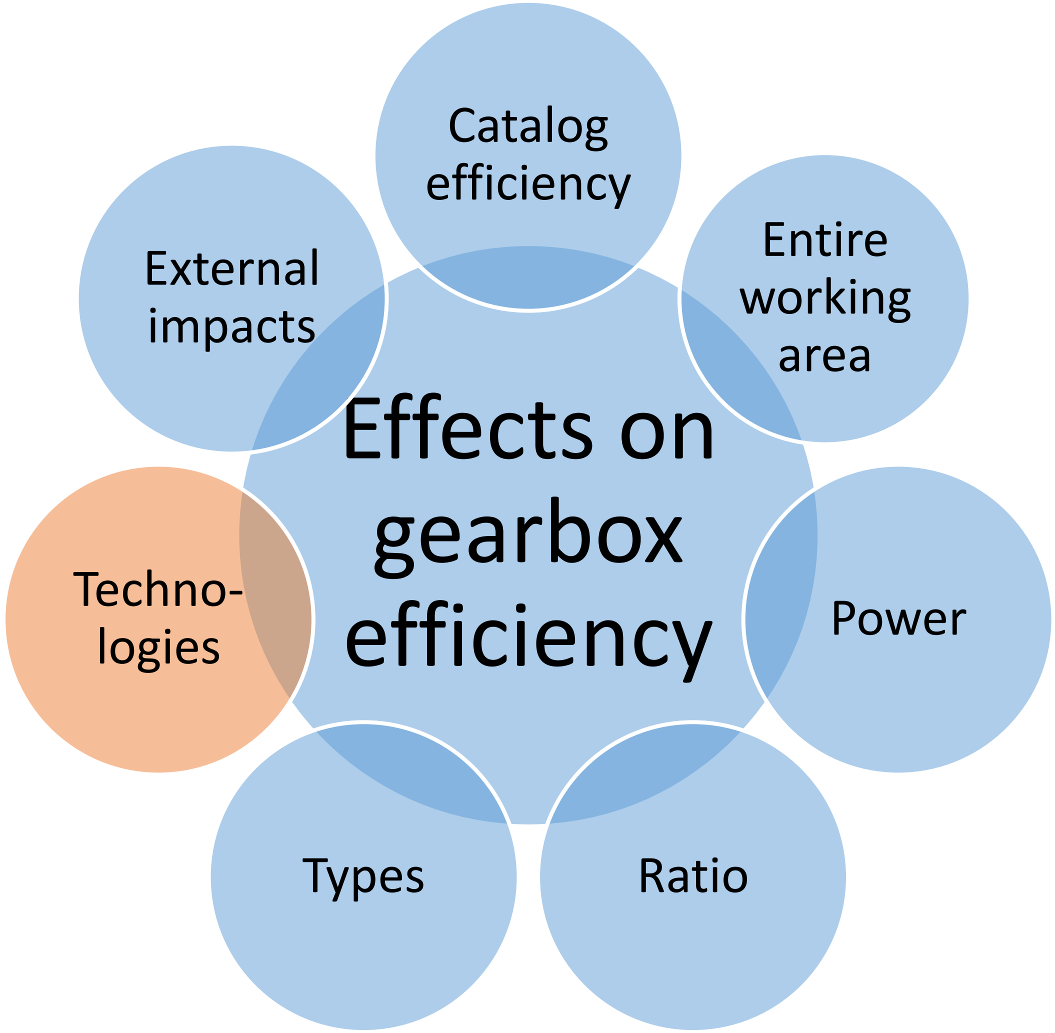
Large price difference!

↓

Prefer straight gears



Tested gears – Relevant questions



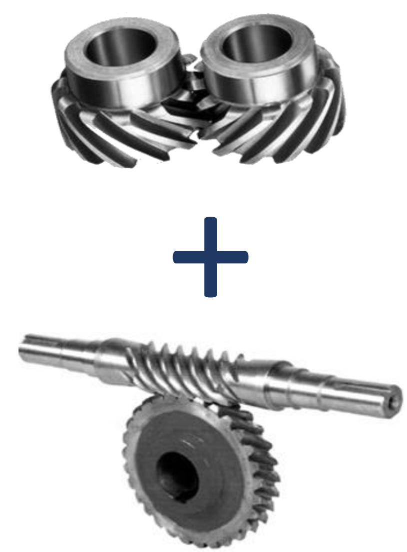
Results – Technology dependency

Observations:

- Commonly known: worm gear efficiency is low and less than bevel gears
  - What is the efficiency difference?
  - In entire working area?

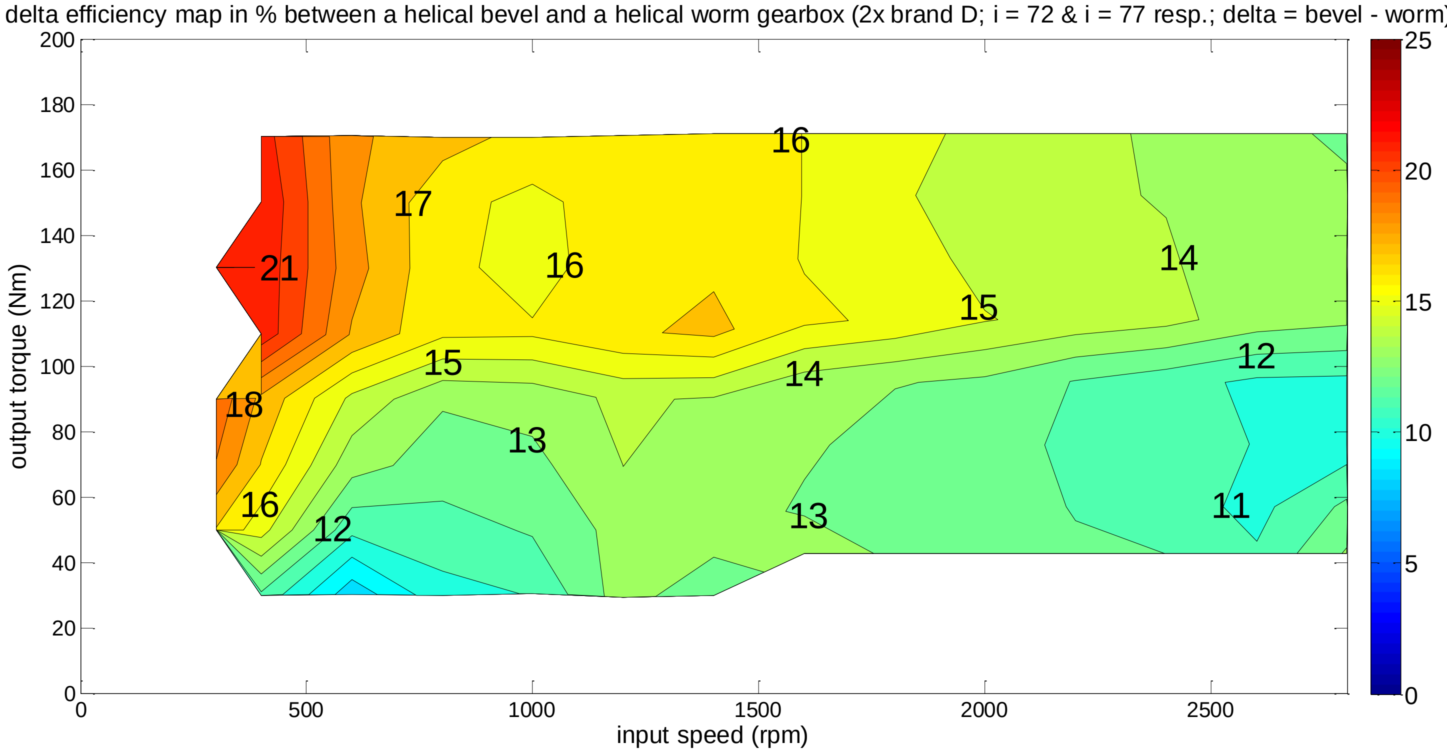
Measurement:

	Brand D	Brand D
Type	Right angled	Right angled
Technology	Helical bevel	Helical worm
Stages	3	2
Ratio	72,21	77
Torque (Nm)	190	180
Power (kW)	0,39	0,34
Catalog efficiency	95%	78%



Results – Technology dependency

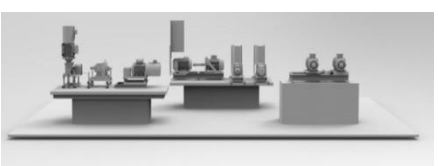
- Bevel vs. worm



Large efficiency difference
↓
Prefer bevel gears

Note:
- Sometimes self-locking from worm gears is desired
- Applications with few running hours

- Bevel gear efficiency highest, at nominal point + 16%



Conclusions on test results

- Catalog efficiency usually HIGHER than real efficiency
  - Higher ratio, smaller power → bigger difference
- Efficiency in entire working area is mainly load dependent
  - Lower torque → lower efficiency
  - Low ratio, higher power → less variation
- Higher power gears → higher efficiency (similar to motors)
- Smaller ratio → higher efficiency
  - For worm gears but also for helical (bevel) gears

Conclusions on test results

- Straight and bevel gear comparable efficient
  - Straight gear a lot cheaper
- Bevel gear always higher efficiency than worm gear
  - Self-locking can be necessary
- External parameters also influence efficiency
  - Temperature
  - Lubricants
  - Oil level

Guidelines for energy efficient belt drives

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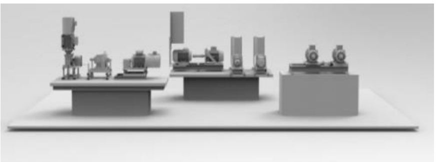
IWT Tetra project nr. 130201

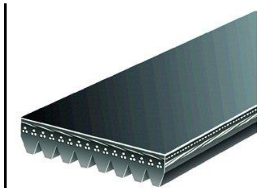


overview

- design
  - belt type
  - load profile
  - number of belts
  - pulley diameter
  - belt tensioner
- lifetime
  - mounting
  - maintenance
    - alignment
    - belt tension
    - wear

design

belt type

				
type	wedge belt (SP) or V-belt	cogged wedge belt (XP) or cogged V-belt	poly V- or ribbed belt	synchronous or timing belt
type in Dutch	smalprofiel V-riem	getande smalprofiel V-riem	poly V-riem	synchroonriem
efficiency according to manufacturer	up to 97%	up to 97%	up to 96%	up to 98%

asynchronous belts

belt type

- no standard on measuring belt drive efficiency exists
    - how to measure
    - which belts to measure (length, profile, pulley diameters, ...)

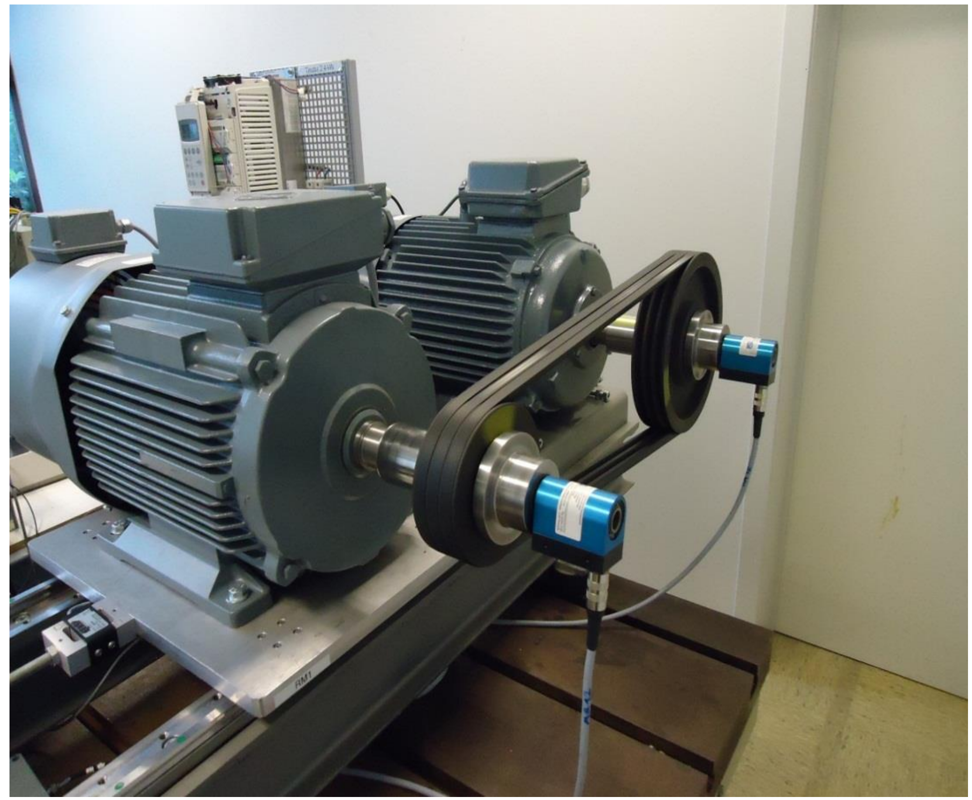
- we created a test procedure
    - phase 1: running in (reproducibility check)
    - phase 2: measuring efficiency under various conditions

    - tested belts are based on real cases in companies

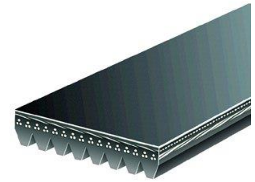
belt type

- construction of belt drive test rig (up to 15 kW)
- based on:

$$efficiency = \frac{Power_{out}}{Power_{in}} = \frac{\omega_{out} * T_{out}}{\omega_{in} * T_{in}}$$

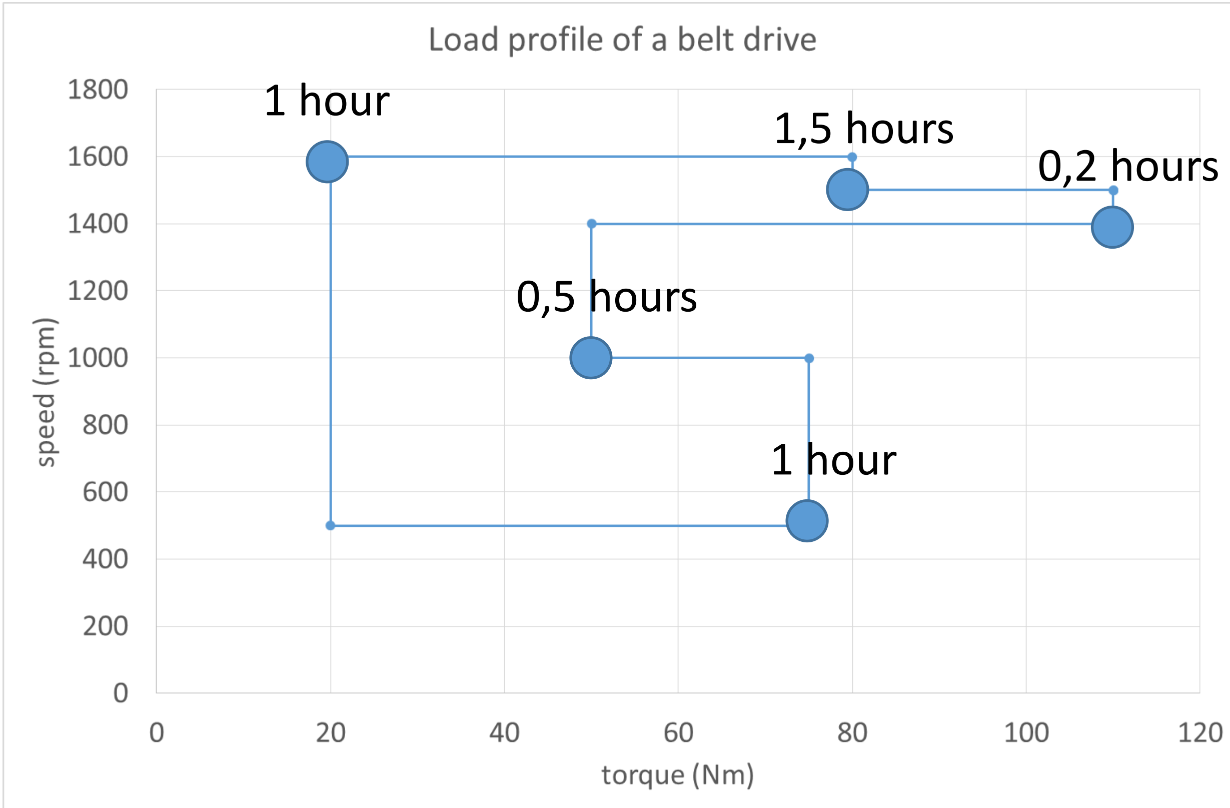


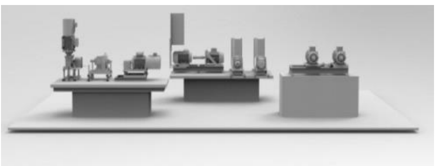
belt type

				
type	wedge belt (SP)	cogged wedge belt (XP)	poly V-belt	synchronous belt
type in Dutch	smalprofiel V-riem	getande smalprofiel V-riem	poly V-riem	synchroonriem
efficiency according to manufacturer	up to 97%	up to 97%	up to 96%	up to 98%
measured	up to 97%	up to 98%	up to 97%	up to 99%

load profile

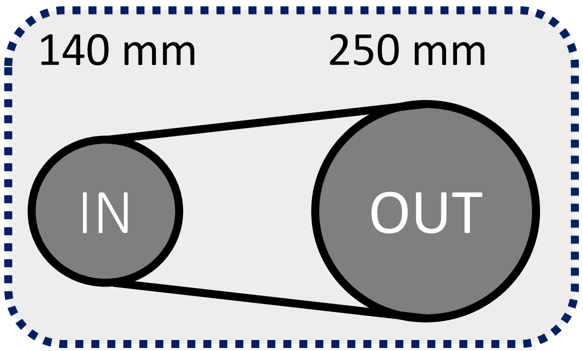
- how can we make a correct estimation of the total efficiency?
  - by using iso efficiency maps

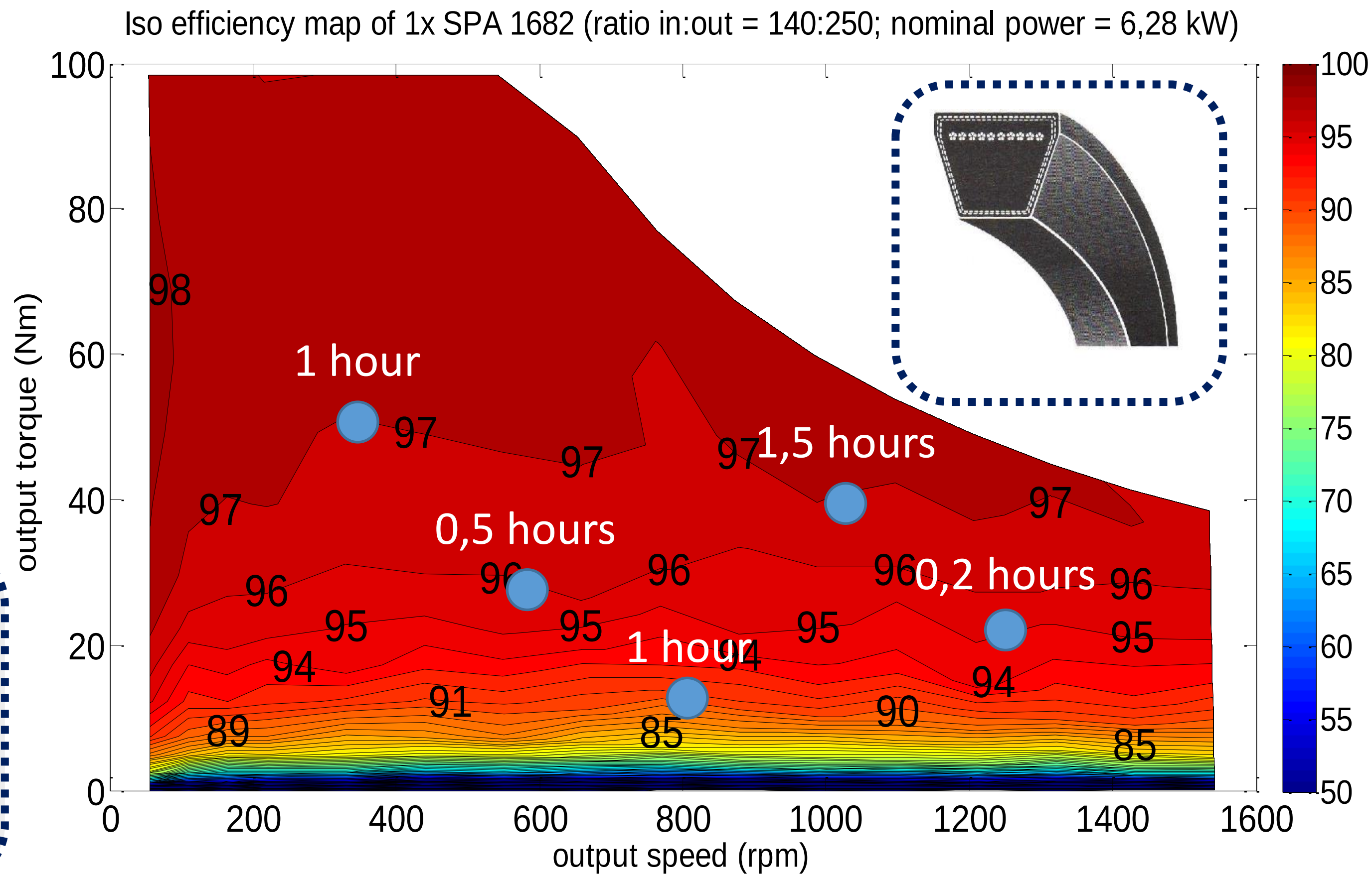




iso efficiency maps

- 1x SPA 1682
- up to 97 %
- load dependent
- efficiency remains high quite long



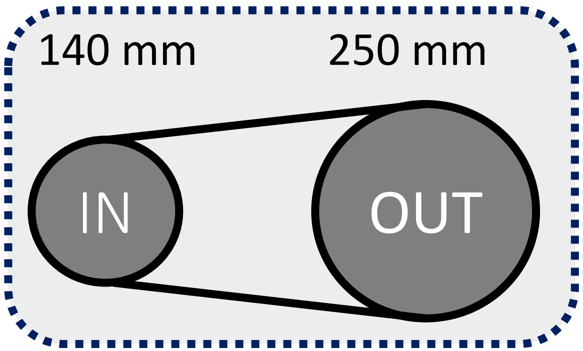


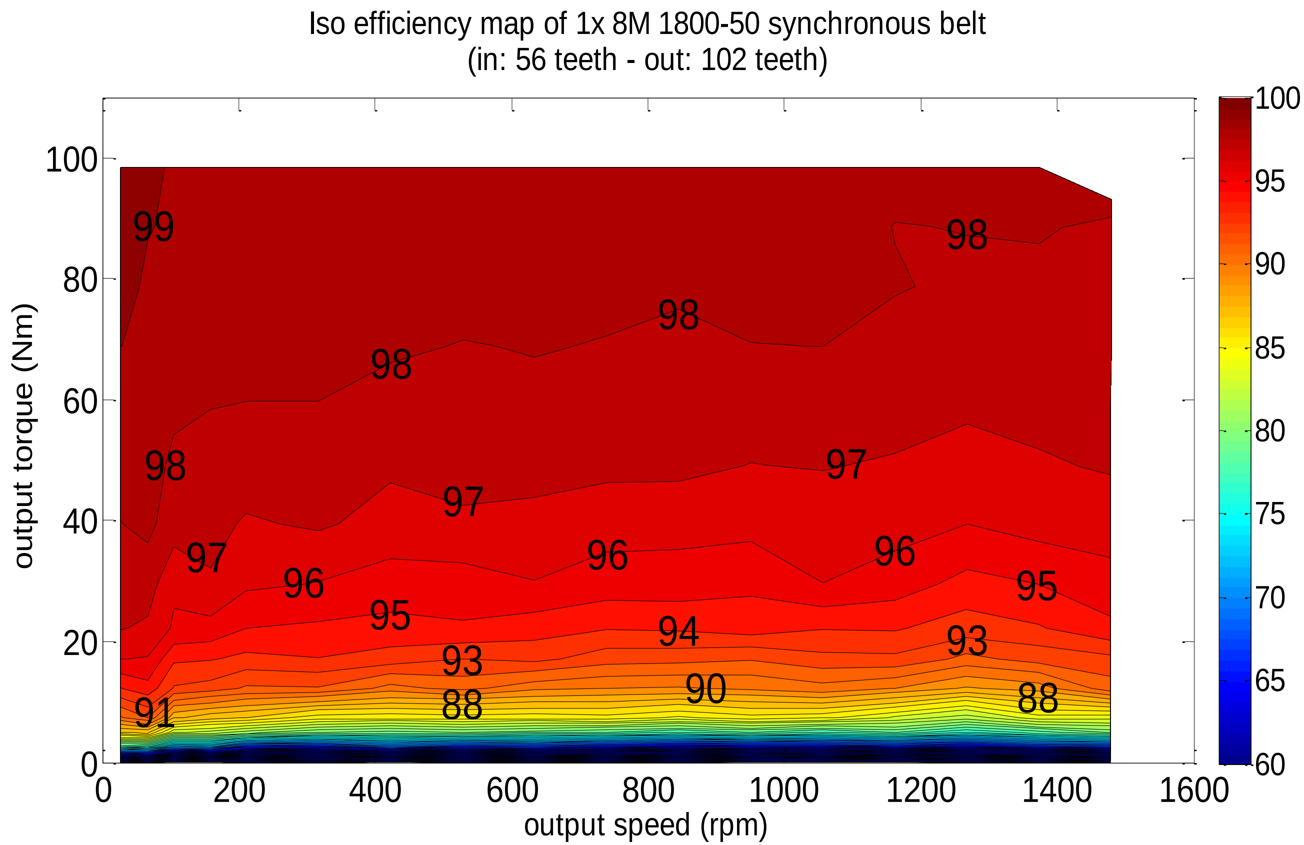
- use load profile for estimating total belt drive efficiency

design

iso efficiency maps

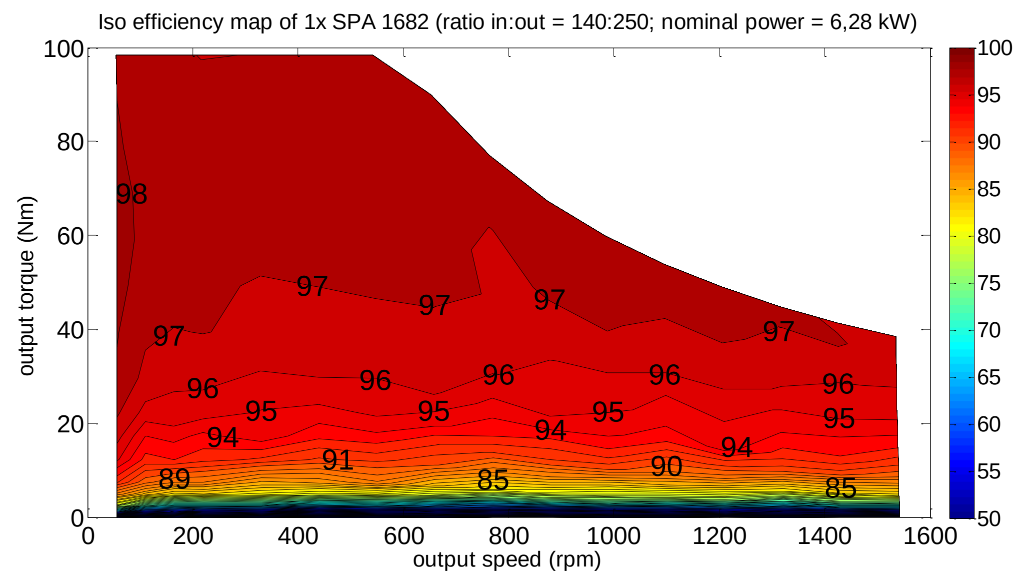
- 1x 8M 1800-50
- up to 99 %
- load dependent
- efficiency remains high very long

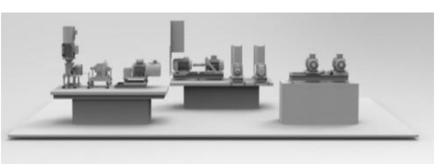




iso efficiency maps: conclusion

- before: only ‘up to’-efficiencies were known
- now: efficiency in the whole working area is known
- all belt types have a similar shaped map

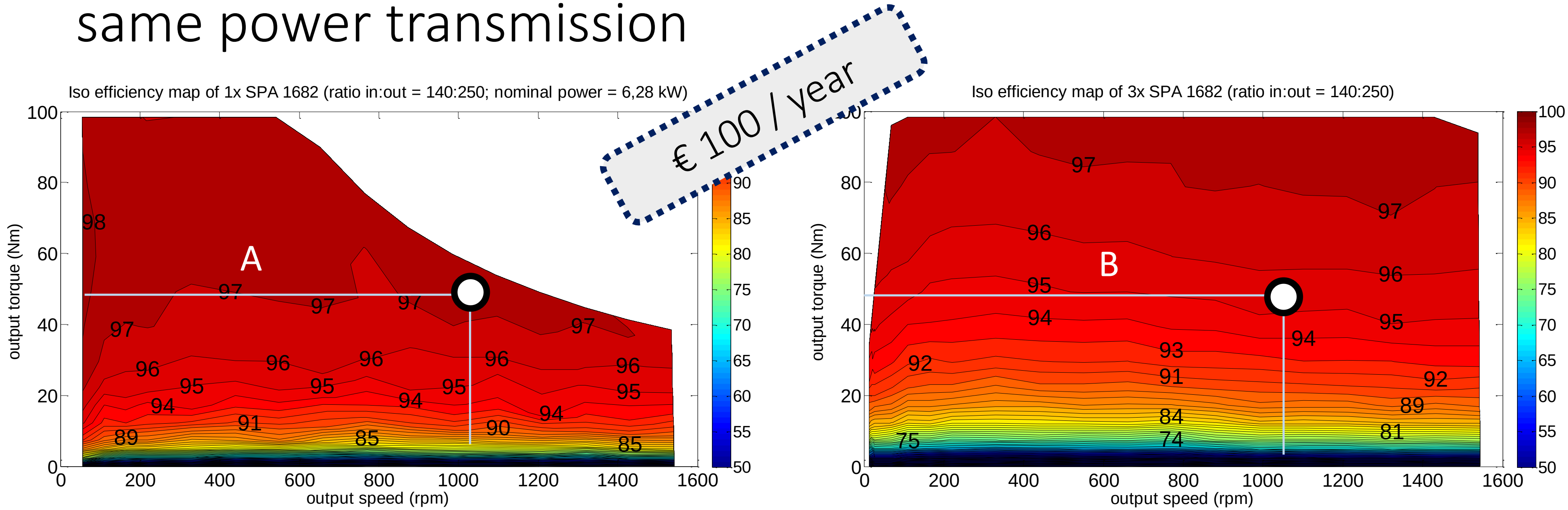




design

number of belts

- important conclusion from iso efficiency maps is to keep the belts well loaded
- 1x SPA 1682 vs. 3x SPA 1682 → 2 % loss using 3x SPA for same power transmission



pulley diameter

- manufacturers state that larger diameter is better
  - efficiency (bigger bending radius = easier to bend for the belt)
  - less belt tension
  - less radial load on bearings

- but: no numbers available!
  - no economic analysis possible

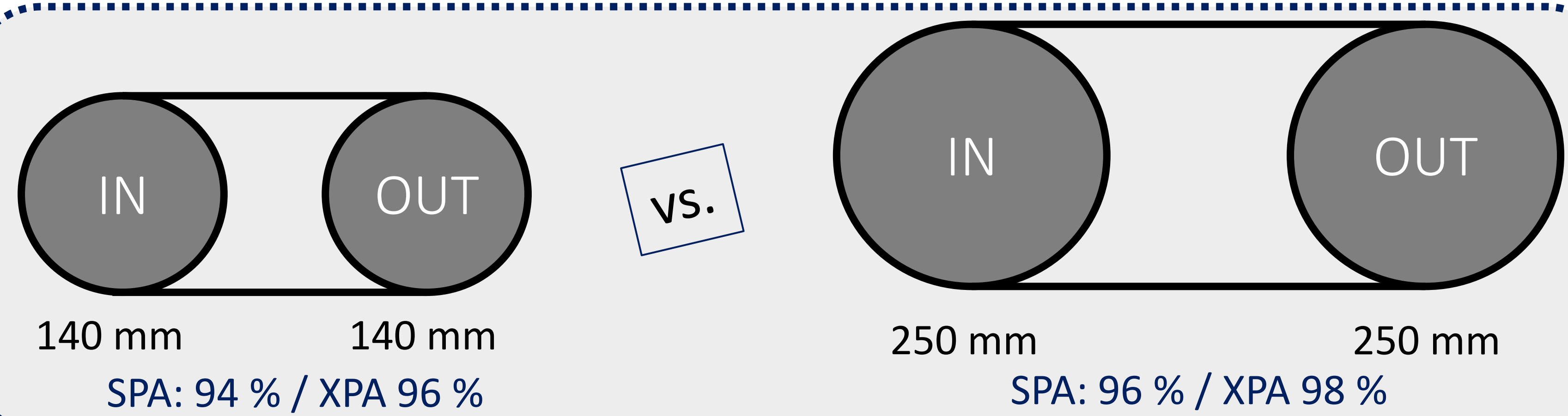
design

pulley diameter

SP type

XP type

- testing the effect of pulley diameter on efficiency
  - ratio 1:1



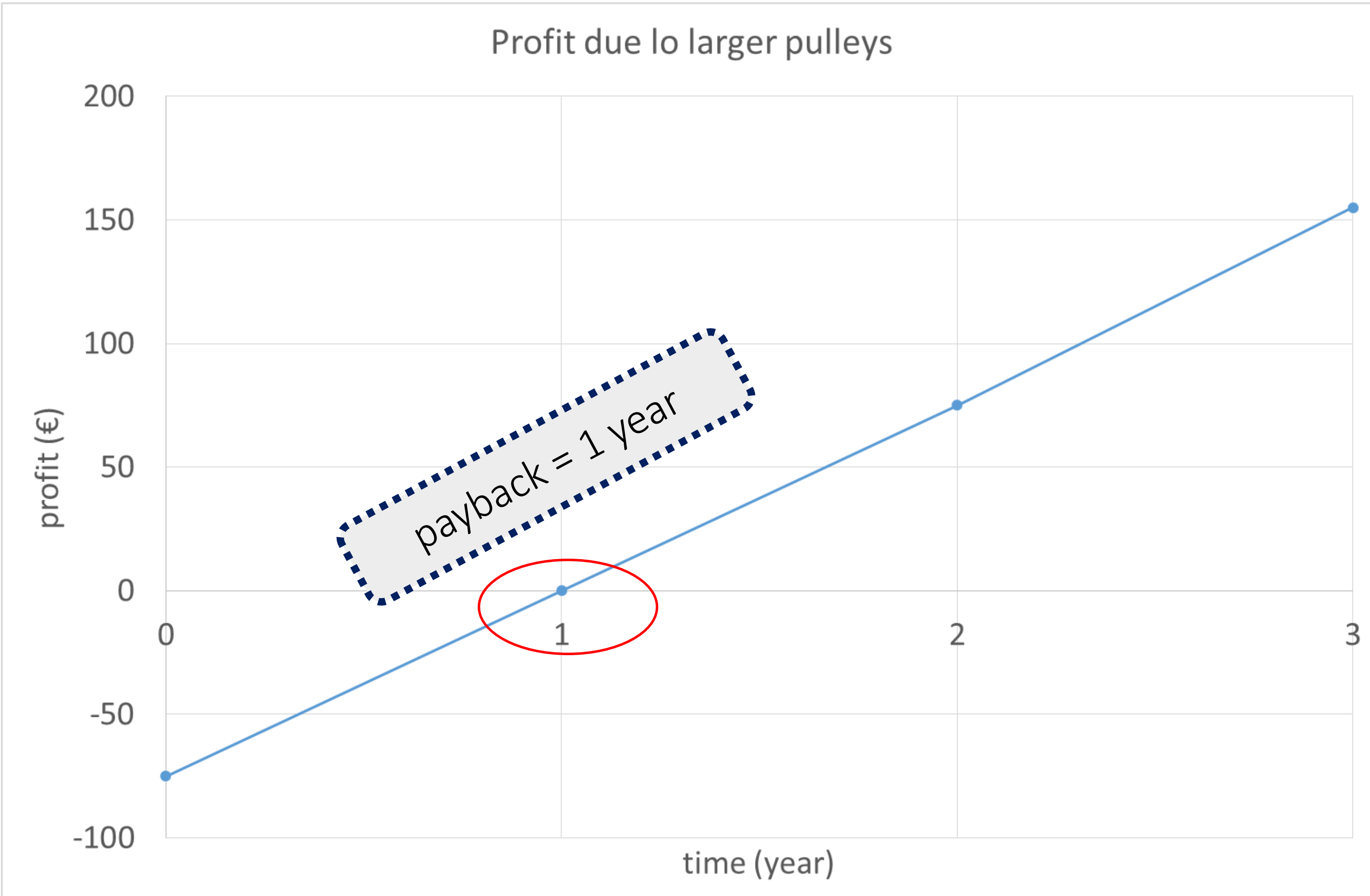
1x SPA/XPA 1532	**€ 25**	€ 135
pulley 140 mm + taper bush (2x)	**€ 55 (2x)**	

1x SPA/XPA 1882	**€ 30**	€ 210
pulley 250 mm + taper bush (2x)	**€ 90 (2x)**	

initial extra cost: € 75

design

pulley diameter

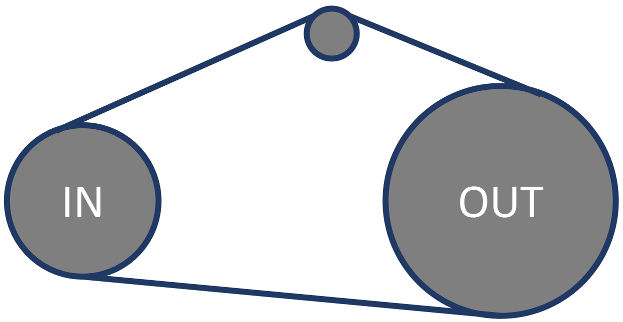


kW	6
cost of energy (€/kWh)	0,12
hours/year	5000
energy cost (€/year)	3600
efficiency gain (%)	2
gain/year (€)	**72**

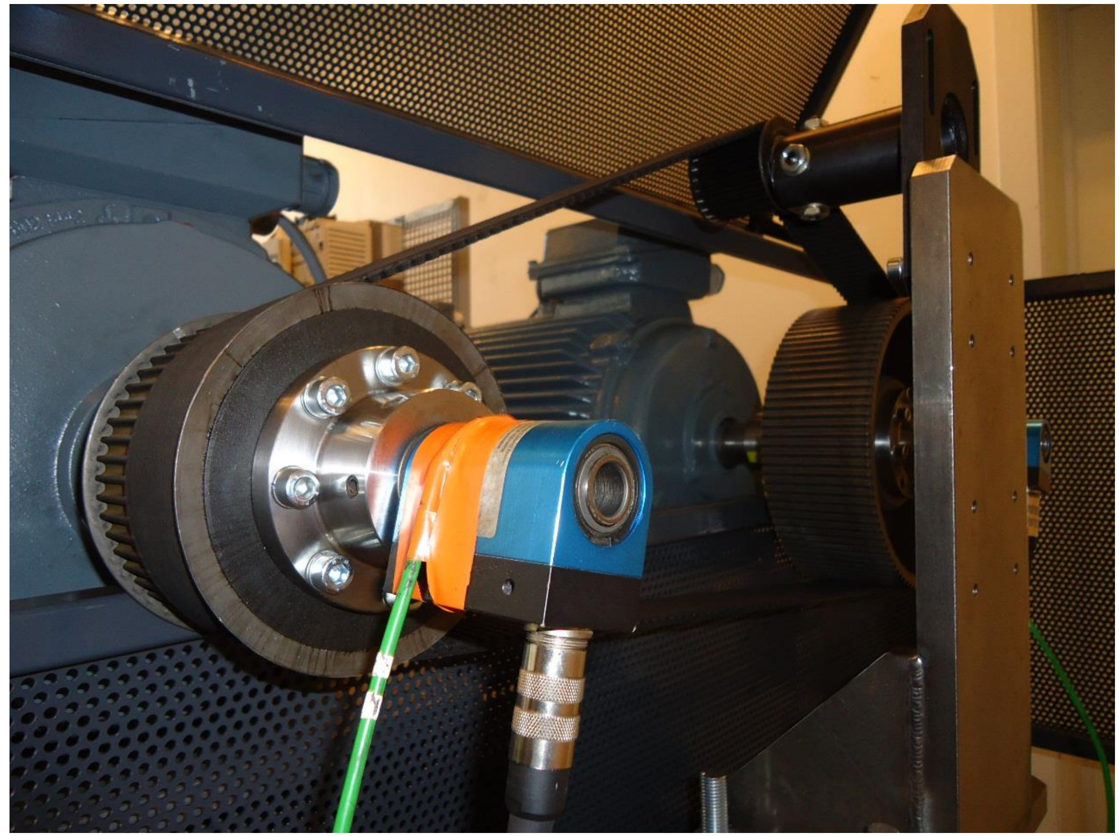
design

belt tensioner

- toothed tensioner is on the inside of the belt
  - at the slack side

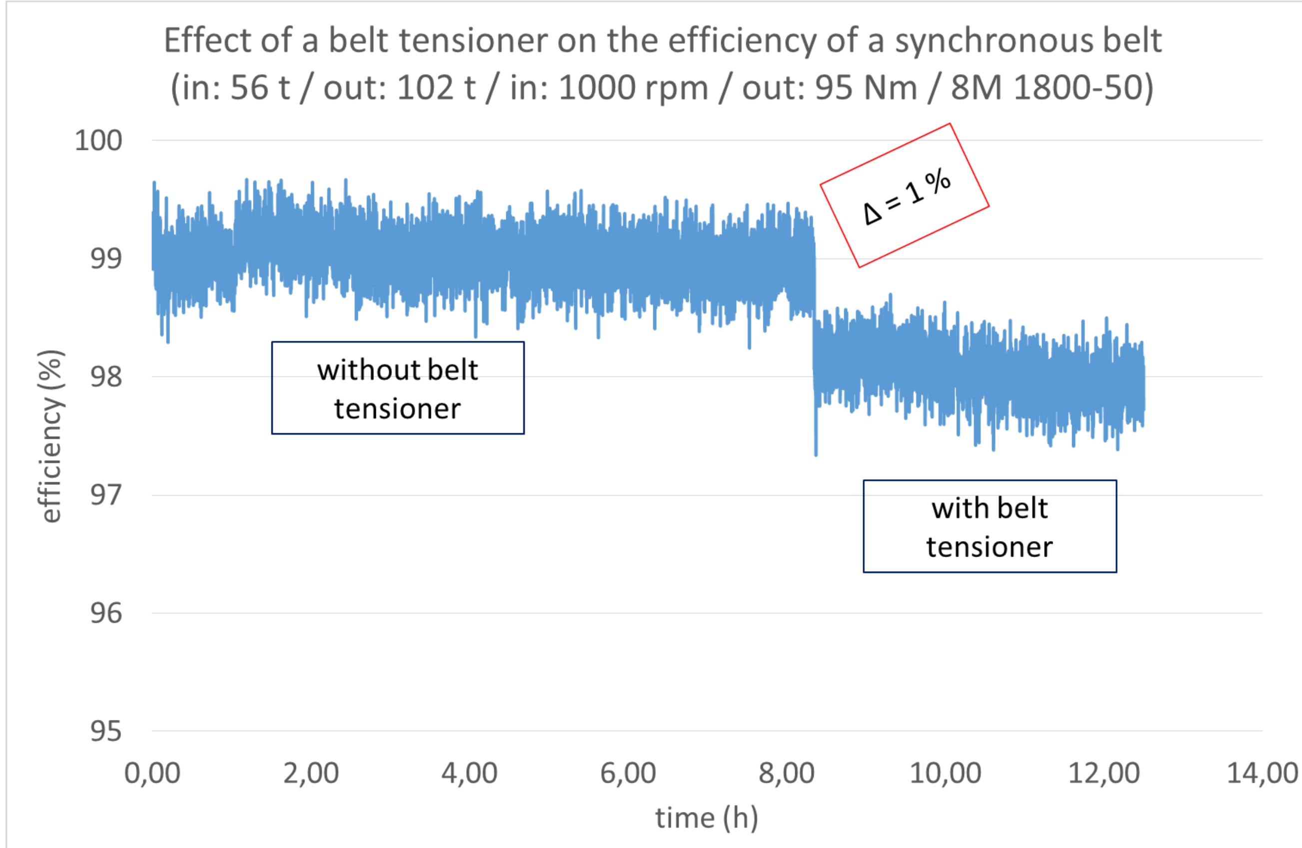


- extra element → extra cost and more losses
  - how much losses?



belt tensioner

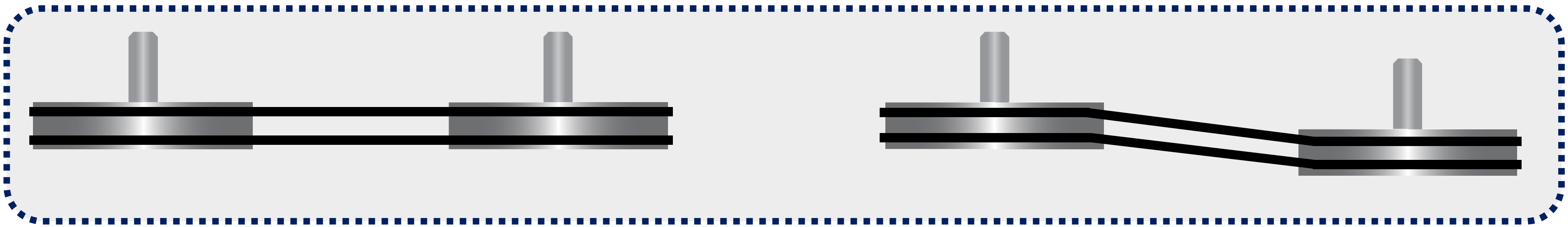
- from 99 to 98 %
- load is spread across more elements



- conclusion
  - pro: less load
  - contra: more moving parts and lower efficiency

alignment

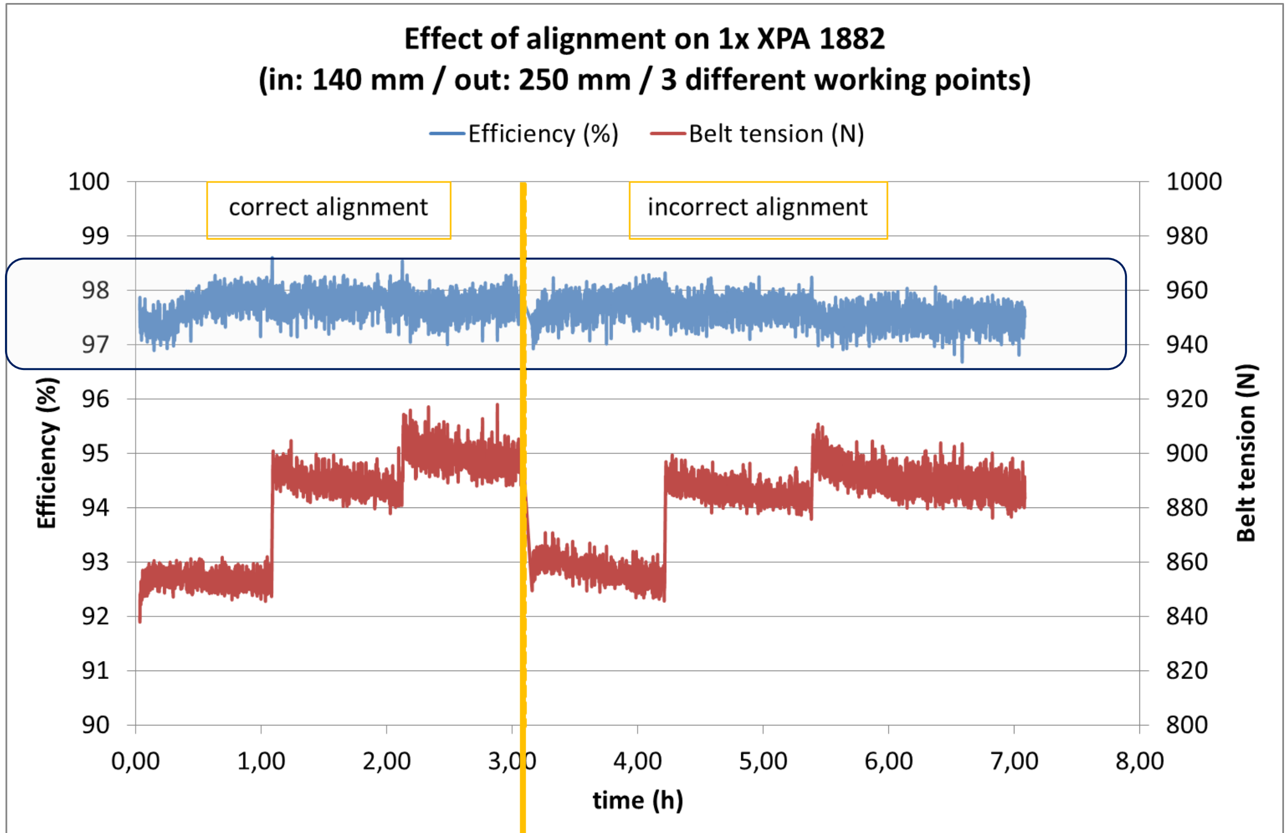
- a lot of equipment on the market
  - are they worth the investment from an energy efficiency point of view?
- test on XPA belts with misalignment of **1,5 cm on 60 cm**
  - XPA belts are less easily twisted axially than SPA belts
  - synchronous belts run off when misaligned → **difficult to align**
  - poly V belts are not included in this test

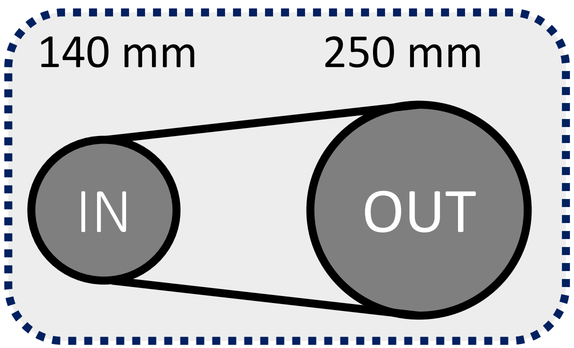


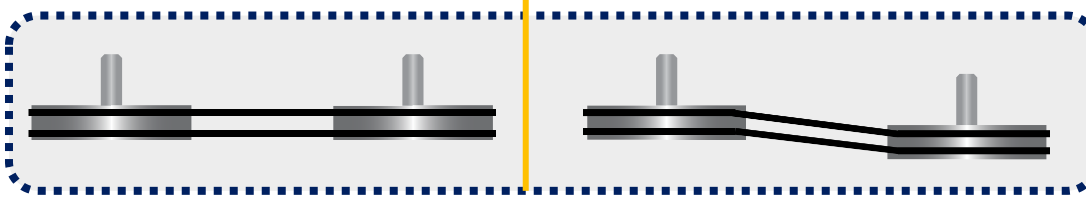
lifetime

alignment

- 1x XPA 1882
- 3 working points
  - correct tension

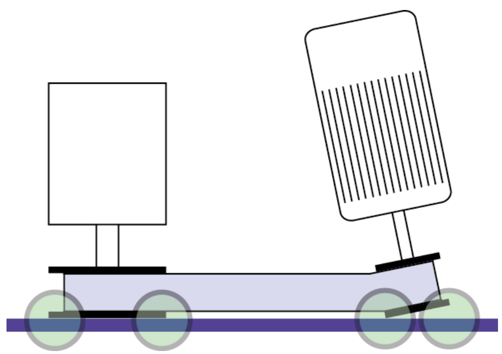


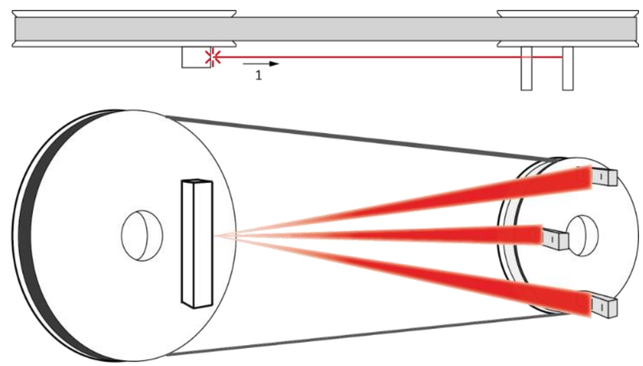




alignment: conclusion

- no measureable effect on energy efficiency
- up to approx. 2 meters a straight bar will do the job
  - longer distance: e.g. laser equipment might be useful since a bar will have the tendency to bend





- but: good alignment most likely extends belt life
  - align until acceptable

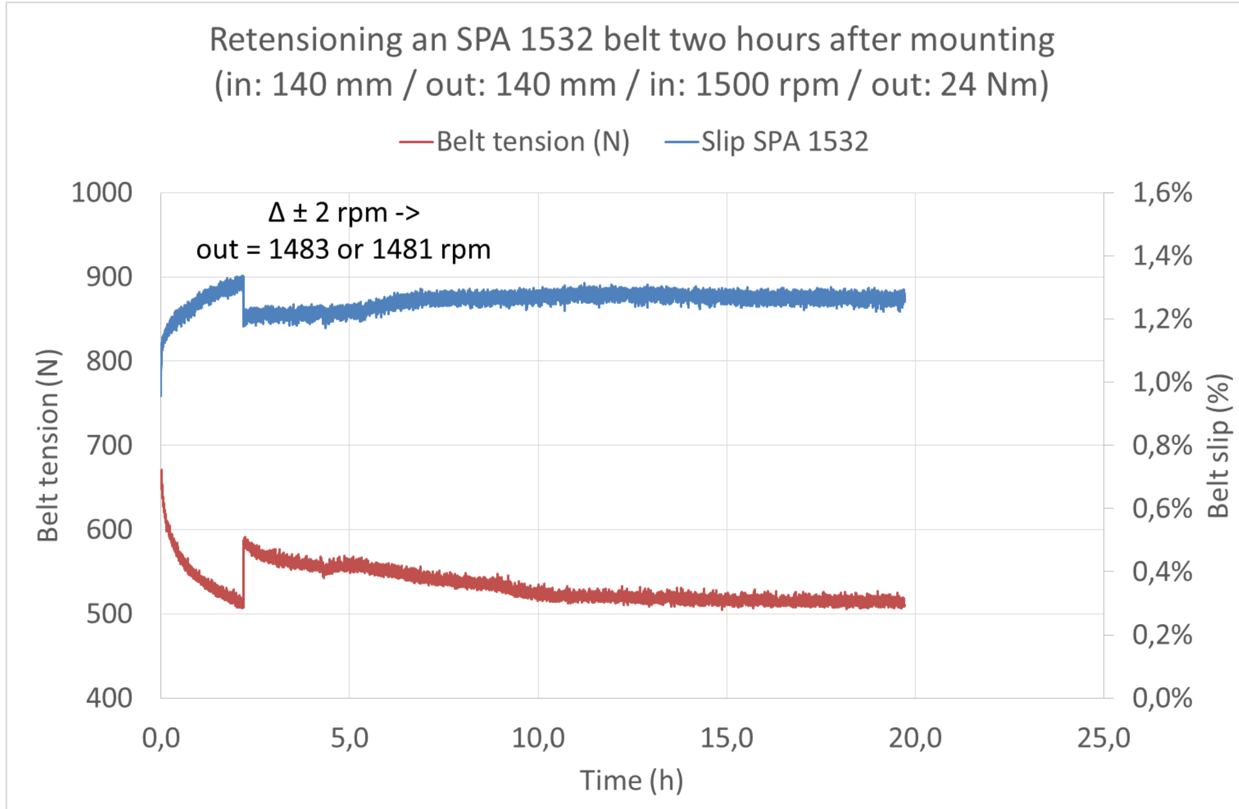
belt tension

- when mounted, belts should be retensioned after 1 hour according to manufacturers
- lower tension of V-belts should result in slip: efficiency ↓
- higher tension is bad for bearings etc.: efficiency ↕

belt tension

- retensioning ± 1 hour after mounting: if possible, do so
  - belt tension drops
  - efficiency is stable
    - Δ = 2 rpm
  - slip: 1 – 3% is ok

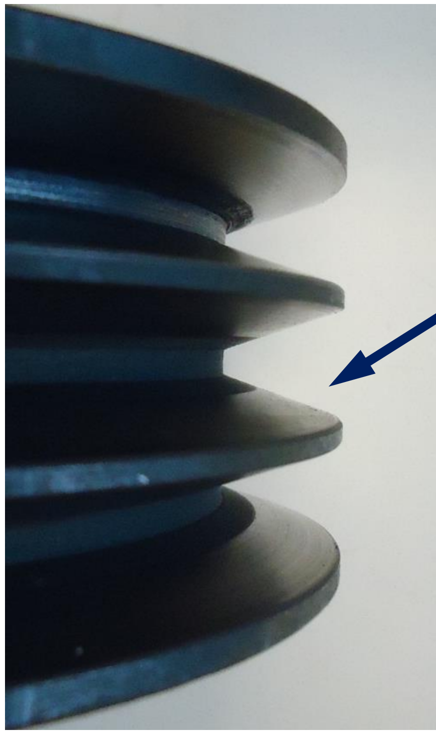
  - some belts are “maintenance-free”, ask your supplier



lifetime

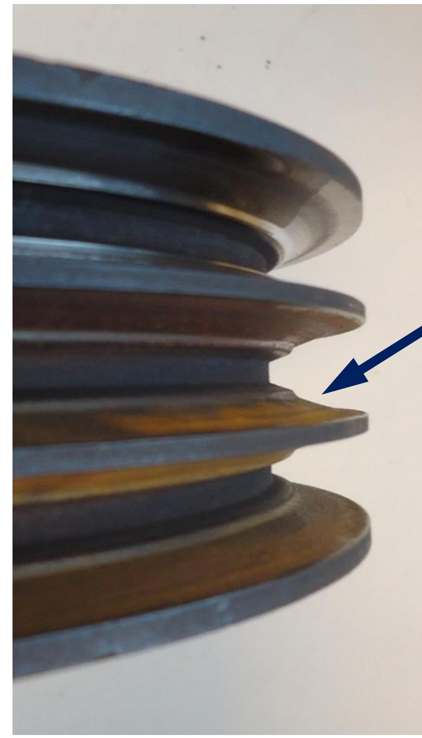
worn pulleys

- test with SPA and XPA belt on worn pulleys



no edge +
straight wall

"V-shape"

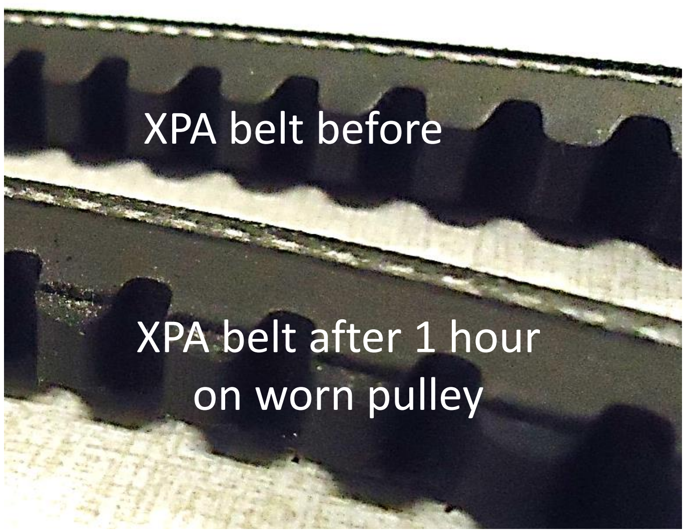


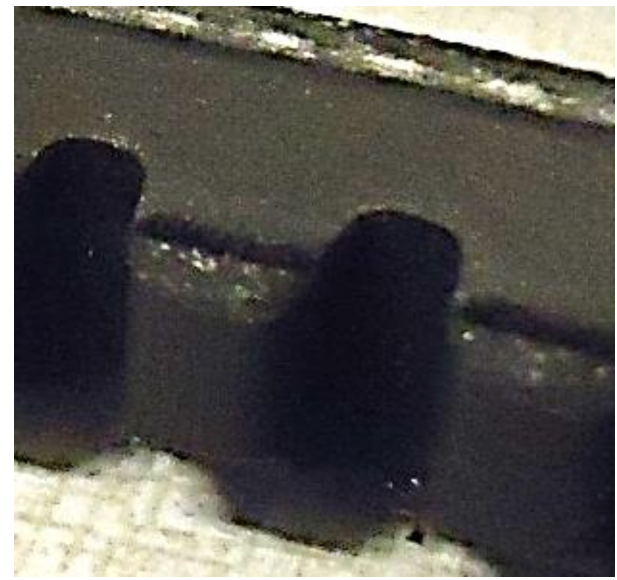
edge +
curved wall

How a pulley should be	How a worn pulley looks like

worn pulleys

- within the first hour efficiency dropped at least 3 % due to slip
- belts show signs of wear as they lie deeper in the pulley





worn pulleys: conclusion

- if a machine starts running slower
  - check for signs of worn out pulleys
  - check belt tension and retension if necessary

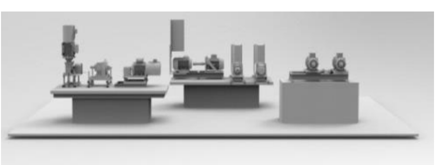
- change worn pulleys immediately

conclusion: design

belt type	Asynchronous: cogged wedge belt (XP) are the most efficient Synchronous: most efficient of all types, but harder to install (alignment) and noisy
load profile	Catalog efficiencies are stated ‘up to’. Use iso efficiency maps to make a good estimation of the total belt drive efficiency
number of belts	Avoid overdimensioning if it is not critical. The savings in energy and in buying fewer belts are worth it. Well loaded belts are more efficient (remember load-dependency in iso efficiency maps)
pulley diameter	Whenever possible, use larger pulley diameters. Efficiency gains were recorded. Machine life will extend as everything is less loaded.
belt tensioner	More moving parts, which are less loaded. As expected, efficiency dropped.

conclusion: lifetime & economics

alignment	From an energy efficiency point of view, this is less crucial. From a belt life point of view, it is assumed that good alignment is to be preferred.
belt tension	Correct tension allows for a constant machine speed (although it will still vary under different loads for asynchronous belts). Higher tension decreases the component's life. Lower tension increases slip and belt wear. Ask your supplier for "maintenance-free" belts.
wear	Worn pulleys need to be changed immediately. Depending on the wear, efficiency drops on a very short time base (hours to days).
cost of energy	Think TCO (Total Cost of Ownership) **Well designed and maintained belt drives might save you 4 to 5 %!**



Load efficiency and EU fan regulation

Elewijn Algoet

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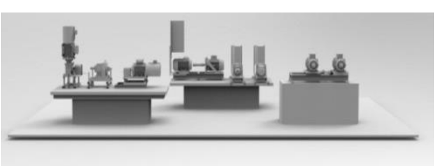
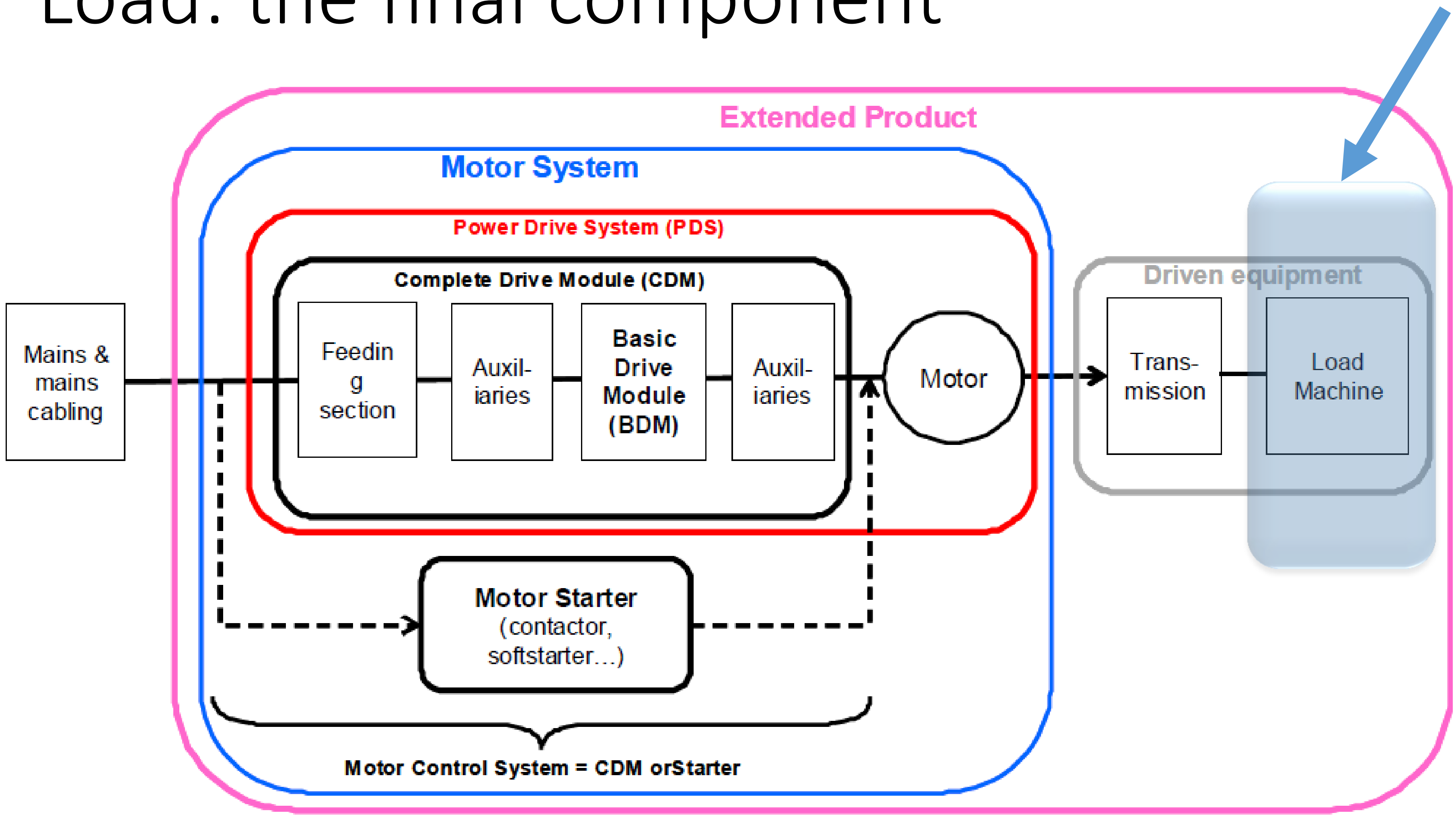
IWT Tetra project nr. 130201

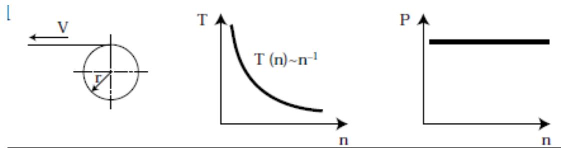


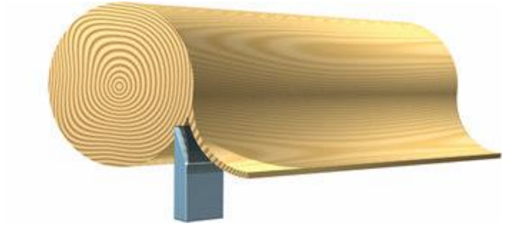
Load: the final component



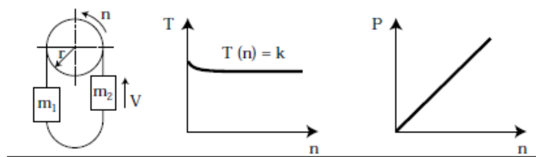
Four different types of load

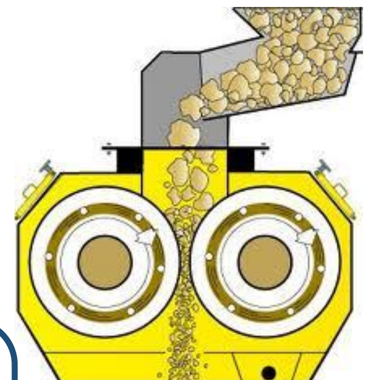
- Winding material under tension



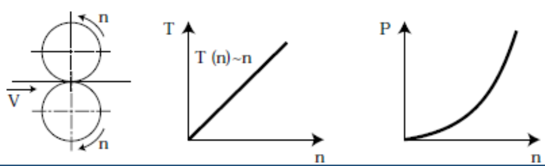


- Conveyor belts, cranes, …

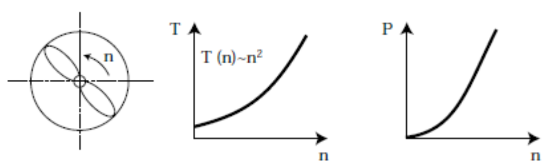




- Rollers, …



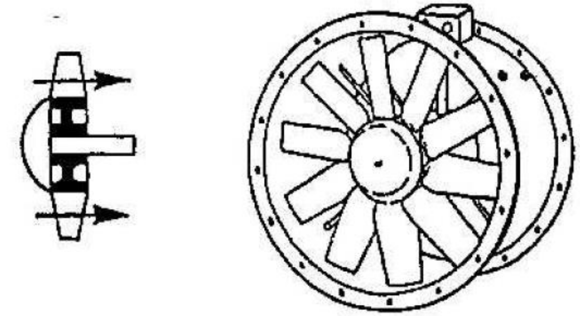
- Centrifugal force (e.g. pumps, fans)



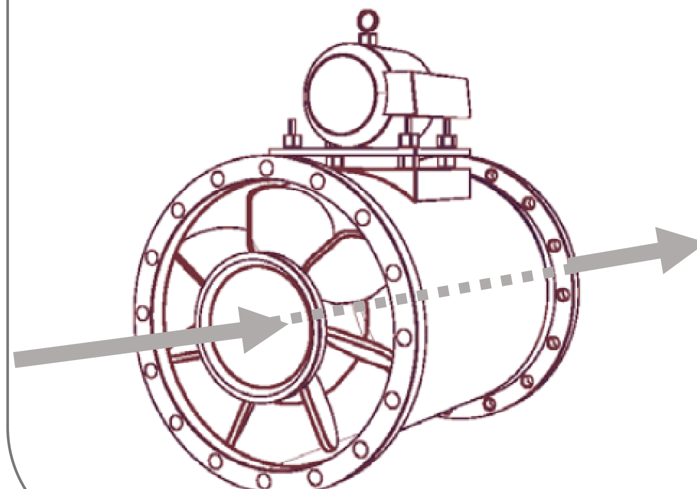
- Local relevance
- EU 20-20-20

Fan efficiency: types of fans

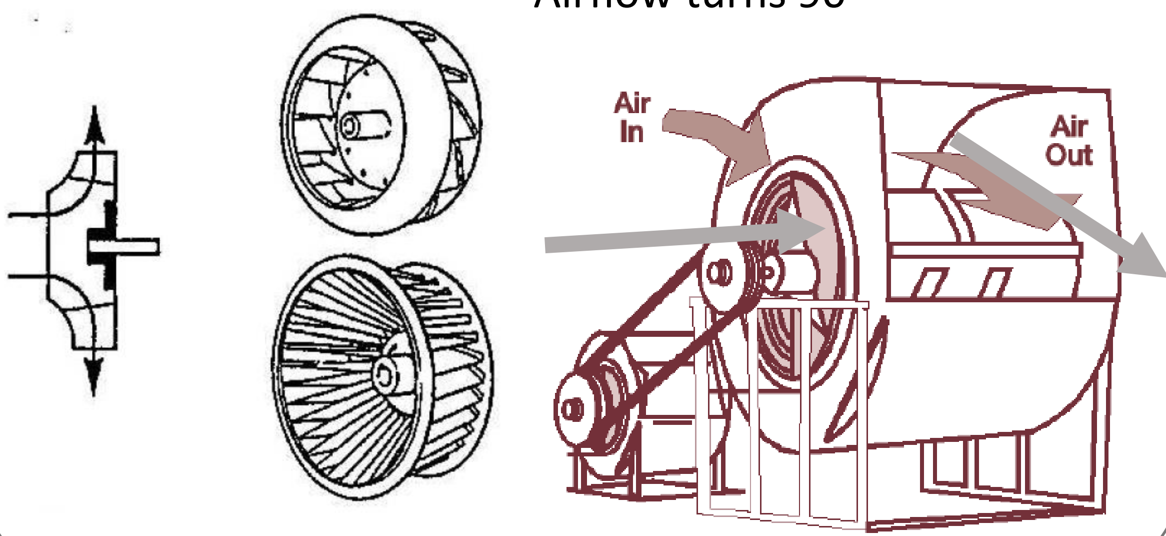
- Two groups: centrifugal and axial



Axial:
Airflow goes straight through

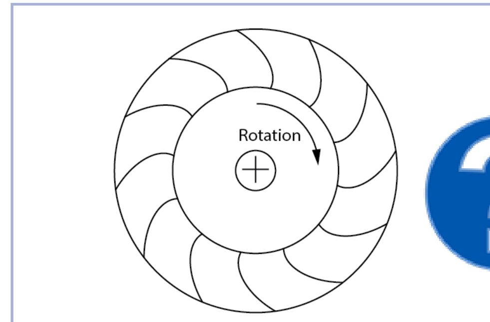


Radial or centrifugal:
Airflow turns 90°



Fan efficiency: types of fans

- Centrifugal fans: construction types



Backward-Curved Blade Fan

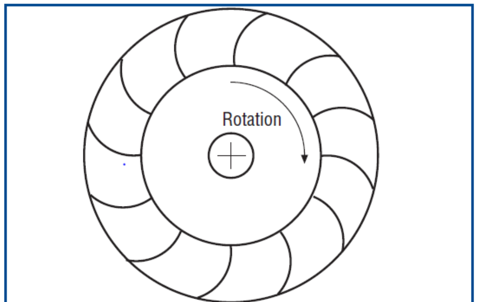


Figure 2-1. Forward-Curved Blade Fan

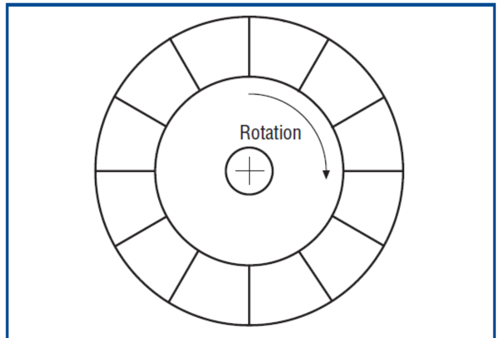


Figure 2-3. Radial-Blade Centrifugal Fan

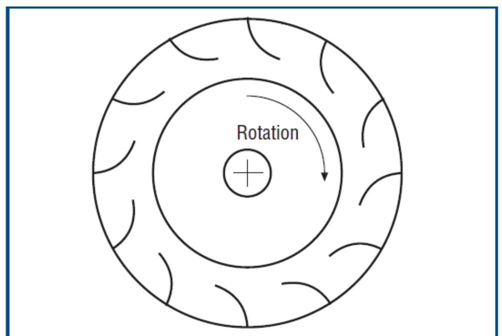


Figure 2-4. Radial-Tip Centrifugal Fan

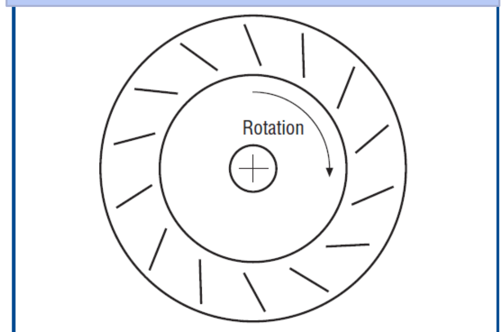


Figure 2-6. Backward-Inclined Fan

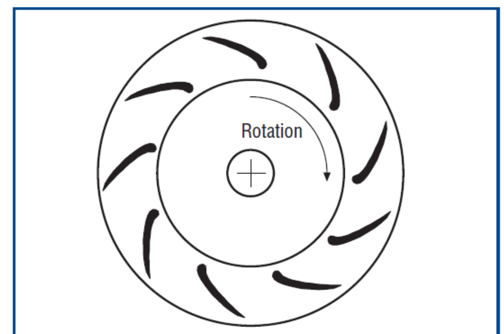


Figure 2-7. Backward-Inclined Centrifugal Airfoil Fan

Fan efficiency: types of fans

- Axial fans: construction types

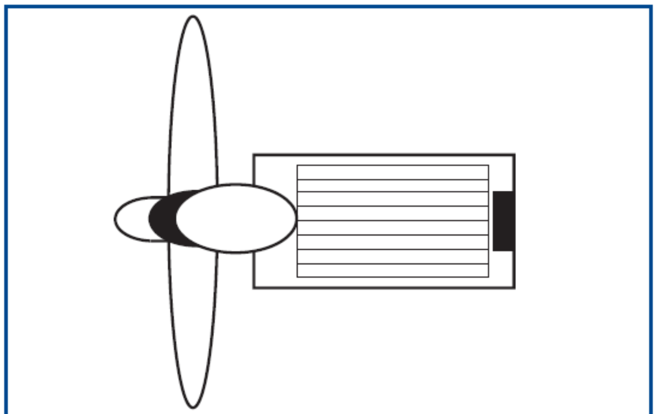


Figure 2-9. Propeller Fan

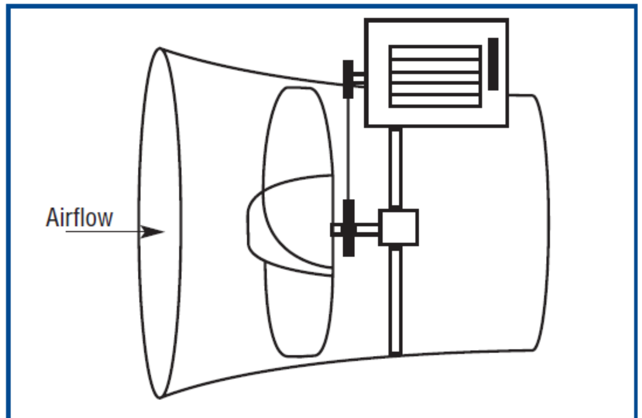


Figure 2-11. Tubeaxial Fan

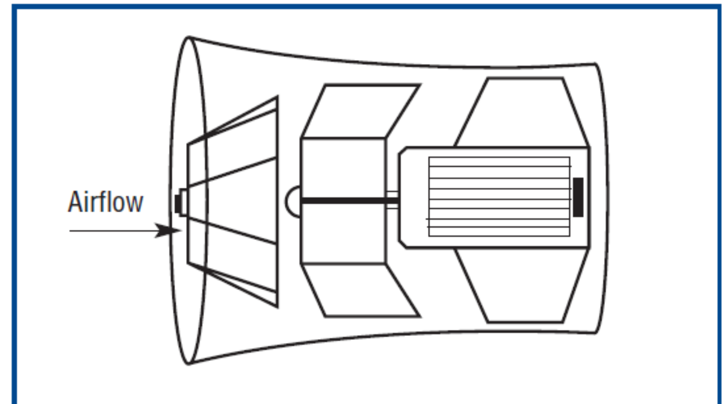
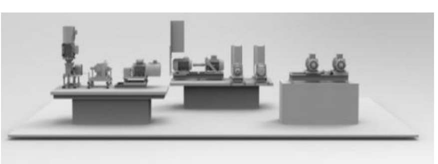


Figure 2-13. Vaneaxial Fan

Fan efficiency: maximum values

Type of fan	Highest efficiency (%)	Highest possible efficiency according to EU (%)
AXIAL		
Propeller	45 – 50	65 – 70
Tubeaxial	67 – 72	74 – 82
Vaneaxial	78 – 85	
CENTRIFUGAL		
Forward curved	60 – 65	70 – 80
Radial	69 – 75	80
Radial tip	72 – 79	89
Backward straight	77 - 80	
Backward curved	79 – 83	85 – 88
Backward airfoil	86 – 88	



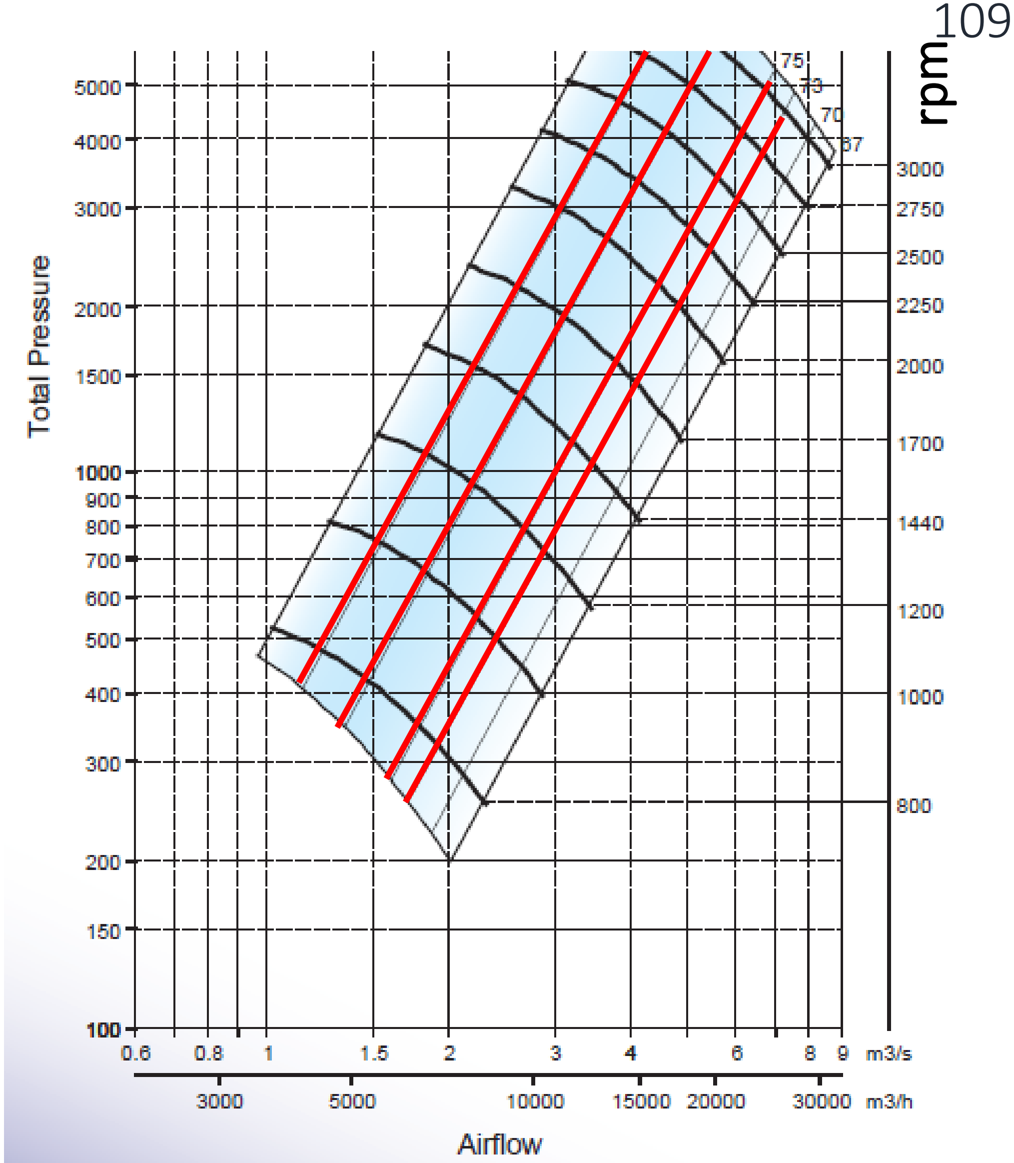
Characterization of different types of fans

- Process parameters
    - Flow rate
    - Pressure
    - Broadly
        - Axial: high flow
        - Centrifugal: high pressure

- Application area
    - Clean air vs. polluted air/material handling

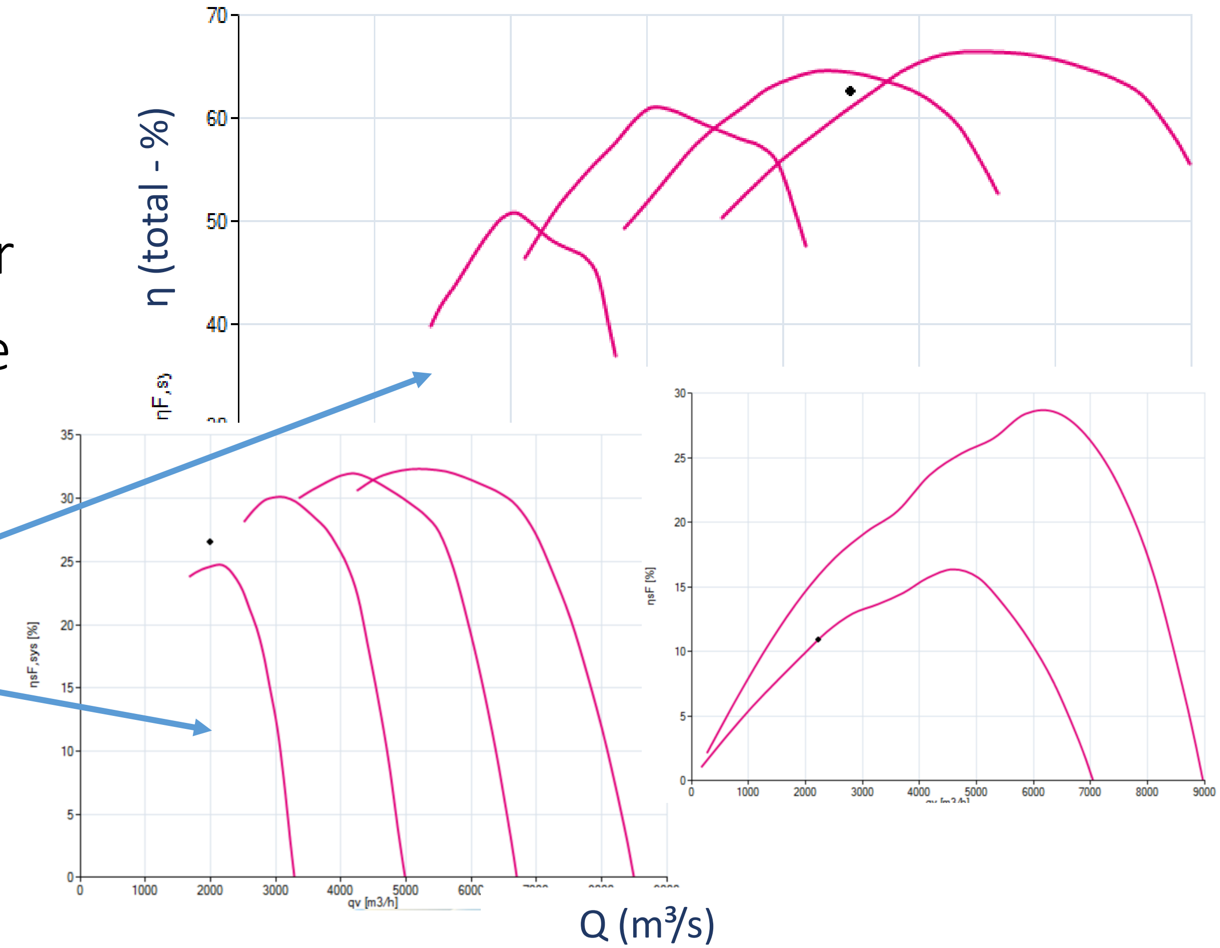
Reading fan curves

- Fan curve
  - Pressure and airflow
- Efficiency curve/line
- Single speed or multiple speed values (this case)
- Power curve
  - not in this example, can be calculated via P = p*Q/η



Part load efficiency of fans

- Via www.fanselect.info (Ziehl Abegg) among other
- Own test rig too expensive
- VSD: efficiency as a function of speed change
  - Centrifugal fans
  - Axial fans
- Not an exact science!



Fan efficiency: maximum values

Type of fan	Highest efficiency (%)	Highest possible efficiency according to EU (%)
AXIAL		
Propeller	45 – 50	65 – 70
Tubeaxial	67 – 72	74 – 82
Vaneaxial	78 – 85	
CENTRIFUGAL		
Forward curved	60 – 65	70 – 80
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Radial tip	72 – 79	89
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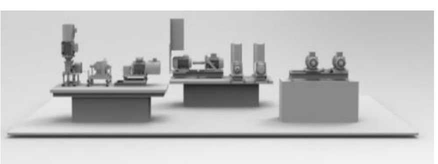
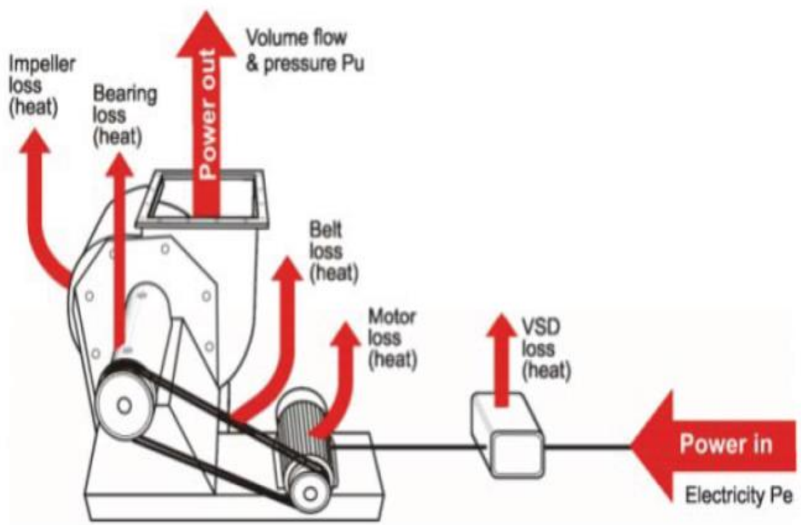
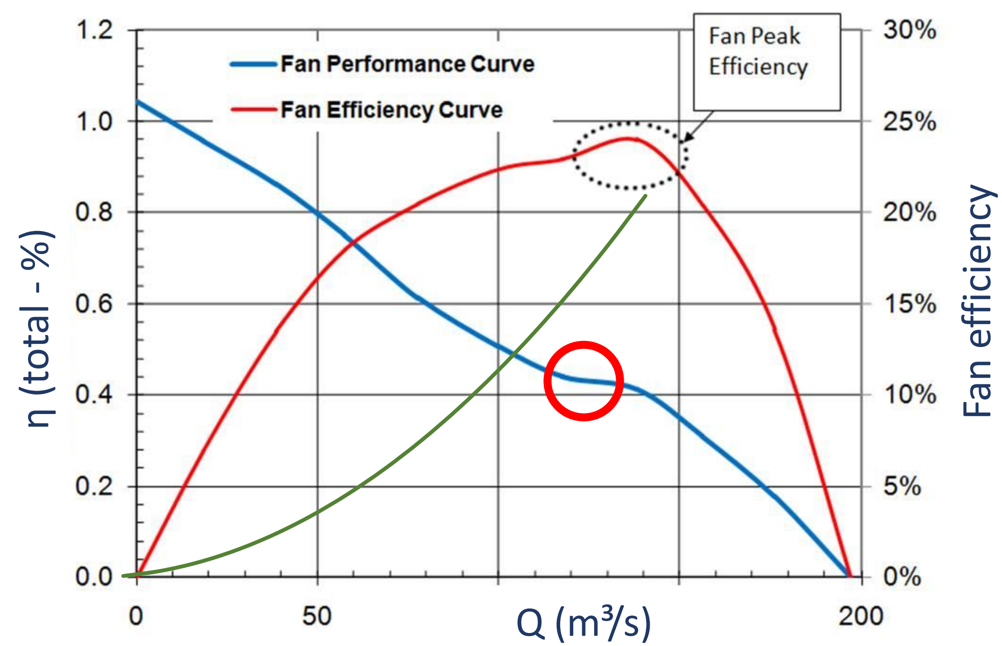
Backward airfoil	86 – 88	



Fan efficiency: regulation 327/2011

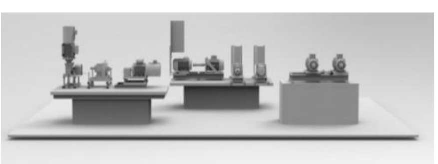
- Applies to
  - Minimum required total system efficiency at Best Efficiency Point or b.e.p. of industrial fans
    - Electric in vs. gas out





Fan efficiency: regulation 327/2011

- Applies to
  - Fans driven by electric motors from **125 W to 500 kW**
  - Fans may or may not be integrated in a product
  - The electric motor may or may not be sold together with the fan
- Into force from
  - 01/2013
  - 01/2015 → stricter version



Fan efficiency: regulation 327/2011

- Practical points concerning 327/2011
  - Regulation includes both fans sold separately as well as integrated in applications
  - CE marking on a fan produced after January 2013 implies compliance to 327/2011
  - The regulation is valid for the EU only

Fan efficiency: regulation 327/2011

- How about existing fans?

2013 ***2015***

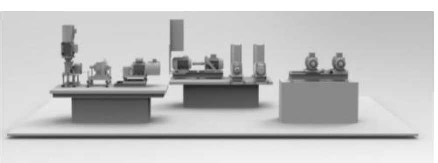
- If working: no need to replace
- If broken: replace according to 327/2011
  - Unless you have a spare and identical fan which was brought to the market before 01.01.2015

- If working: should already be compliant to EU 327/2011
- If broken: needs to comply to stricter version of 327/2011

- No worries if it is CE marked

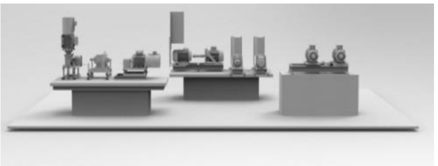
Fan efficiency: regulation 327/2011

- The future
  - Revision in April 2015 (see: www.fanreview.eu)
    - Updated regulation will be based on this revision
  - In brief
    - Higher efficiency values from 2018 or 2020 on
    - More exemptions (EU wanted fewer)
      - E.g.: demand to exclude spare parts from regulation – or at least a 5 year grace period
  - The next step
    - Determine a new metric based on a functional pressure/volume flow approach instead of the current geometry based one
    - Implementing noise requirements in the efficiency metric



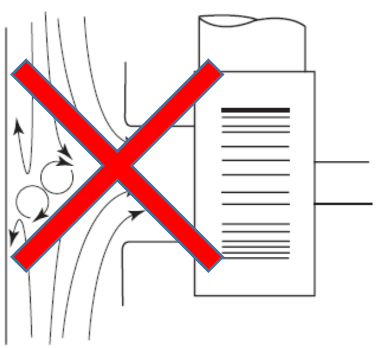
Fan efficiency: regulation 327/2011

- Control by authorities
  - None has been done in EU as far as we know
  - Average cost per test estimated at €3000
  - Fan manufacturers start building their own test equipment according to ISO 5801
  - Government is waking up on this topic
    - Expect first controls in the coming year

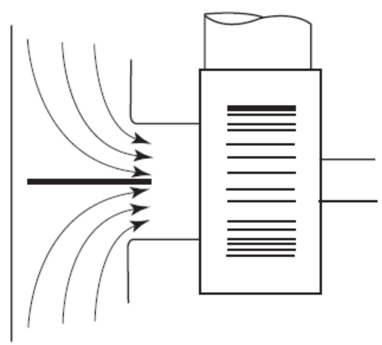


Fan efficiency: optimisation

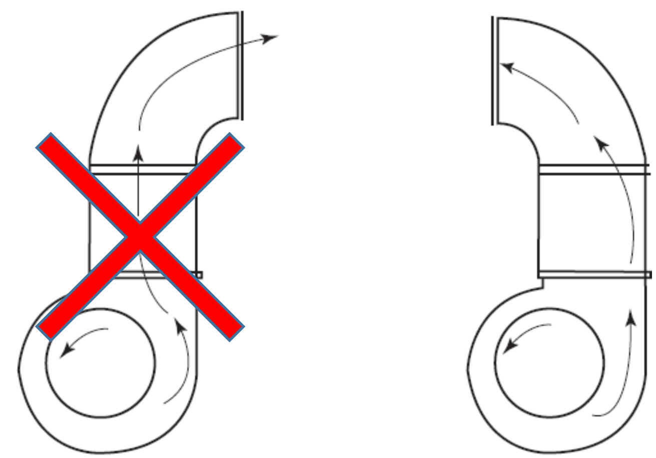
- System level
  - Make sure air flow gets fluently in and out of the fan
    - Avoid tight turns just before or after the fan
      - Use vanes if possible (accumulation!)
      - Try a vaneaxial fan if possible
    - Split the air flow at a T-inlet
    - Align outlet flow direction and following bends



Placing the fan inlet too close to the tee can impair fan performance.

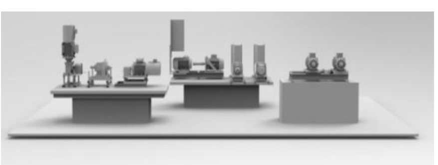


If space constraints force a close gap, the use of a splitter plate is recommended.



Fan efficiency: optimisation

- System level
  - Bigger diameter of duct: + 10% → losses - 62% (Cory, 2000; EEMODS) [original diameter not found]
  - Use round ducts instead of square: losses x 3 from round to square! (Cory, 2000; EEMODS)
  - Avoid leakages when connecting ducts



Fan efficiency: optimisation

- Fan level

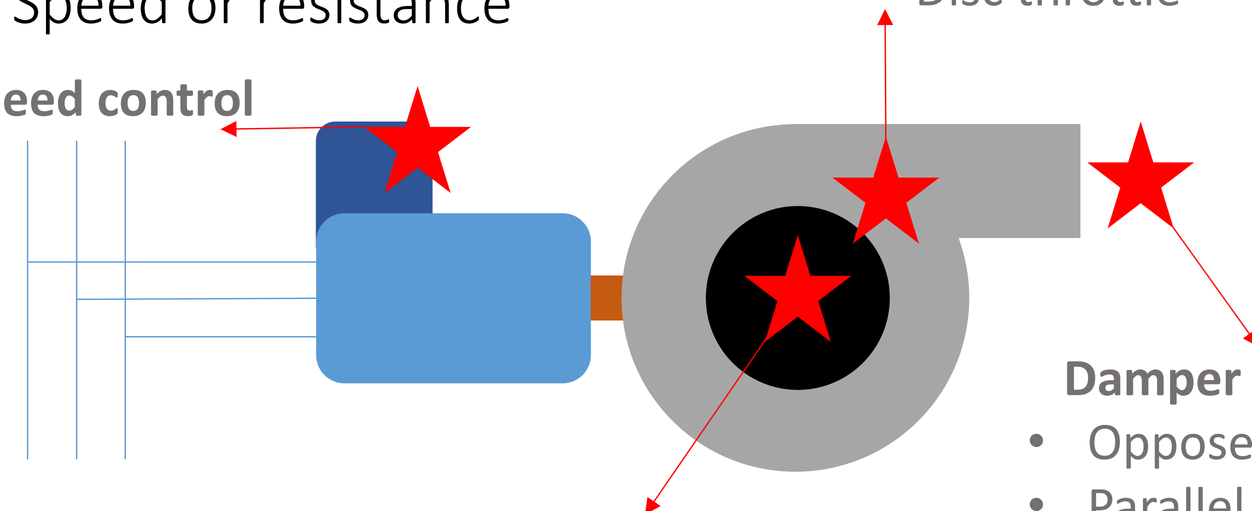
Axial	Centrifugal
Increase number of blades (for rather clean air)	
Minimise clearance between housing and blades	
Use a 'spinner'	

Fan efficiency: optimisation

- Control level
  - Speed or resistance

Variable geometry fans
- Blade pitch control
- Disc throttle

Variable speed control
- VSD

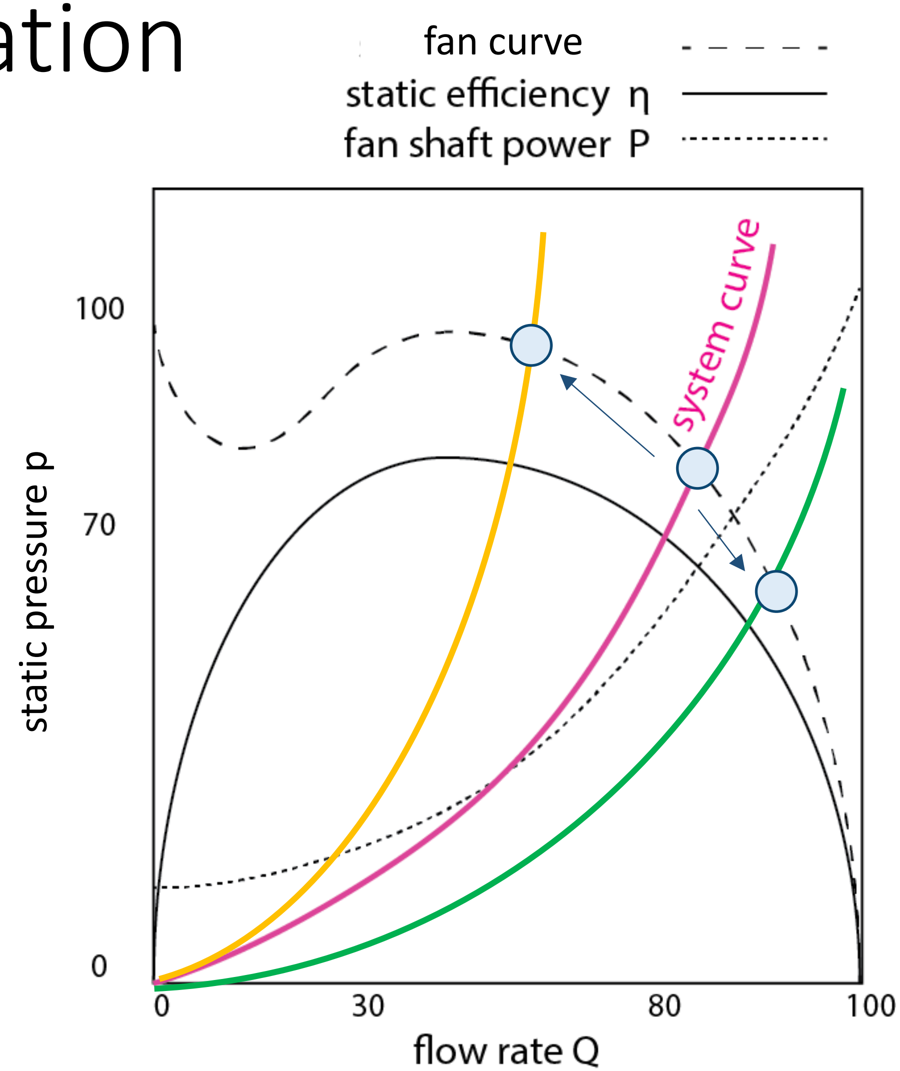


Damper control: outlet
- Opposed blade damper
- Parallel blade damper

Damper control: inlet
- Inlet box damper
- Nested inlet vane damper
- External inlet vane damper

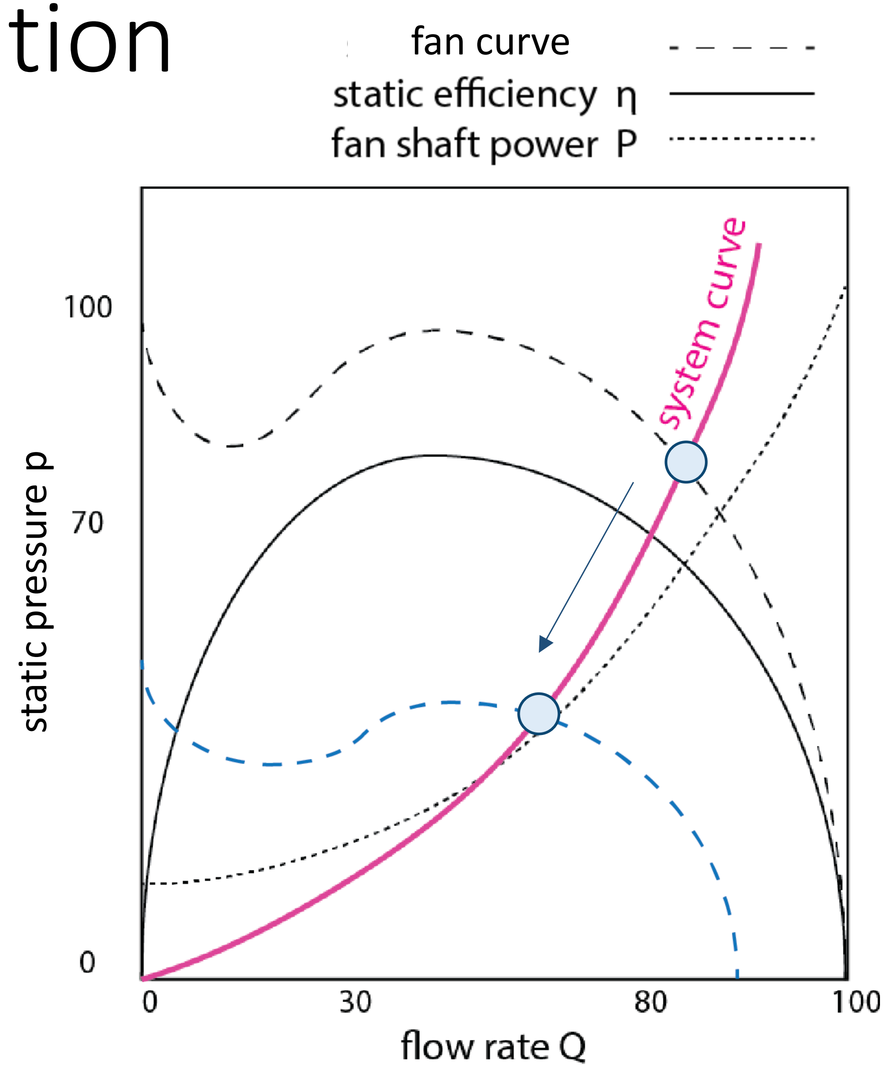
Fan efficiency: optimisation

- Control level
  - Changing resistance/pressure in the system



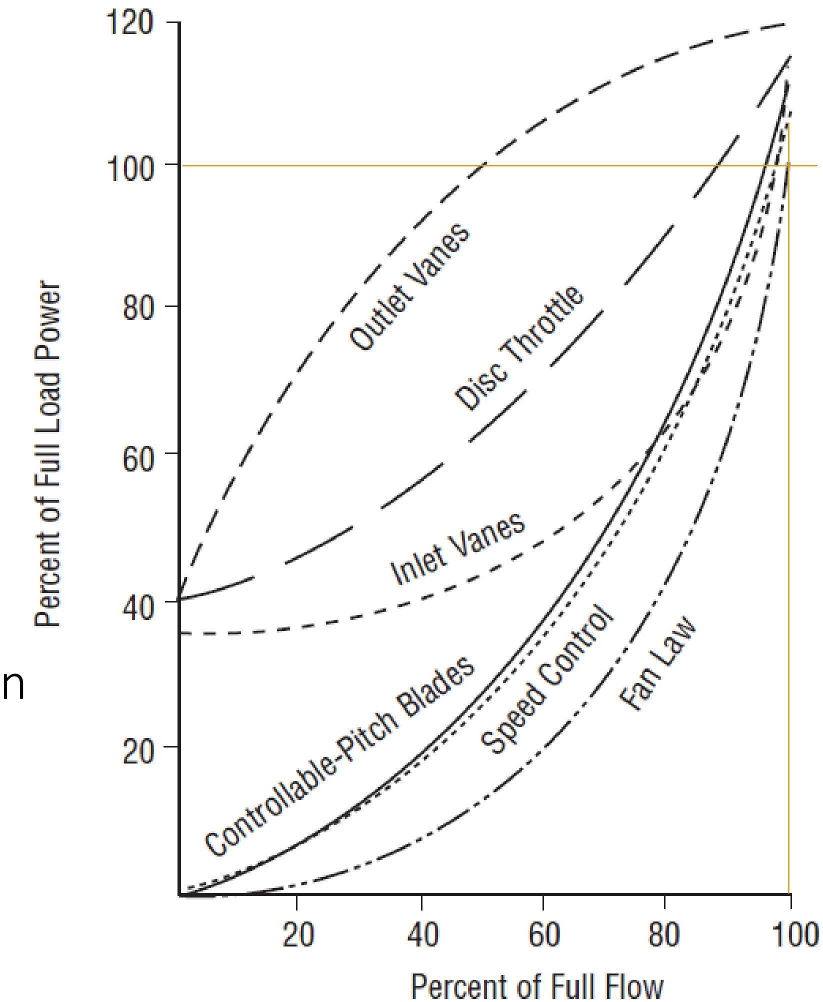
Fan efficiency: optimisation

- Control level
  - Changing fan speed



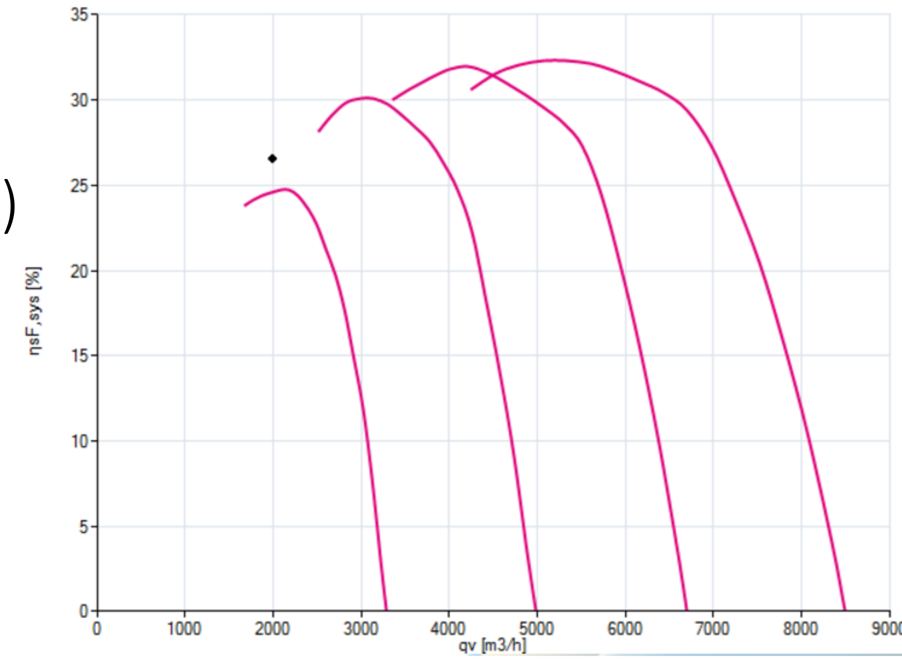
Fan efficiency: optimisation

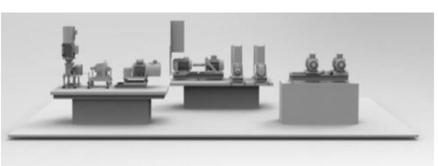
- Control level: VSD
  - Most efficient way
  - Blade pitch control is almost as efficient
  - Inlet vanes
    - Efficient if throttling range is between 80-100% of flow

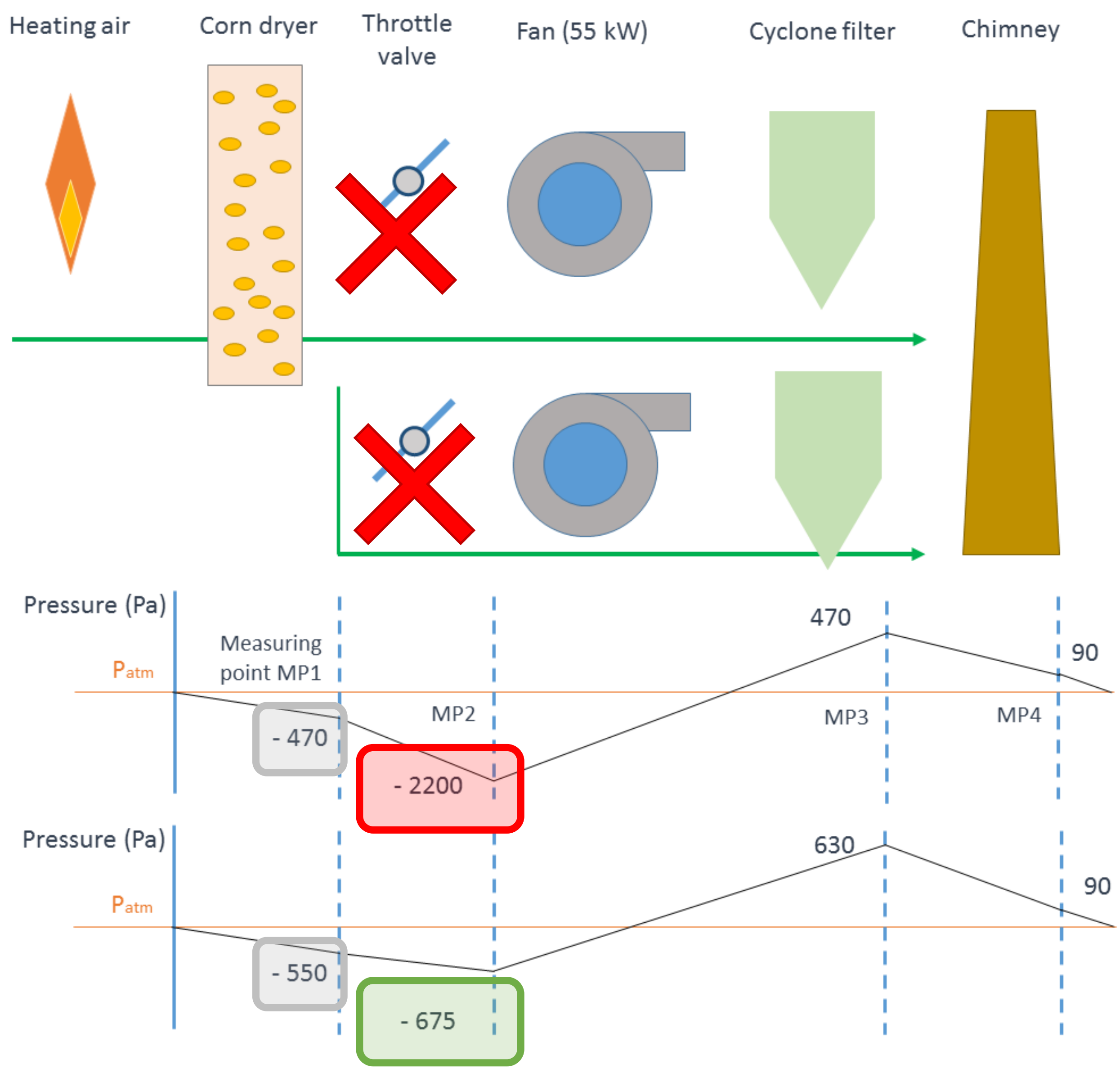


Fan efficiency: optimisation

- Control level: VSD
  - Lower speed might cause efficiency to decrease (see before)
    - Gain by cubic power-speed relation will most likely be greater
    - Ask your fan supplier!
  - $\frac{P_{fan\,old}}{\eta_{fan\,old}} = P_{motor\,old}$
  - $\frac{P_{fan\,new}}{\eta_{fan\,new}} = P_{motor\,new}$







Before
(with throttle)

After
(with VSD)