Doctoral dissertation work
for obtaining the scientific-academic degree of
Doctor of Philosophy (PhD.) in Industrial Engineering

Dr. MSc. Hartmut Steck-Winter, MBA

A practice-oriented procedure for engineering time estimation of industrial plant design for small and medium enterprises

Ein praxis-orientiertes Zeitaufwandsschätzverfahren für die Projektplanung der Entwicklung und Konstruktion kleiner und mittlerer Unternehmen des Anlagenbaus

Dissertation outline

This dissertation is a search for a new approach to a practice-oriented procedure for engineering design effort estimation

Dissertation outline:

1. Nature of the problem and solution approach
2. Research approach and methodology
3. Research hypotheses
4. Background and related work
5. The engineering design process
6. Effort drivers and influence factors of engineering design
7. Explorative research of completed engineering design projects
8. **A new praxis-oriented procedure for engineering time estimation**
9. Validation and conclusions

Nature of the problem

Why is this topic important? What is the nature of the problem?

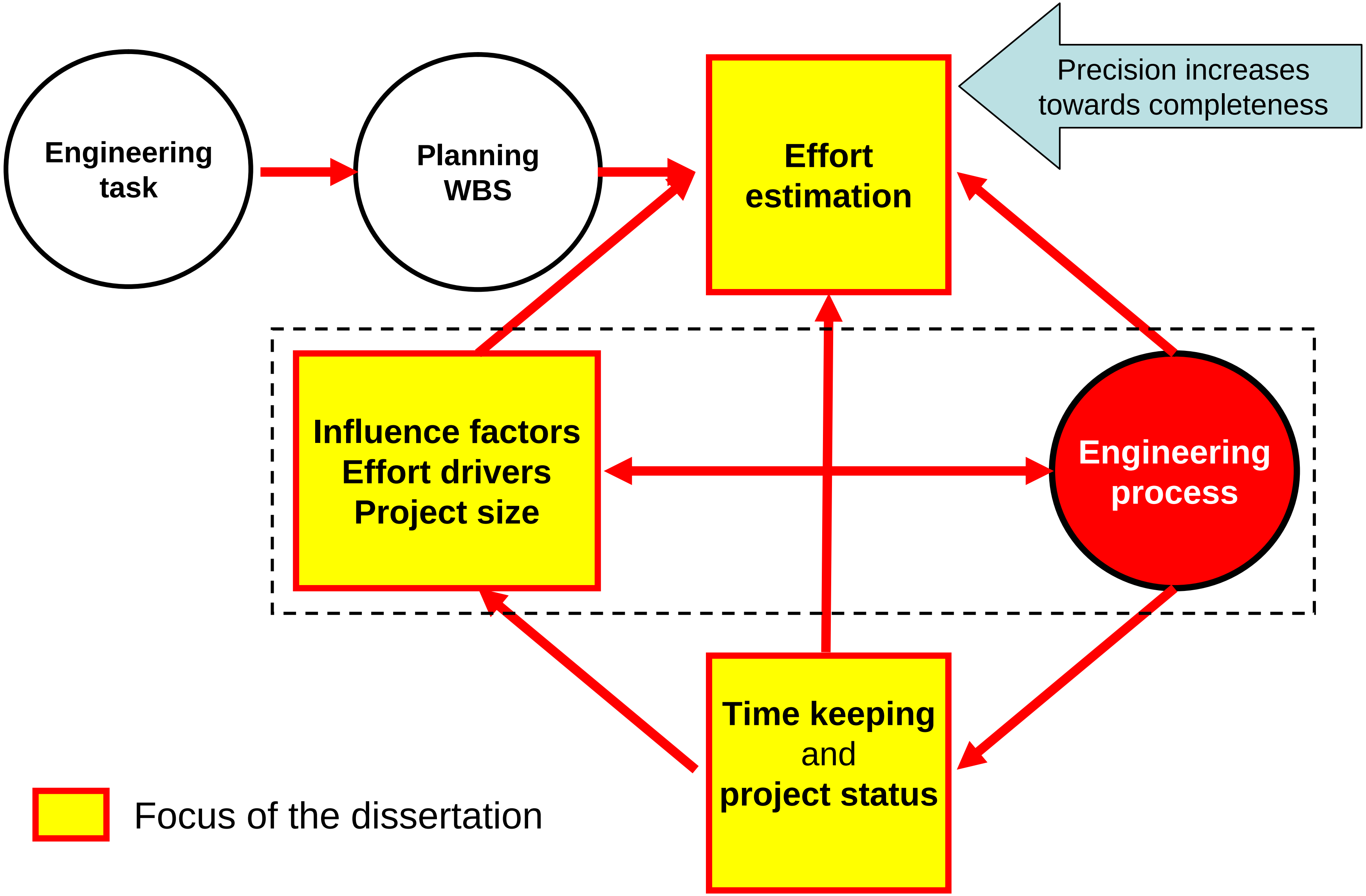
- Expenditures have to be estimated and targets have to be set
- The most important cost factor is the engineering time
- Estimation requires a good knowledge of the engineering process

But, there are regular cost overruns and schedule slips

Therefore,

- there is a need for empirically tested models which exploit the results already achieved in related engineering fields
- rather than using rules of thumb, engineering cost estimation should be parametric and persistent

The basic parts of an engineering effort estimation



Hypothesis 1 (of 6)

The central proposition at the core of this research is:

In practice, **nominal effort* of an engineering task** (in the industrial plant industry) **is not computable**, because the wealth of engineering solutions can not be described with mathematical methods alone.

However, **partial algorithmic solutions to weight the nominal estimate are possible and useful**.

*) Nominal effort is the estimated basic effort to solve an engineering problem. Nominal effort does not include any weighting factors to adapt the estimation to the dynamics of the environment or others.

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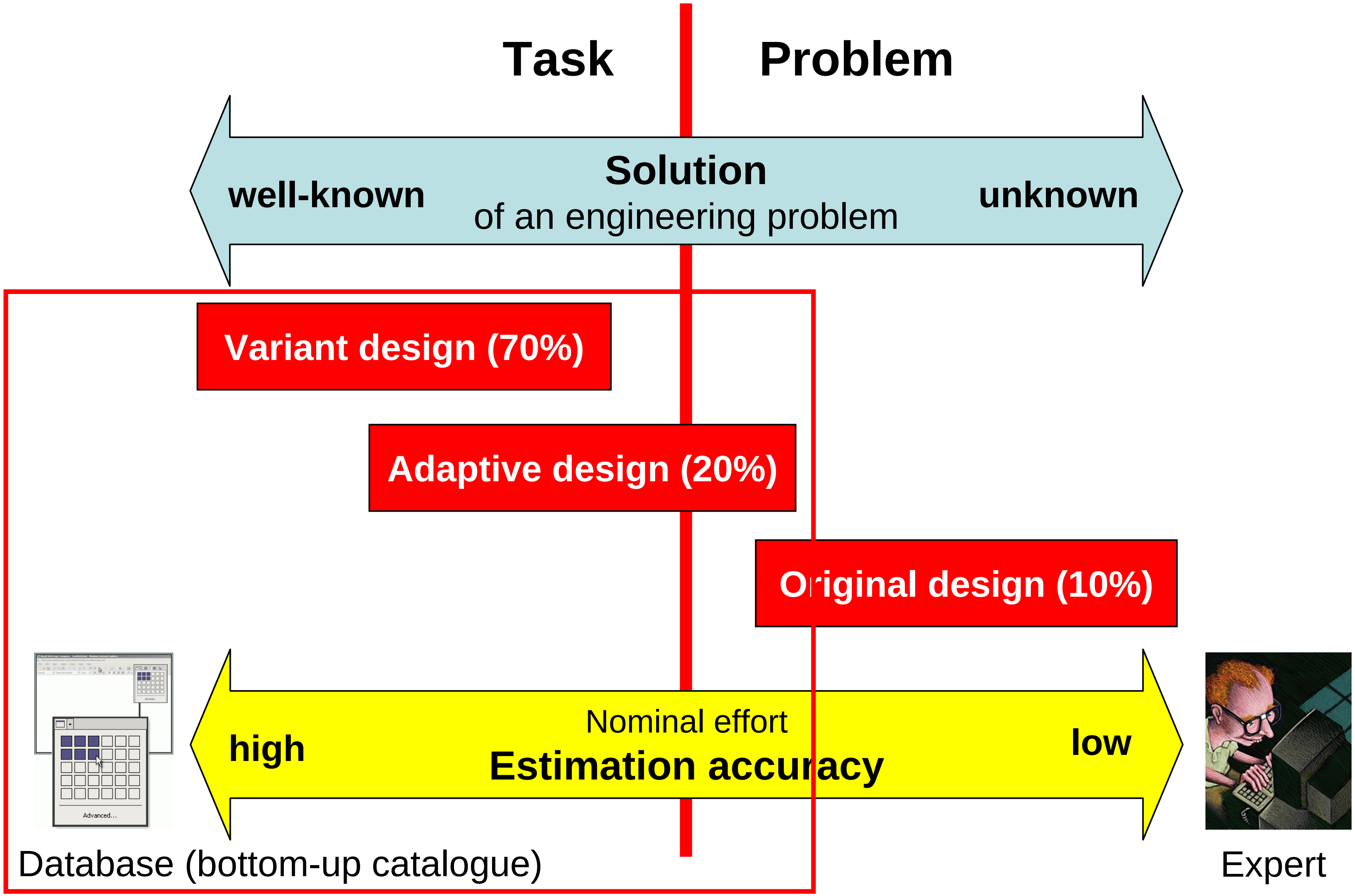
Type of engineering – the distinctive factor



Types and phases of design

- Three types of engineering design can be differentiated, original design (10%), adaptive design (20%) and variant design (70%)
- VDI 2221 lists four design stages
- New or original design: requires all four design stages, it is by far the most difficult and complex type
- Adaptive design: the basic function structure remains unchanged but some parts may be redesigned
- Variant designs: no or minor extra design effort, just build more of the previously designed

<table>
<tr><th rowspan="3">Types of design</th><th colspan="4">Design stages</th></tr>
<tr><th colspan="2">Plan</th><th>Sketch</th><th>Elaborate</th></tr>
<tr><td>clarification of task</td><td>conceptual design</td><td>embodiment design</td><td>detail design</td></tr>
<tr><td>New or original design</td><td colspan="4">10%</td></tr>
<tr><td>Adaptive design</td><td></td><td></td><td colspan="2">20%</td></tr>
<tr><td>Variant design</td><td></td><td></td><td></td><td>70%</td></tr>
<tr><td>Degree of standardization</td><td colspan="4"></td></tr>
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Literature review and explorative research

What are the drivers of engineering design effort?

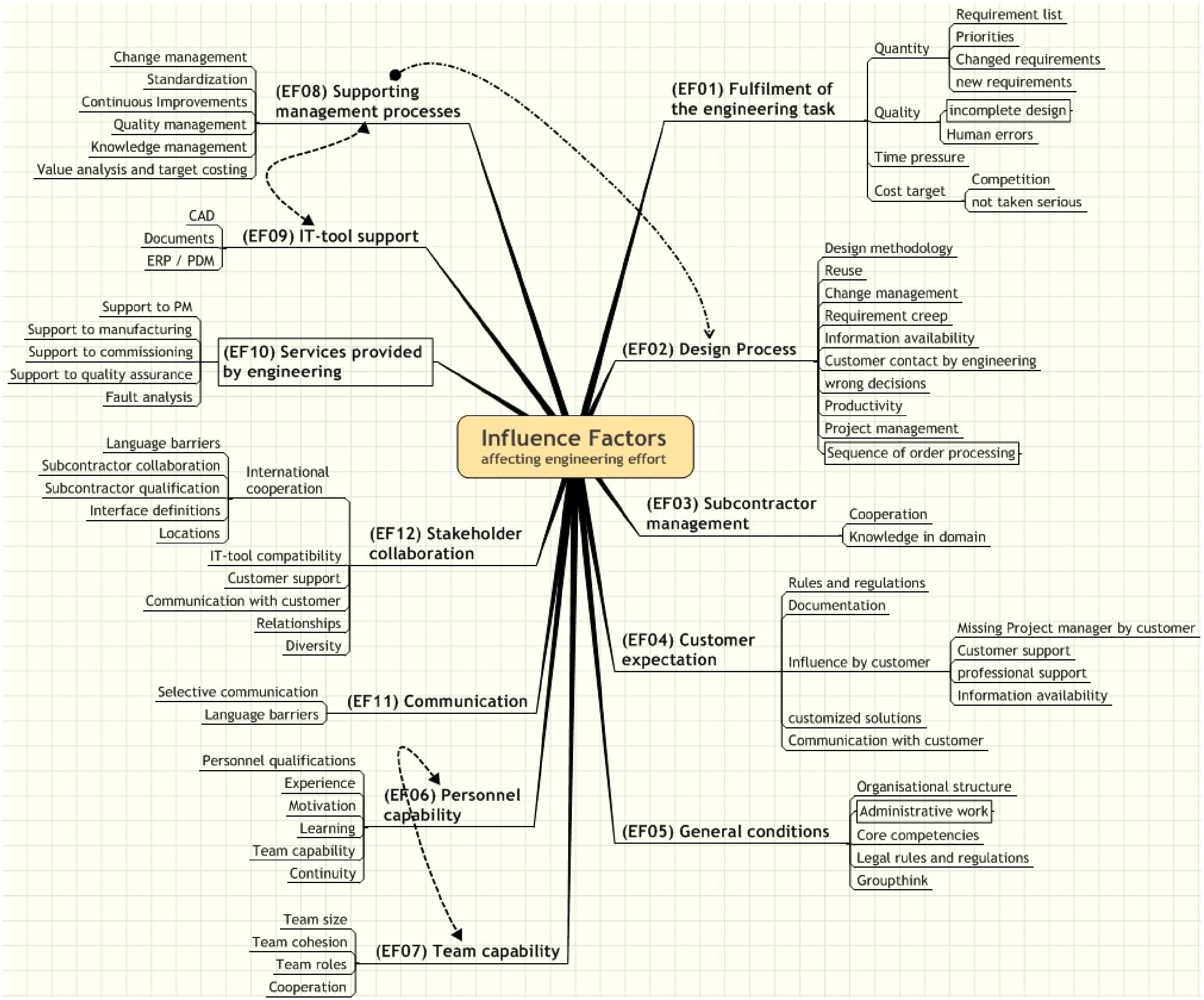
Research of influence factors, effort drivers and a project size driver

Literature review to identify the relevant factors or drivers in engineering design effort estimation. The reviewed scientific literature included books, industry journals, conference proceedings and dissertations.

Explorative research of 5 executed engineering design orders. Search of time consuming engineering activities and common problems.

- The engineering design took place during the period from March 2003 until December 2005.
- Data set with **2.327 records** , it took almost **32 months** to collect data
- These data has also been used to develop, check and calibrate the new procedure.

Literature review of influence factors (Mind Map)



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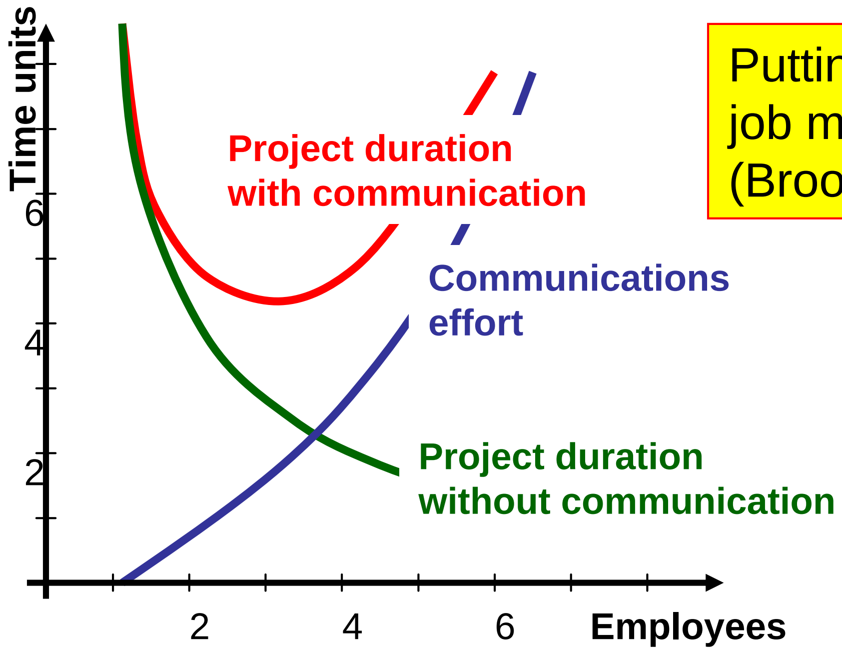
Project size driver (GF)

The project size driver represents the diseconomy of scale

Larger tasks require proportionally more engineering effort, because of:

- Integration overhead (small changes generate disproportionally large effort)
- Communication overhead

Based on parametric software cost estimation size driver is 1,003

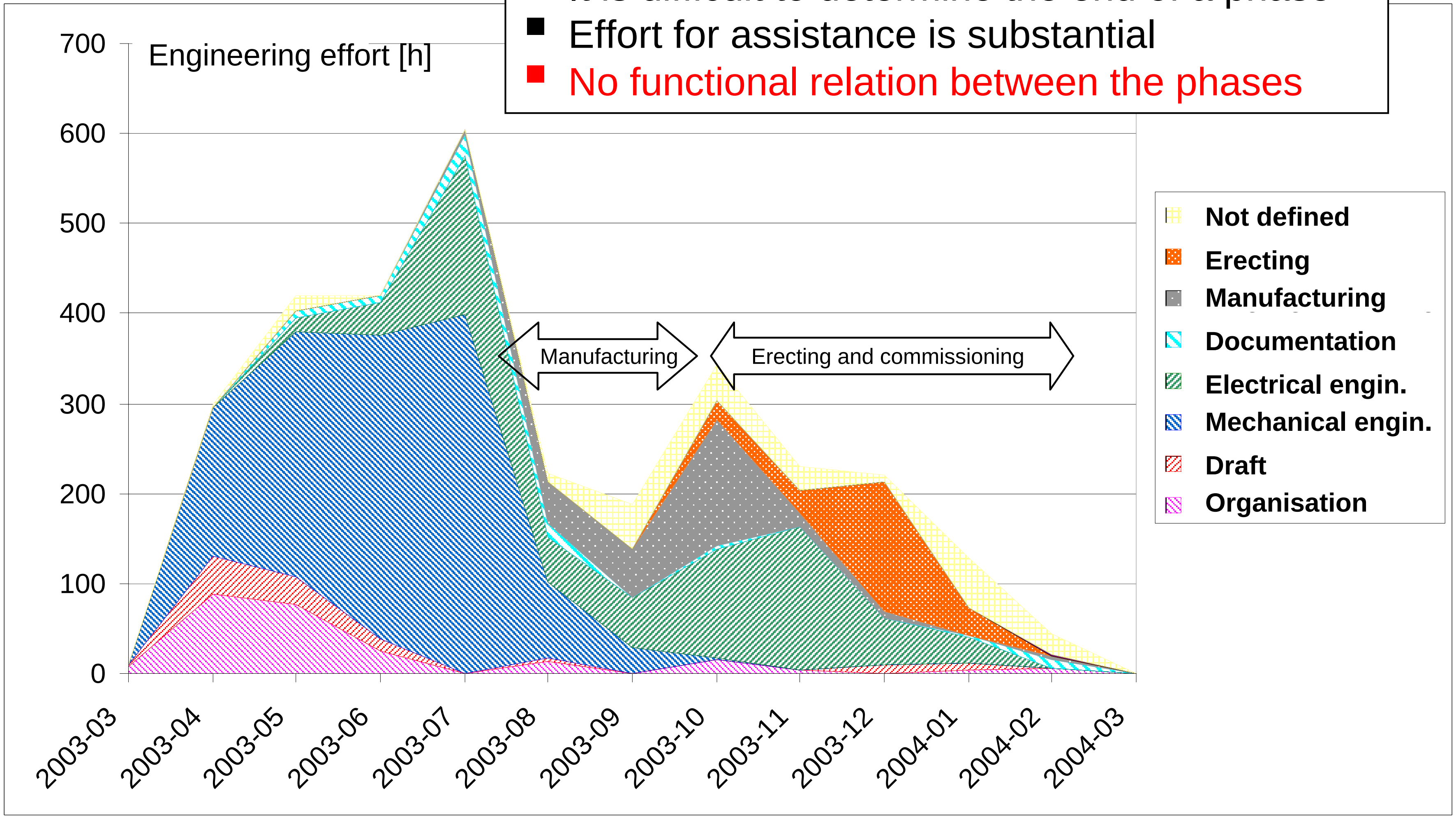


Putting more people on a late job makes it later.
(Brooks, 1975)

--> Chapter 7

Example of a time course analysis

- Phases of design are visible, but overlapping
- Some phases seem to be endless
- It is difficult to determine the end of a phase
- Effort for assistance is substantial
- No functional relation between the phases



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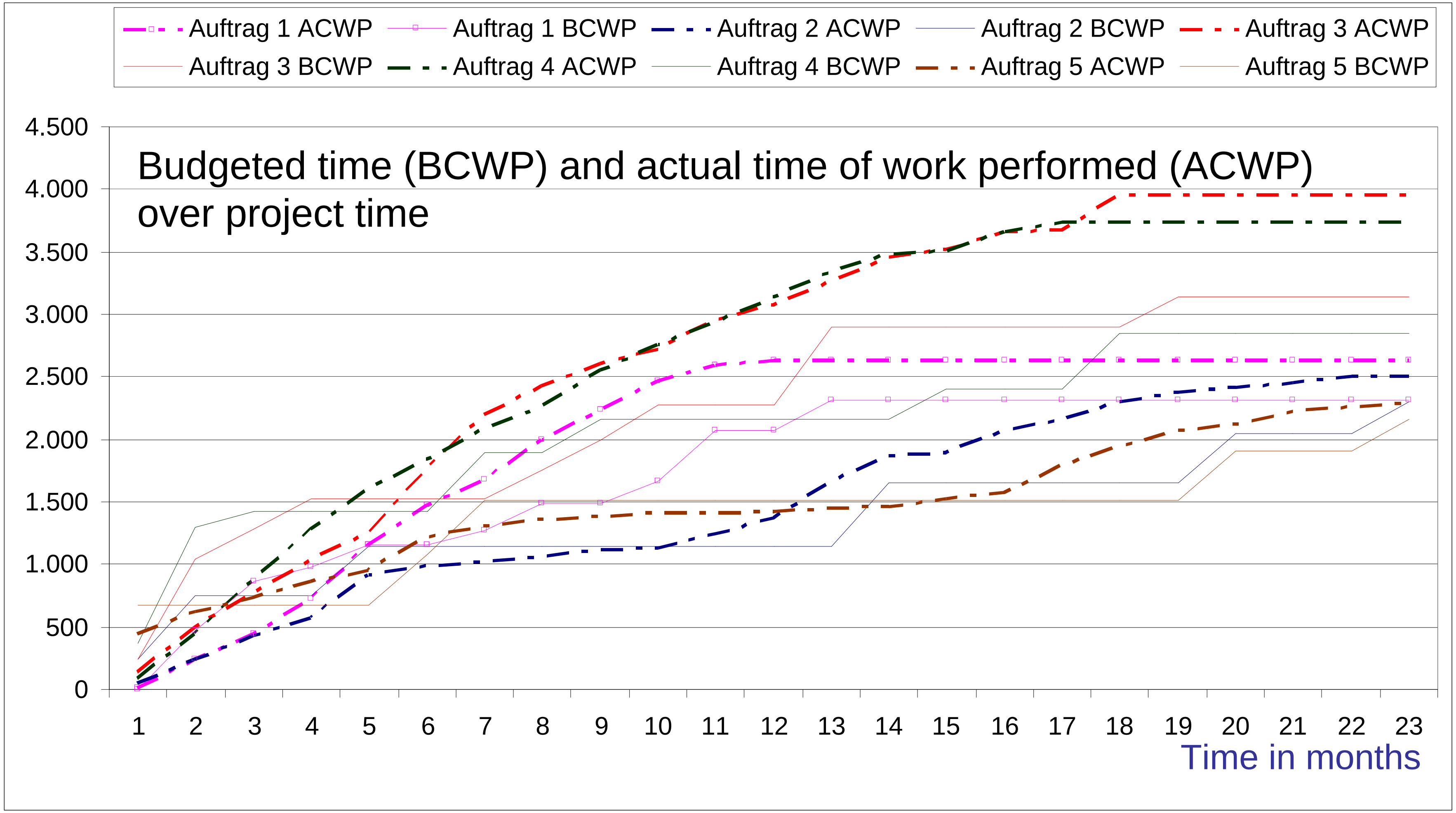
Earned Value Analysis



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A new praxis-oriented effort estimation procedure

What are the basic constituents of the new procedure?

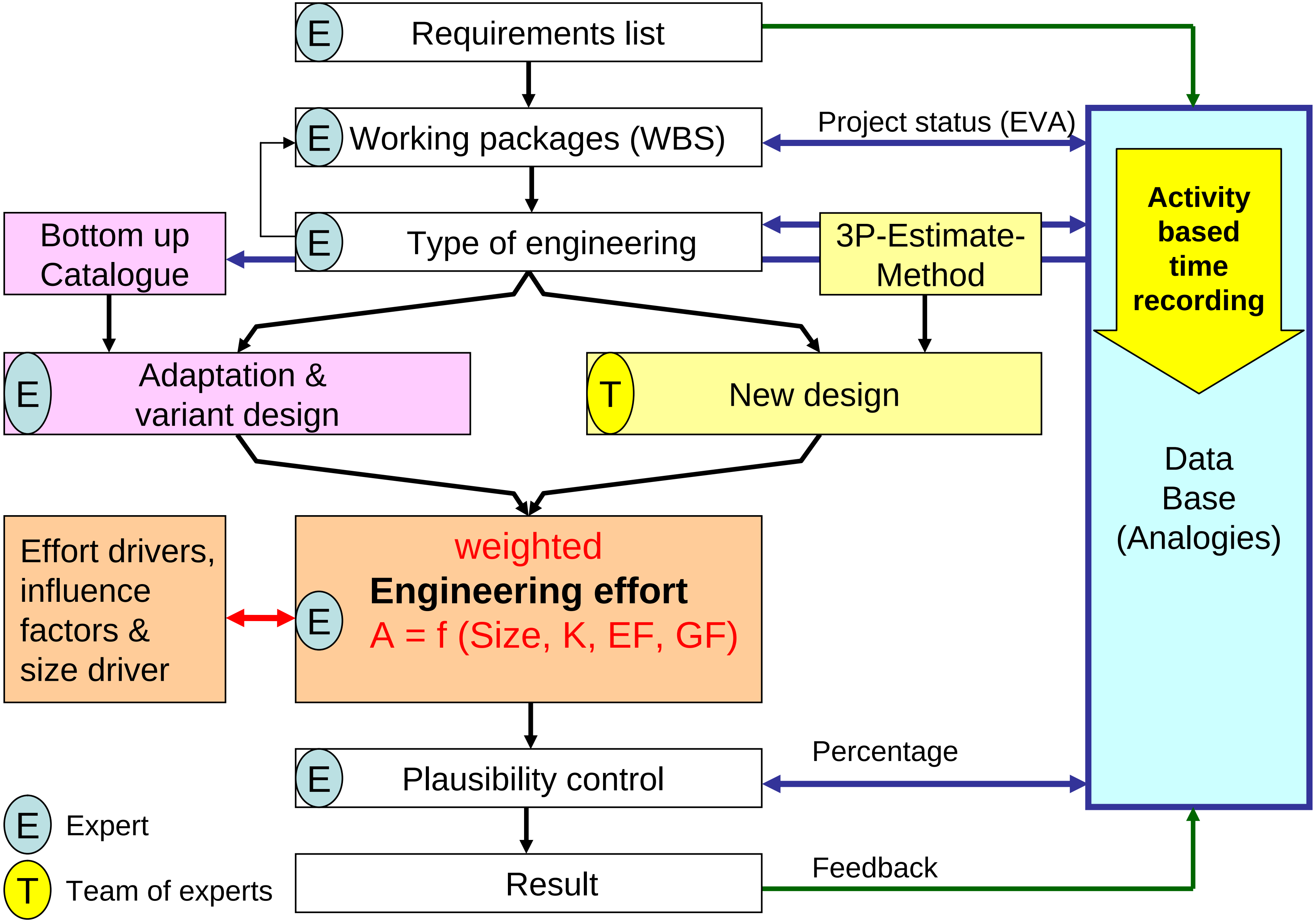
The new semi-parametric effort estimation procedure shares commonalities with existing approaches in adjacent engineering disciplines

Core is a semi-parametric method to weight nominal effort

The new procedure includes :

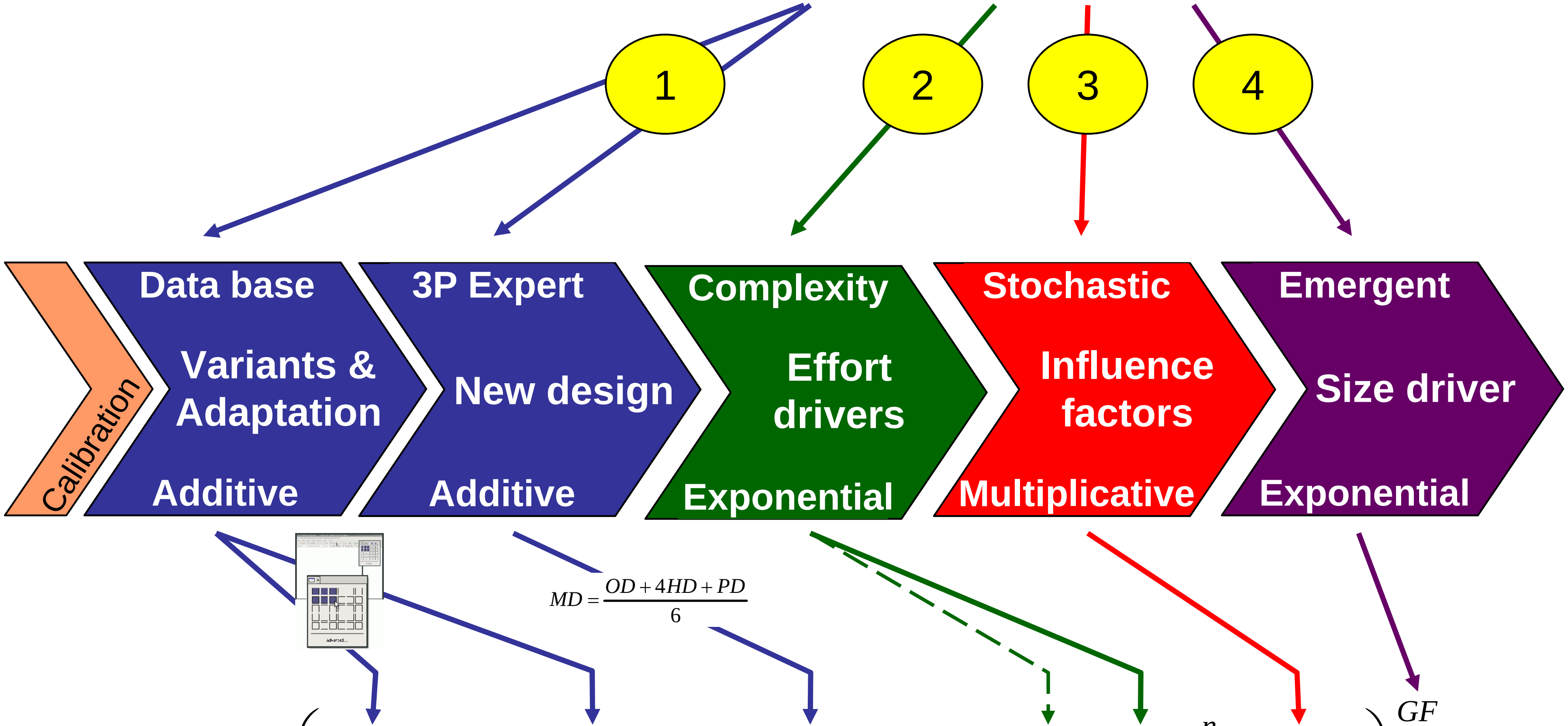
- Distinction of the **three types of engineering design** (nominal effort)
- Definition and metrics of 6 **effort drivers** (project complexity)
- Definition and grouping of 12 **influence factors** (project dynamic)
- A method and metric to evaluate influence factors
- Definition and metric of a **size driver** (project size)
- Activity based time recording method (hours already spend)
- Improved Earned Value Analysis (work completed)

A new praxis-oriented effort estimation procedure



Engineering effort estimation equitation

$$A = f\,(\text{nominal Size}, K, EF, GF)$$



$$A = C \cdot \left(\left(A_{VarKo} + A_{AnpKo} + A_{NeuKo} + AT \right)^{K} \prod_{i=1}^{n} EF_i \right)^{GF}$$

A_{xxxKo} - Nominal size

$$A = C \cdot \left(\left(A_{VarKo} + A_{AnpKo} + A_{NeuKo} + AT \right)^K \prod_{i=1}^{n} EF_i \right)^{GF}$$

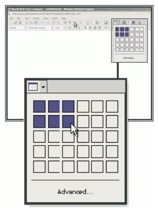
Nominal size is the principal determinant of engineering effort
Nominal size estimation is dependent on type of design

$$A = C \cdot \left(\left(A_{VarKo} + A_{AnpKo} + A_{NeuKo} + AT \right)^K \prod_{i=1}^{n} EF_i \right)^{GF}$$

Accurate nominal size estimation is difficult at an early stage. It will be affected by decisions that have not yet been made.

Variant design (70%)

Adaptive design (20%)



Database
does not consider complexity

Original design (10%)

$$MD = \frac{OD + 4HD + PD}{6}$$

3 point estimation

Expert estimations depend on knowledge of the estimator, who may be biased, optimistic, pessimistic or unfamiliar with the project

There is no purely mathematical nominal size estimation method.
Nominal size is always derived by expert estimation

K - Complexity factor

$$A = C \cdot \left(\left(A_{VarKo} + A_{AnpKo} + A_{NeuKo} + AT\right)^{K} \prod_{i=1}^{n} EF_i \right)^{GF}$$

AT1: Product complexity	0 to 10,0	[0,0100]
AT2: Product immaturity	0 to 10,0	[0,0100]
AT3: Number and complexity of interfaces	0 to 2,5	[0,0025]
AT4: Level of automation	0 to 5,0	[0,0050]
AT5: Share of subcontractors	0 to 2,5	[0,0025]

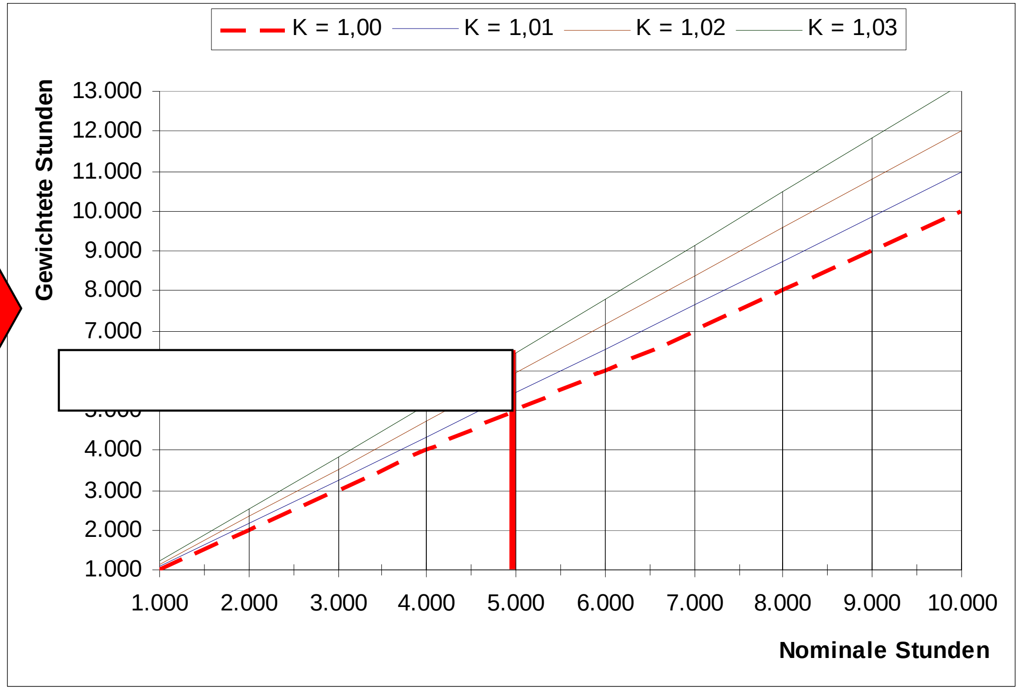
Metric is intuitive. Not all drivers have the same metric!

Each effort driver (AT) has a rating level, ranging from very low to extra high

Complexity factor (K) summarizes all effort drivers (AT)

$$K = 1 + 0{,}001 \times \sum_{i=1}^{i} AT_i$$

Equitation is similar to COCOMO, but multiplier is 10 times smaller! K ranges between 1,00 and 1,03



EF - Influence factors

$$A = C \cdot \left(\left(A_{VarKo} + A_{AnpKo} + A_{NeuKo} + AT \right)^{K} \prod_{i=1}^{n} EF_i \right)^{GF}$$

Sensitivity analysis is an assessment method to analyse large effects caused by minor impact

Matrix:
1 = weak effect
2 = medial effect
3 = strong effect

All factors are compared with one another, pair wise

Standard Sensitivity Analysis according to Vester

Nr	Influence factor (chance or risk)	Fulfilment of the Engineering task	Engineering design process	Supplier management	Fulfillment of customer expectations	General conditions	Personnel capability	Team capability	Supporting management processes	IT-tool support	Services provided by engineering	Kommunikation	Stakeholder collaboration	Active sum AS	Passive sum PS	Quotient (AS/PS) Q	Product (ASxPSxVS) P	Product in % P [%]
1	Fulfilment of the Engineering task		0	0	3	0	0	0	2	0	0	0	0	5	25	0,2	163	5
2	Engineering design process	3		2	3	0	0	0	1	1	0	0	1	11	19	0,6	272	9
3	Supplier management	2	2		2	0	0	0	1	0	1	1	3	12	22	0,5	343	11
4	Fulfillment of customer expectations	2	1	2		2	0	0	1	0	0	1	2	11	24	0,5	343	11
5	General conditions	2	0	1	1		0	0	2	0	1	2	2	11	12	0,9	172	5
6	Personnel capability	3	3	2	3	0		3	1	2	0	2	2	21	5	4,2	137	4
7	Team capability	3	3	2	3	0	3		1	2	0	2	2	21	5	4,2	137	4
8	Supporting management processes	3	3	3	3	2	0	0		0	3	3	3	23	16	1,4	478	15
9	IT-tool support	1	2	2	1	0	0	0	0		0	0	2	8	5	1,6	52	2
10	Services provided by engineering	1	1	2	0	2	0	0	3	0		0	2	11	8	1,4	114	4
11	Kommunikation	3	3	3	3	3	2	2	2	0	1		3	25	14	1,8	455	14
12	Stakeholder collaboration	2	1	3	2	3	0	0	2	0	2	3		18	22	0,8	515	16
		25	19	22	24	12	5	5	16	5	8	14	22	**177**	**177**	**1,0**	**3.180**	**100**

Adaptations made by the author

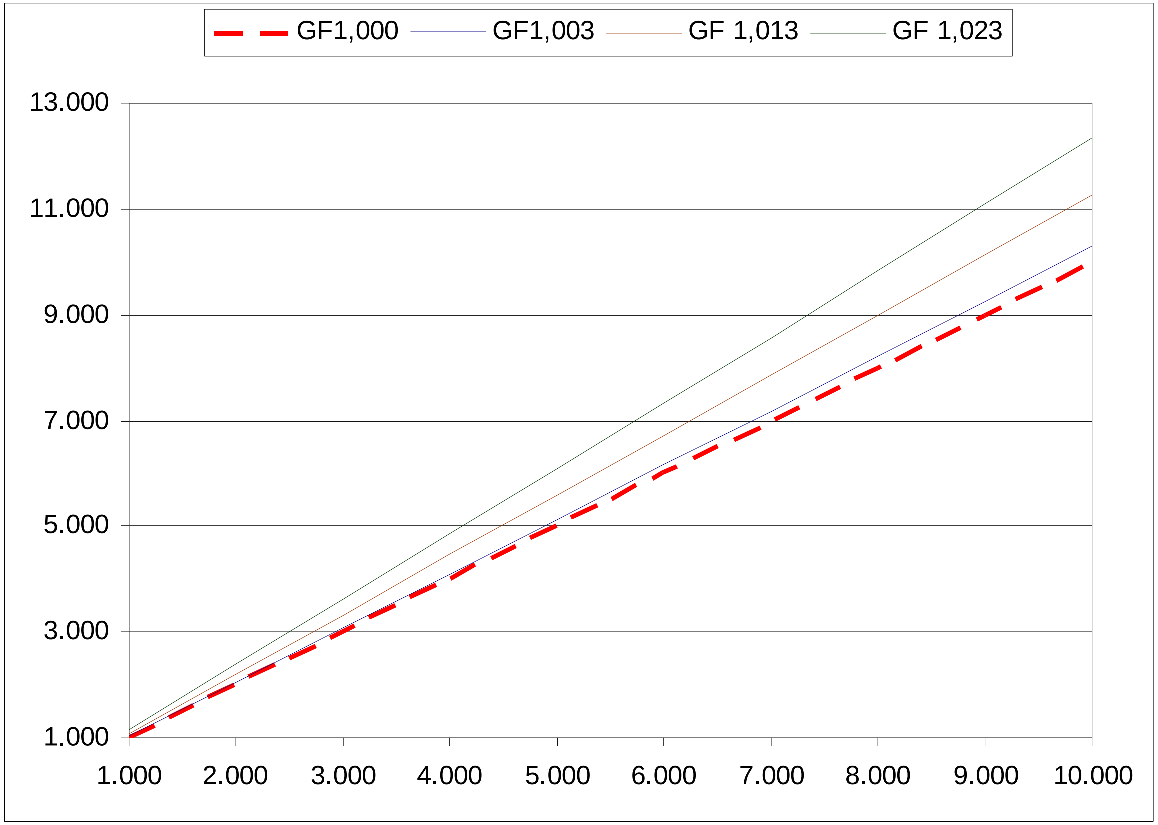
Nr	AS weighted AS*	PS weighted PS*	Product (AS*xPS*VS) P*	Product* in % P*[%]	Risk probability (Chance - Risk RK	Improvement factor VB	Deterioration factor VS	Weighted multiplier GM	Outcome to influence factor EF
1	2,5	12,5	40,6	5,1	**0,25**	0,90	1,30	**1,00**	**0**
2	5,5	9,5	67,9	8,5	**0,25**	0,90	1,30	**1,00**	**0**
3	6,0	11,0	85,8	10,8	**0,25**	0,90	1,30	**1,00**	**0**
4	5,5	12,0	85,8	10,8	**0,25**	0,90	1,30	**1,00**	**0**
5	5,5	6,0	42,9	5,4	**0,25**	0,90	1,30	**1,00**	**0**
6	10,5	2,5	34,1	4,3	**0,25**	0,90	1,30	**1,00**	**0**
7	10,5	2,5	34,1	4,3	**0,25**	0,90	1,30	**1,00**	**0**
8	11,5	8,0	119,6	15,0	**0,25**	0,90	1,30	**1,00**	**0**
9	4,0	2,5	13,0	1,6	**0,25**	0,90	1,30	**1,00**	**0**
10	5,5	4,0	28,6	3,6	**0,25**	0,90	1,30	**1,00**	**0**
11	12,5	7,0	113,8	14,3	**0,25**	0,90	1,30	**1,00**	**0**
12	9,0	11,0	128,7	16,2	**0,25**	0,90	1,30	**1,00**	**0**
	89	**89**	**795**	**100**					

Nominal size 1.000
Sum of influences 0

- Influence factors are connected (see impact matrix)
- Risk probability factor (RK)
- Perspectives of the risk factor: impact on effort vs. probability of occurrence
- AS*, PS* and P* weighted by risk factor (RF)
- Improvement factor (VB) and deterioration factor (VS)
- Computed multiplier (GM), numerical assessment of influence factors (EF)

GF - Project size driver

$$A = C \cdot \left(\left(A_{VarKo} + A_{AnpKo} + A_{NeuKo} + AT\right)^{K} \prod_{i=1}^{n} EF_i \right)^{GF}$$



Metric adapted from COSYSMO

- The size driver is exponential to all other factors.
- Influence on engineering effort is rather low

Validation with real projects

$$A = C \cdot \left(\left(A_{VarKo} + A_{AnpKo} + A_{NeuKo} + AT \right)^{K} \prod_{i=1}^{n} EF_{i} \right)^{GF}$$

Factor	Project 1		Project 2		Project 3		Project 4		Project 5	
	Factor	Hours	Factor	Hours	Factor	Hours	Factor	Hours	Factor	Hours
Nominal effort estimation in Hours		**2.315**		**2.295**		**3.145**		**2.845**		**2.155**
Effort drivers										
Product complexity	2,00		2,00		2,00		2,00		2,00	
Product maturity	0,00		2,00		4,00		2,00		0,00	
Interfaces	0,50		0,50		0,50		1,50		1,00	
Level of automation	2,00		2,00		2,00		2,00		2,00	
Share of sub-suppliers	1,00		1,00		2,00		1,00		1,00	
Complexity factor (K=0,001 x ΣAT)	1,0055	**101**	1,0075	**137**	1,0105	**278**	1,0085	**199**	1,006	**102**
Influence factors	RK		RK		RK		RK		RK	
Fulfilment of engineering task	0,25	-4	0,25	-4	0,40	94	0,30	33	0,25	-13
Engineering design process	0,70	128	0,70	127	0,70	183	0,70	174	0,30	9
Supplier management	0,25	-35	0,25	-35	0,25	-36	0,40	28	0,25	-34
Customer expectations	0,25	-6	0,25	-6	0,40	90	0,30	29	0,25	-20
General conditions	0,25	-6	0,25	-6	0,40	97	0,30	30	0,25	10
Personnel capability	0,25	-14	0,25	-14	0,25	-19	0,25	-17	0,25	-13
Team capability	0,25	17	0,25	17	0,25	23	0,25	21	0,25	16
Supporting management processes	0,25	33	0,25	33	0,25	75	0,25	61	0,25	42
IT-tool support	0,30	-16	0,30	-16	0,30	-21	0,30	-19	0,30	-35
Services provided by engineering	0,50	103	0,50	102	0,50	166	0,60	186	0,90	203
Communication	0,35	8	0,35	8	0,35	36	0,35	22	0,35	8
Stakeholder collaboration	0,25	-8	0,25	-8	0,30	32	0,25	6	0,25	-4
Sum of influence factors		**201**		**199**		**720**		**553**		**168**
Size Driver	1,003	**63**	1,003	**63**	1,003	**105**	1,003	**89**	1,003	**57**
Sum of effort estimation		**2.679**		**2.694**		**4.247**		**3.687**		**2.482**
Time keeping		2.695		2.577		4.212		3.582		2.461
Deviation previous		-380		-282		-1.067		-737		-306
Deviation with new procedure		**-16**		**117**		**35**		**105**		**21**
Deviation previous in %		-14%		-11%		-25%		-21%		-12%
Deviation with new procedure in %		-1%		5%		1%		3%		1%

Conclusion

- A new semi-parametric effort estimation procedure has been developed
- The new method has been tested and validated utilising five real engineering design projects
- The complexity factor, respectively the five effort drivers have been rather low
- The effects of the twelve influence factors could be predicted with good accuracy
- The project size driver did not critically impact the overall estimation
- The estimation accuracy was surprisingly uniform
- For now the Hypothesis has been verified!