Process Control of the Rheology of Self-Compacting Concrete Based on Cusum Control Charts

Prozesssteuerung der Rheologie von selbstverdichtenden Betonen anhand von Kusum-Kontrollkarten

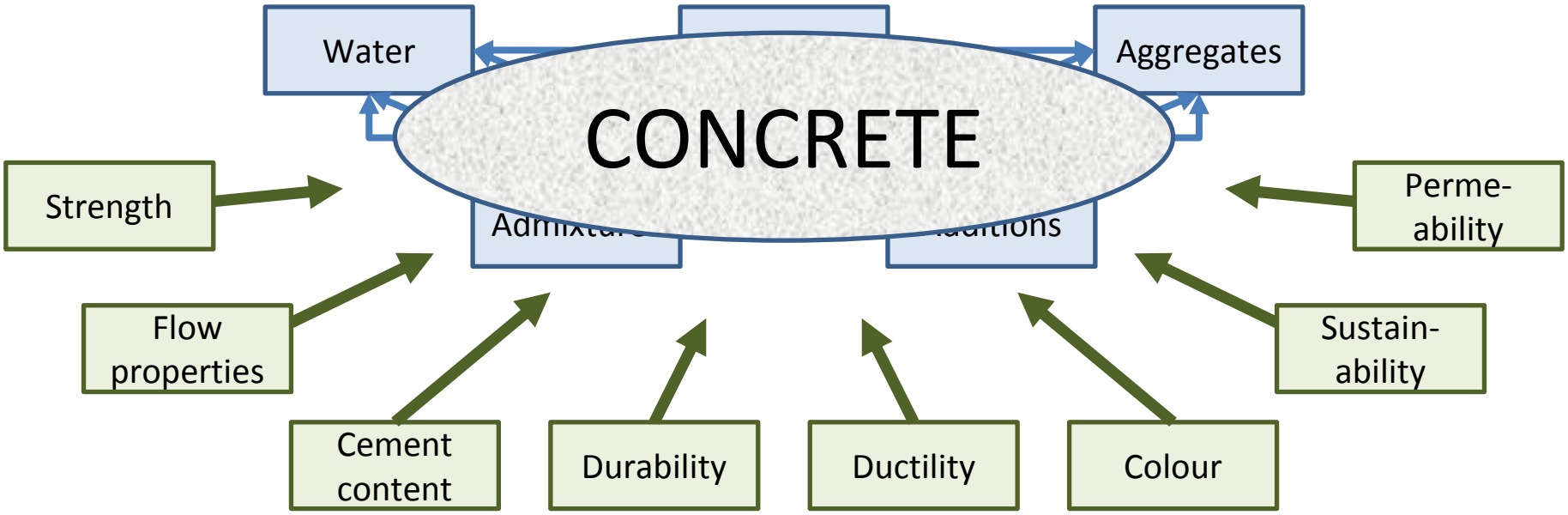
Wolfram Schmidt

BAM Federal Institute for Materials Research and Testing, Berlin

Introduction

Concrete today

- Regarding performance or other specifications of concrete, there are hardly no limitations today.
- Design criteria can be very versatile.
- The challenge „Mix Design“ has become an exciting challenge,
- but the complexity of the system makes it prone to scatter.



Reasons for quality scatter in concrete production

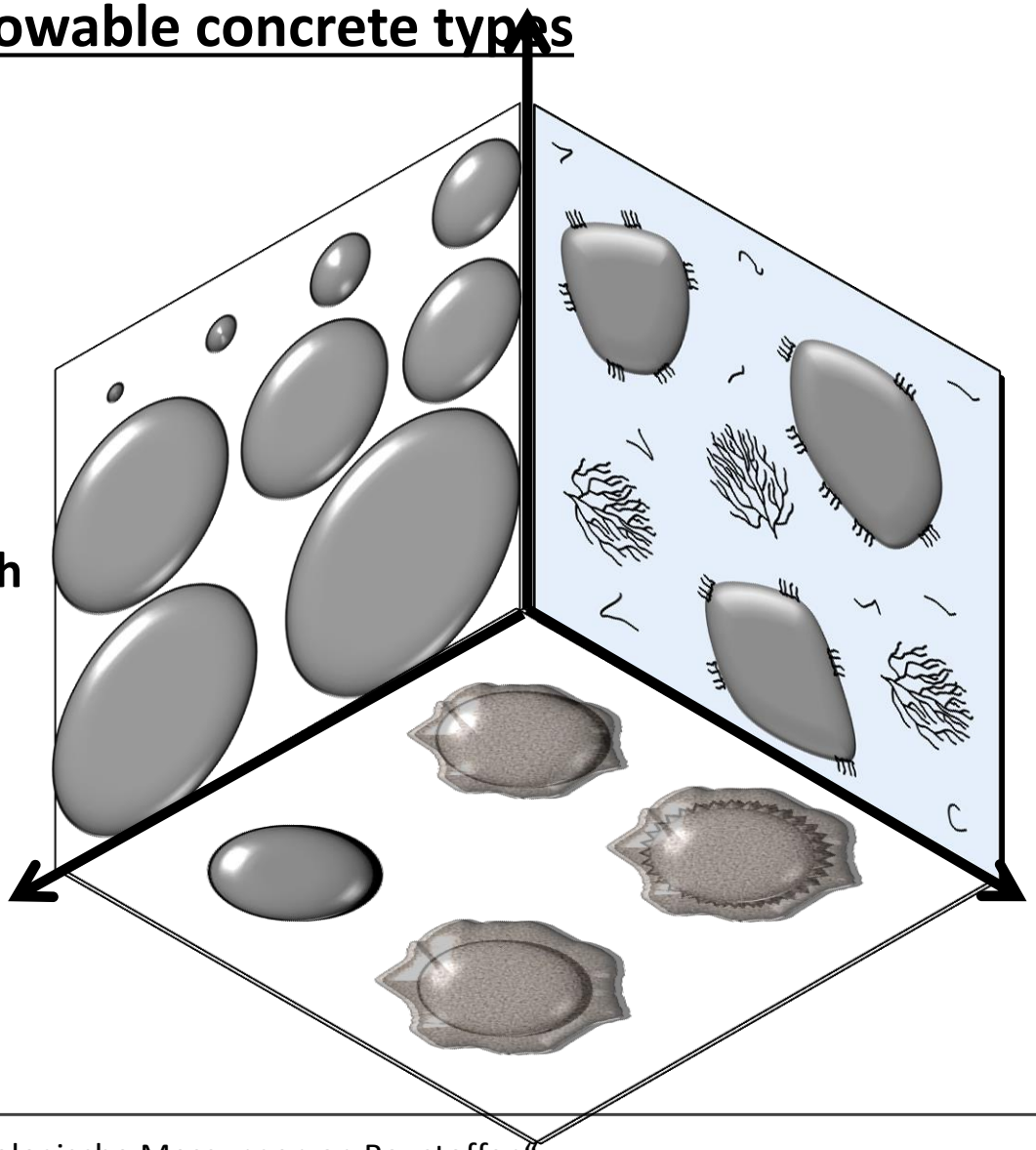
- **Cement undergoes scatter**
  - Set retarder may alter
  - Fineness
  - Chemistry (Fuels / Raw materials / Kiln temperature)
- **Fines, Sand, and aggregates**
  - Particle size distribution and powder content
  - Surface properties
  - Humidity
- **Chemical admixtures**
  - Precursers are often purchased globally depending upon price.
- **Water**

Reasons for quality scatter in concrete production

- Staff
- Equipment
- Handling
- Supply chains
- Timing
- Post-processing
- …

Complexity of modern flowable concrete types

- Multi-phase-system
- Effects occur in multiple scale dimensions.
- Time effects



The concept of one mix-design does not fit in with the requirements of modern flowable concrete! Mixtures have to be adjustable!

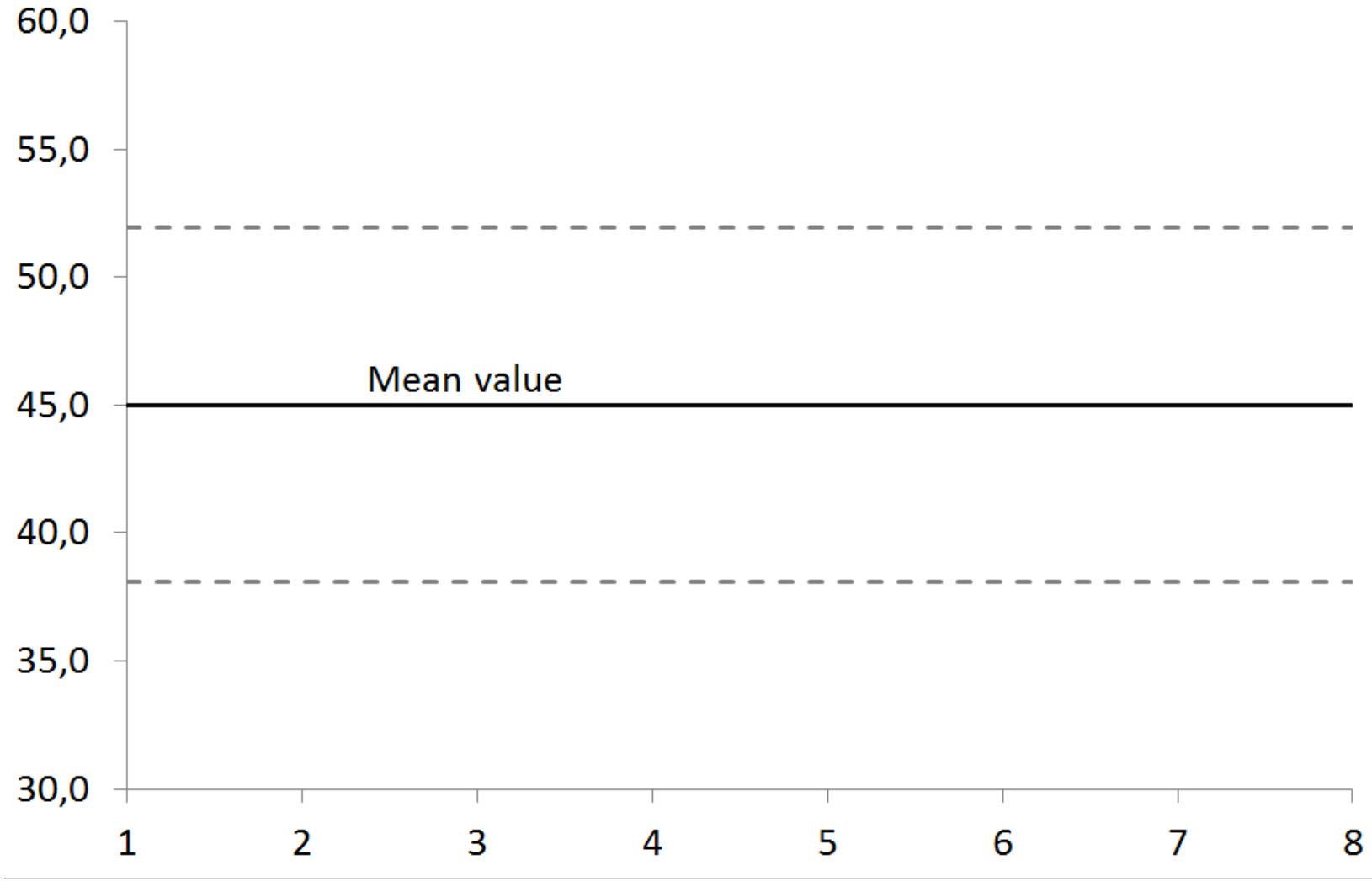
For flexibility, production has to be controlled efficiently.

Reasons to set up a functioning quality control tool

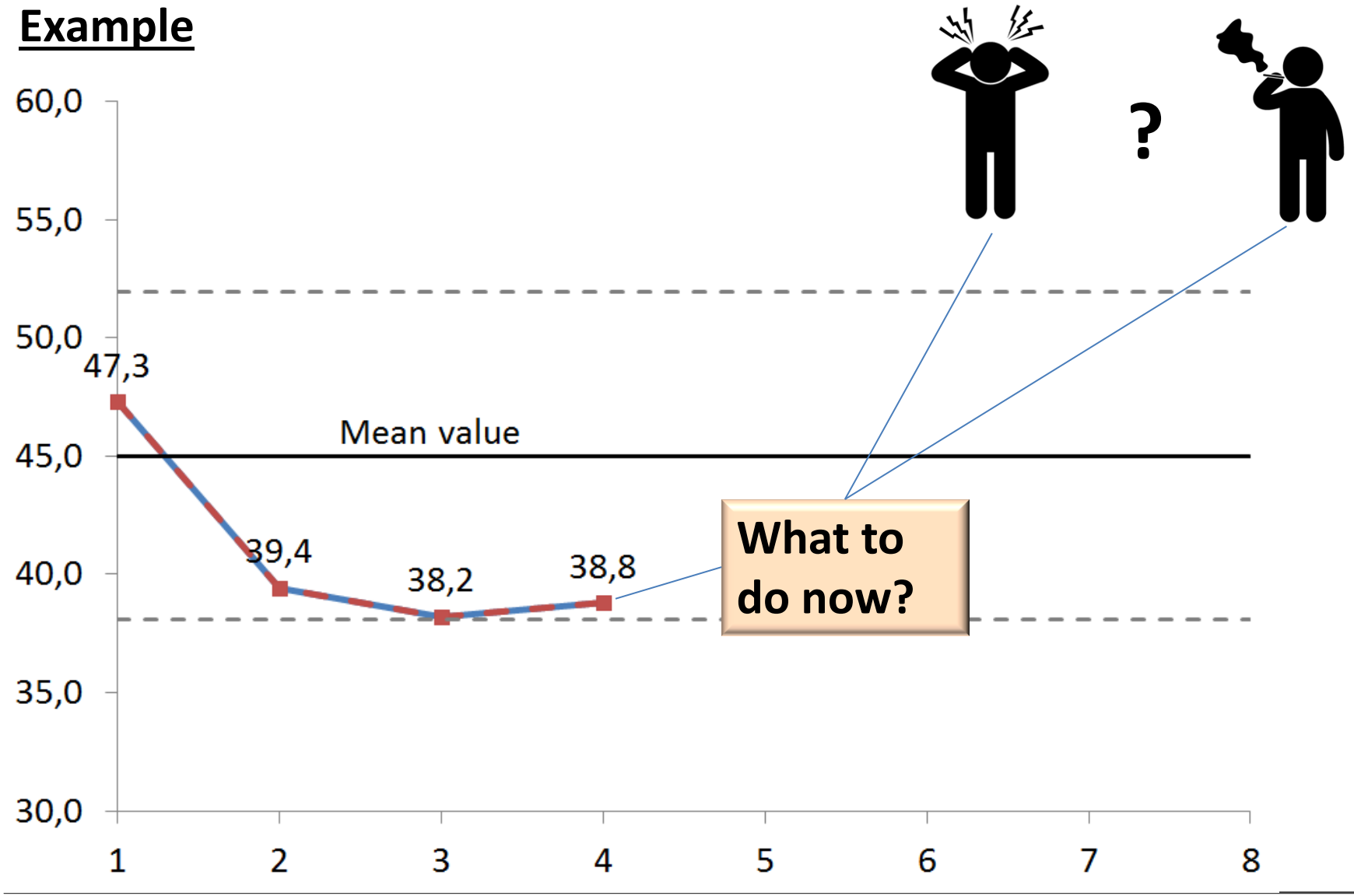
- **Safety aspects**
  - Standards demand for a steady quality control to make sure that the concrete is conforming with the standards.
  - Customers may demand quality control in order to make sure that they receive the expected quality.
  - For everything related to public safety, it is important to make sure that the demanded safety level is achieved.
- **Cost aspects**
  - Functioning quality control mechanisms help saving money.
  - Producers may want to show their quality control to customers as a selling point.
- **Knowledge aspects**
  - Producers may want to understand their parameters and how they affect the process.

Challenges in assessing processes

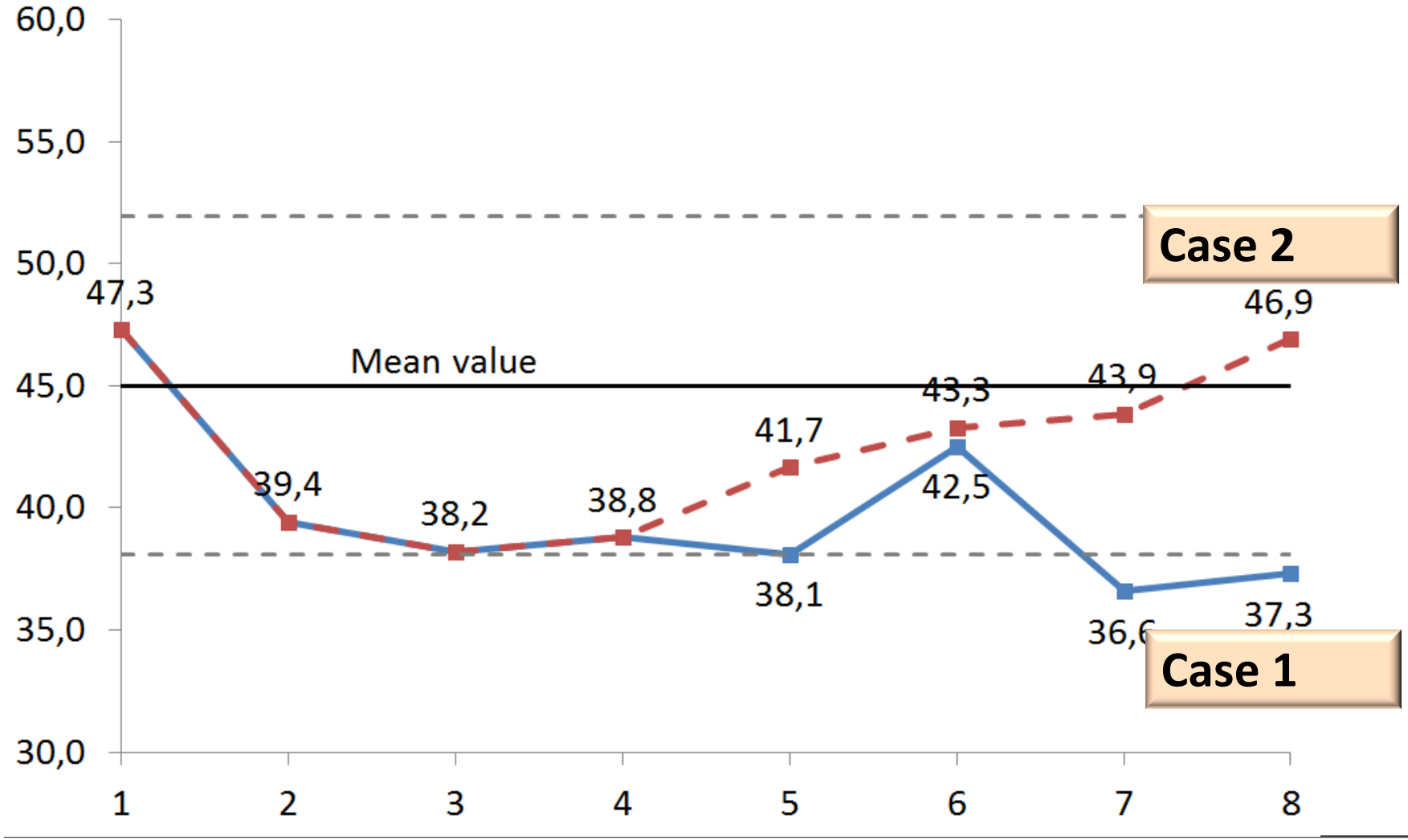
Example



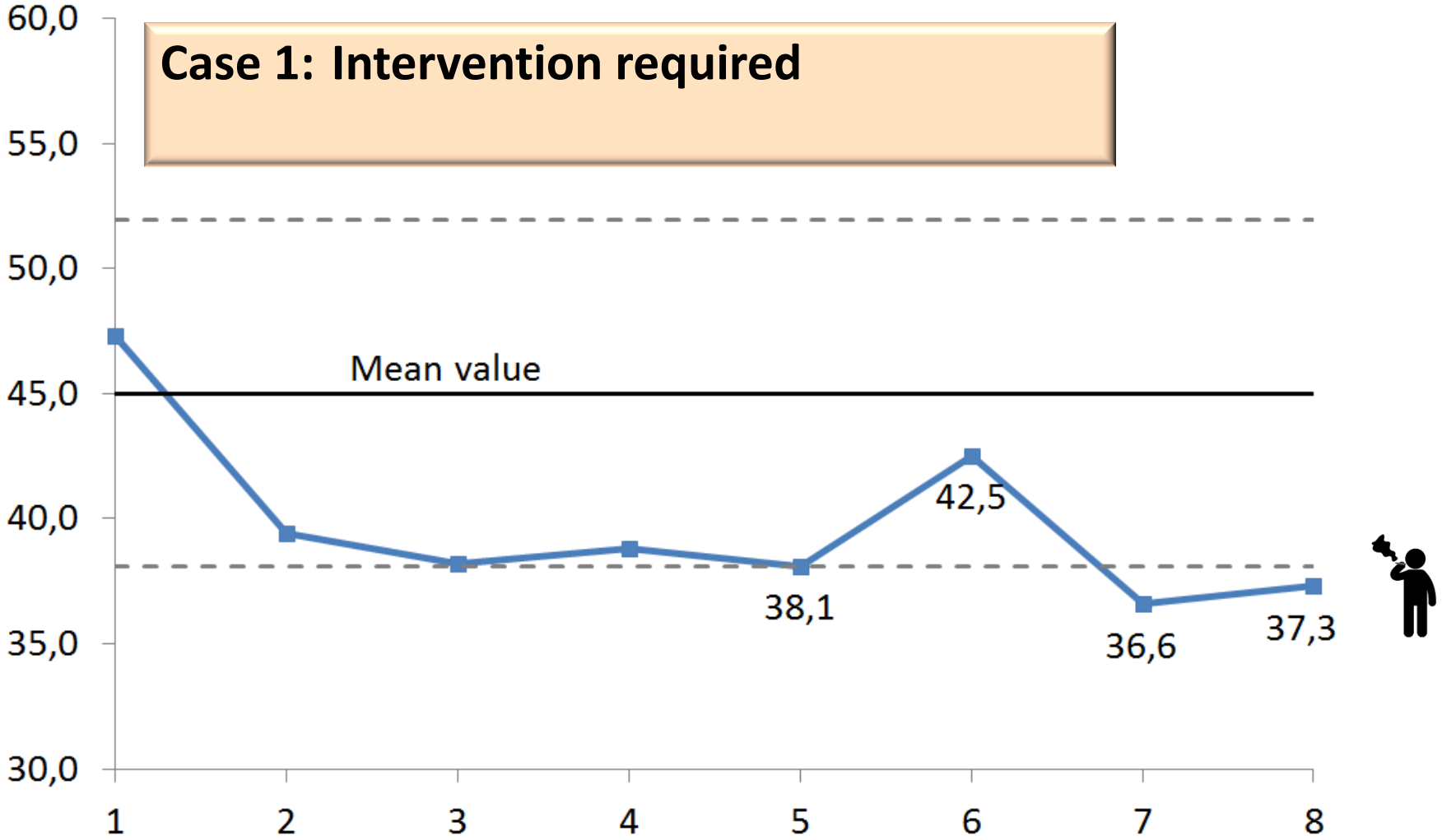
Example


60,0
55,0
50,0
45,0
40,0
35,0
30,0
1
2
3
4
5
6
7
8
47,3
39,4
38,2
38,8
Mean value
?
What to do now?

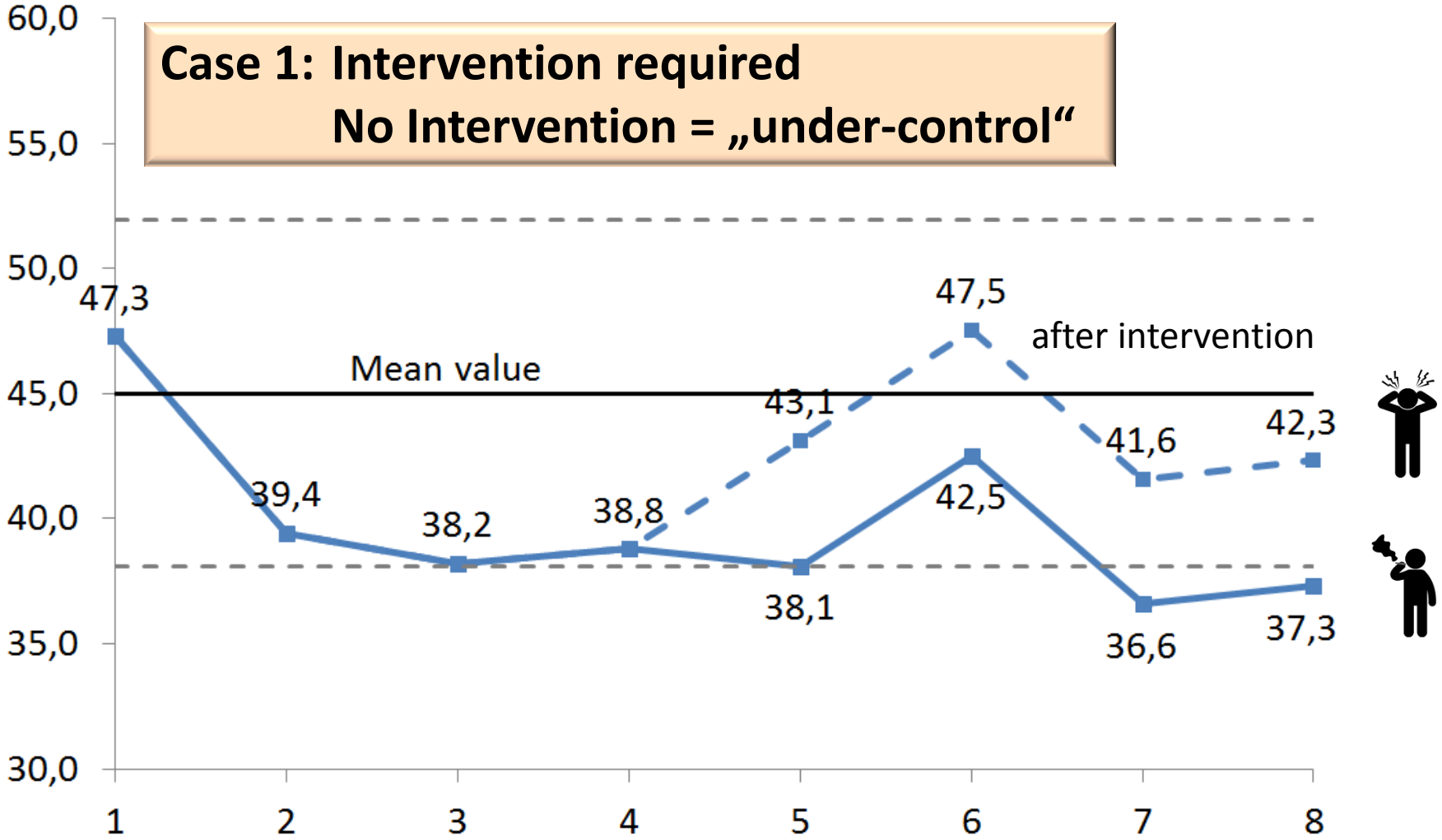
Example


60,0
55,0
50,0
45,0
40,0
35,0
30,0
1
2
3
4
5
6
7
8
47,3
39,4
38,2
38,8
41,7
43,3
43,9
46,9
Mean value
42,5
38,1
36,6
37,3
Case 2
Case 1

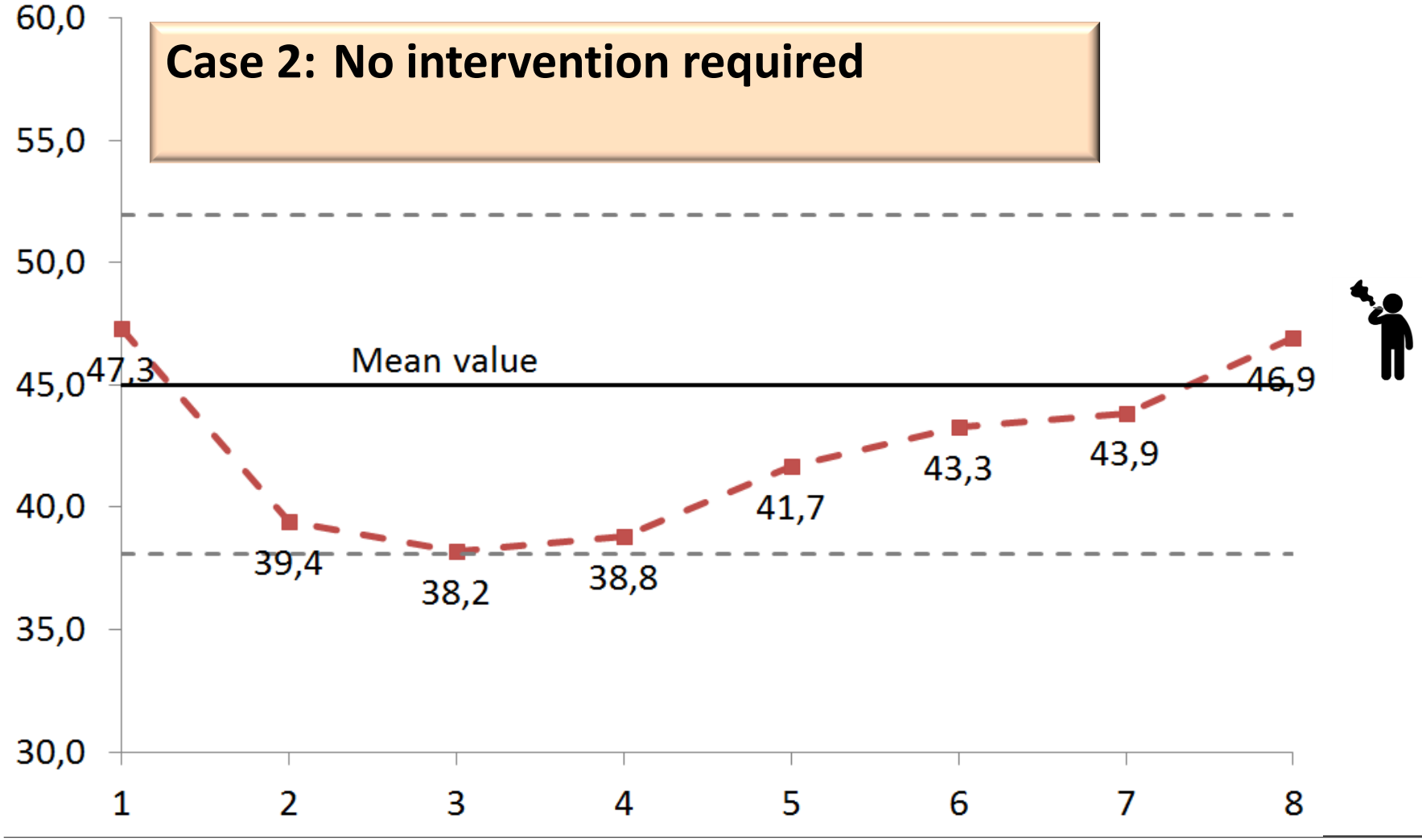
„Under-control“



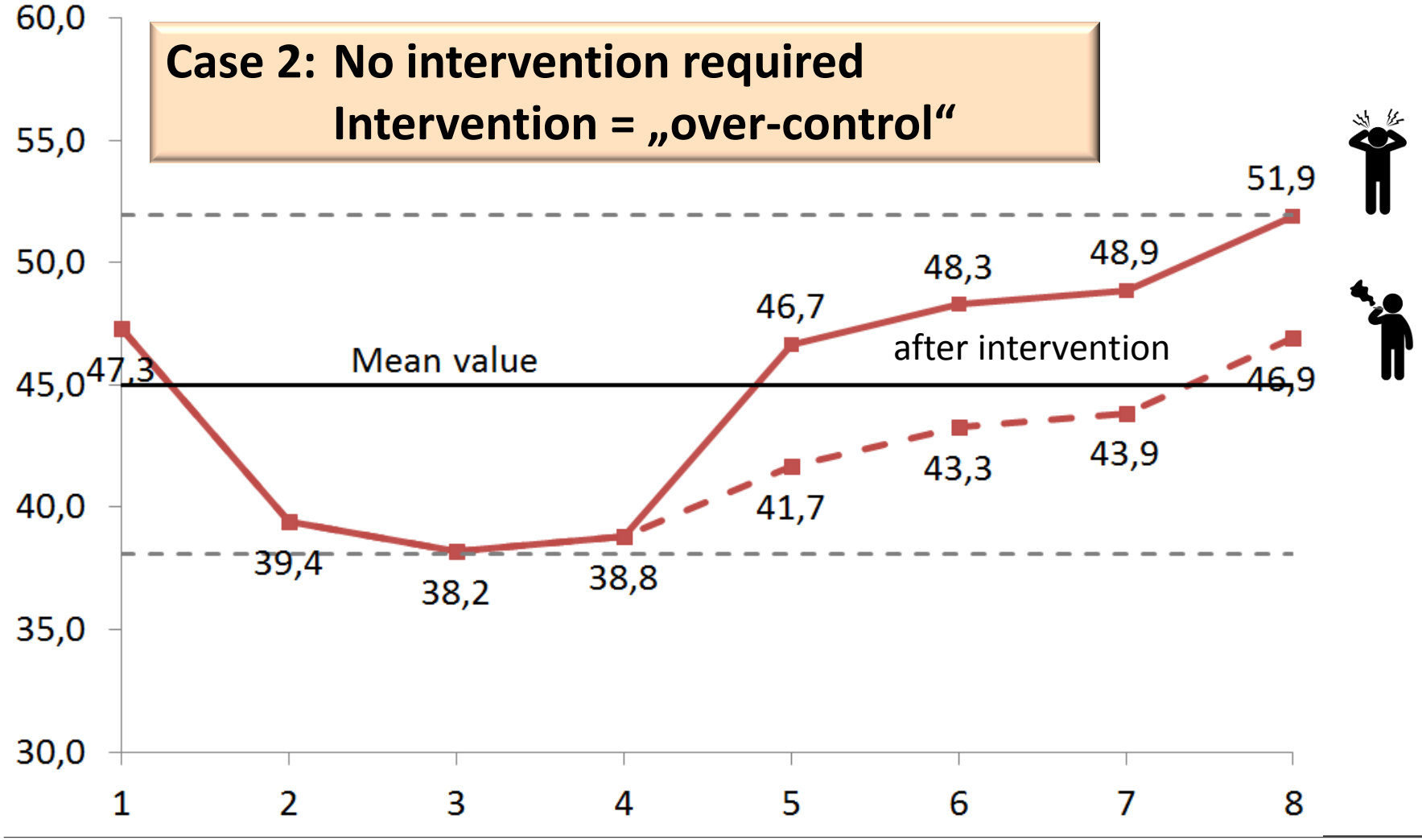
„Under-control“



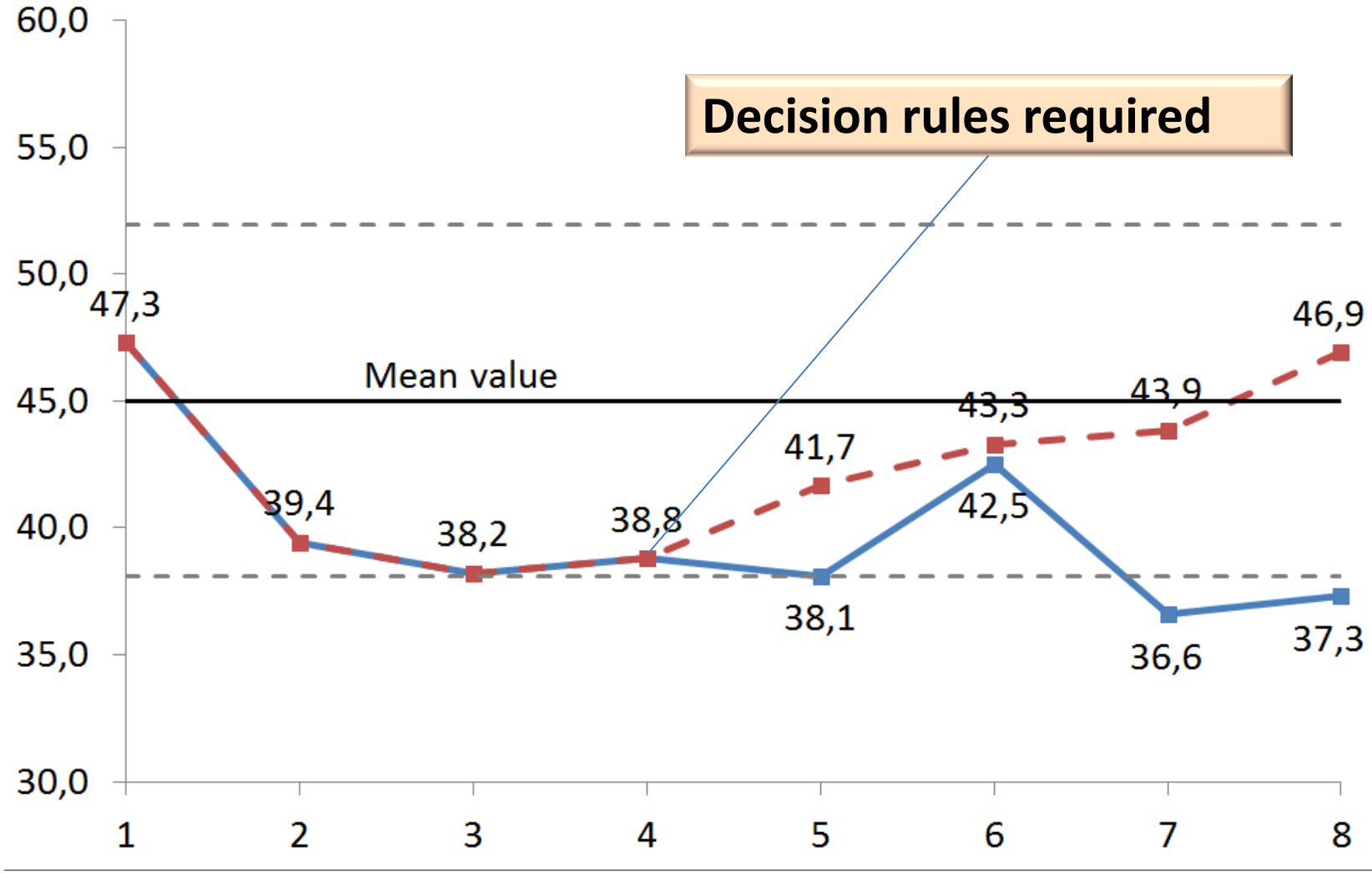
„Over-control“



„Over-control“



Example


Decision rules required
60,0
55,0
50,0
45,0
40,0
35,0
30,0
1
2
3
4
5
6
7
8
Mean value
47,3
39,4
38,2
38,8
38,1
42,5
36,6
37,3
41,7
43,3
43,9
46,9

Process control

- **A good process control should**
  - indicate processes running out of control early
  - and should avoid that actions are taken too early.

- **It is thus a compromise between „over-control“ and „under-control“.**

- **Observing process values along a time axis (so called Shewhart charts) are a simple tool but not efficient in detecting systematic changes quickly.**

- **It is difficult to find clear decision rules.**

- **Cusum control charts are much more efficient.**

Cusum control charts

Introduction of CUSUM charts

- Observing the technical data of a production process
  - Has a slow reaction time.
  - Does not detect systematic errors easily.
  - Does not locate easily where/when the error occurred.

- CUSUM were developed in the 1950‘s by E. S.Page for the quality control of continuous manufacturing processes.

- The aim was to generate a system with higher detection sensititivity for small systematic changes.

Introduction of CUSUM charts

- Cusum was recently incorporated into EN 206 for the conformity of concrete.
- However, cusum is a process control tool, not a conformity assessment tool.
- It has been used in concrete production efficiently in UK, South Africa, Australia for the production control.

Introduction of CUSUM charts

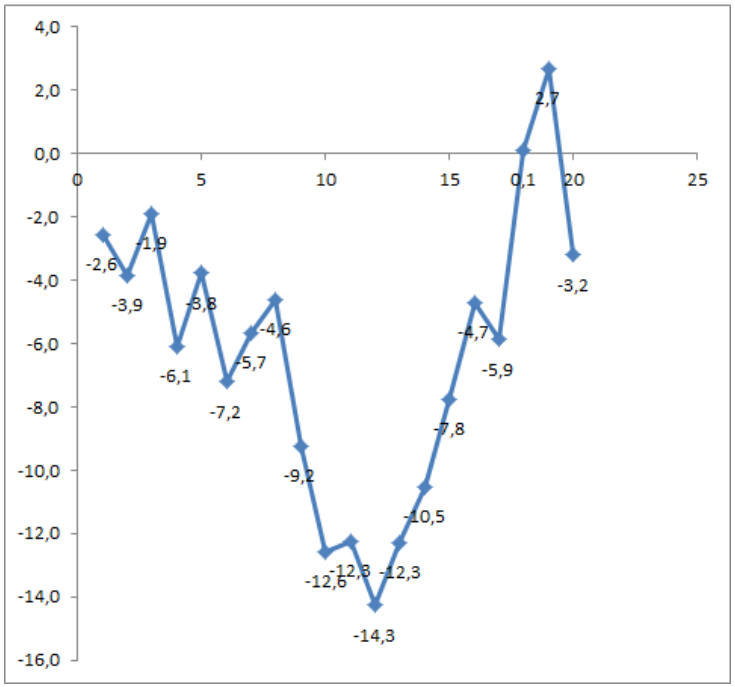
- CUSUM does not observe production data but the deviation of production data from a target value.

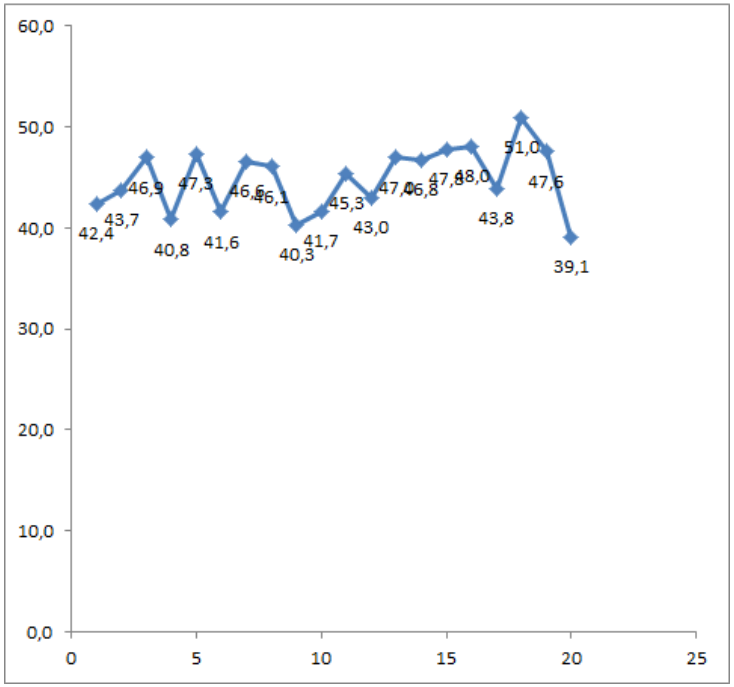
$$C(n) = \sum_1^n (f_{ci} - f_{cta})$$

- Principle:
  - Set target value.
  - Calculate difference between each production value and its target value.
  - Sum up these values chronologically.

- The following observations can be made:
  - Horizontal trend → Process is running as required
  - Upward drift → Production is higher than target
  - Downward drift → Production is lower than target

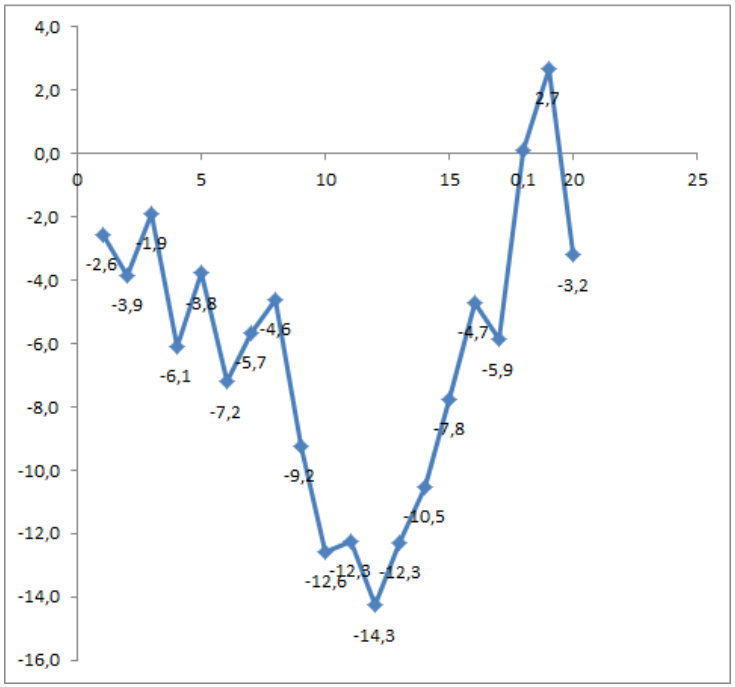
CUSUM vs. steady process data control

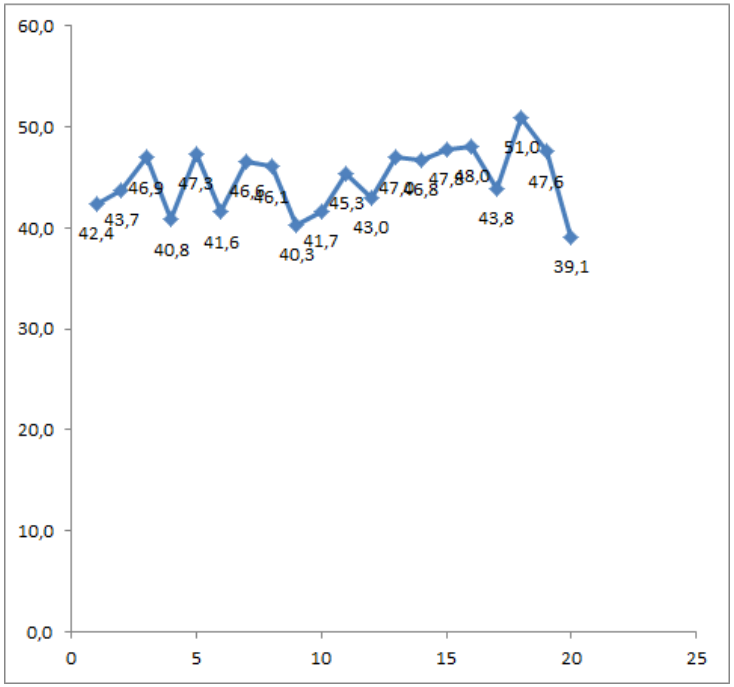




- **CUSUM observes the slope rather than the ordinate**

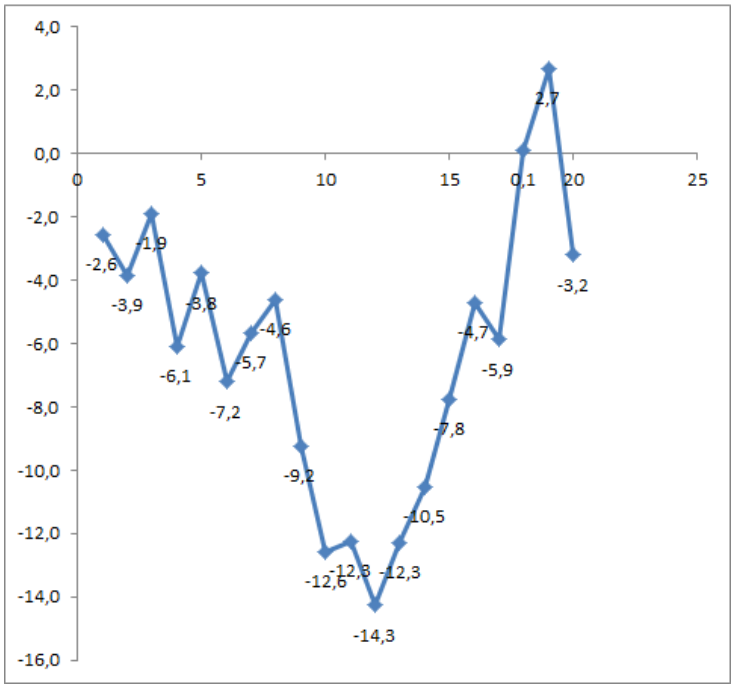
CUSUM vs. steady process data control

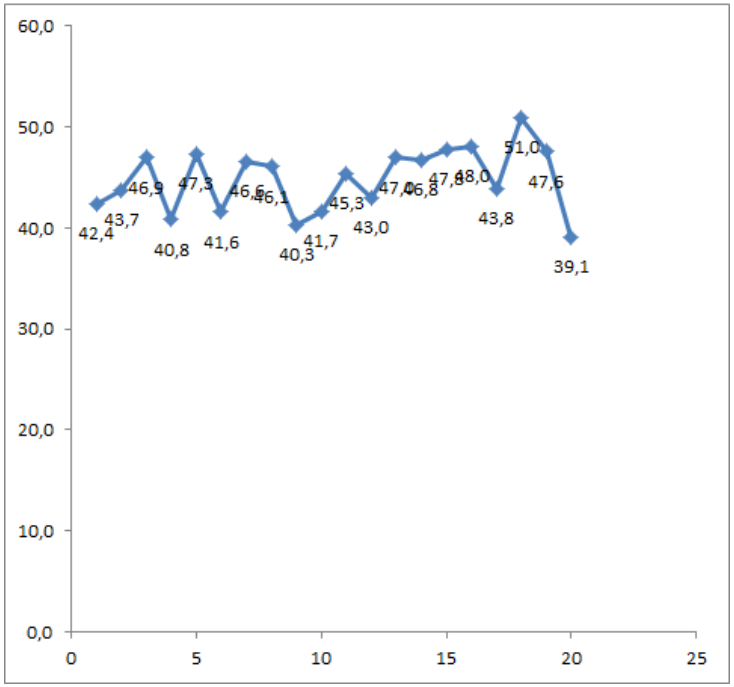




- **Advantages of CUSUM:**
  - More vivid illustration
  - Higher efficiency
  - Clearly indicates, where the process has changed

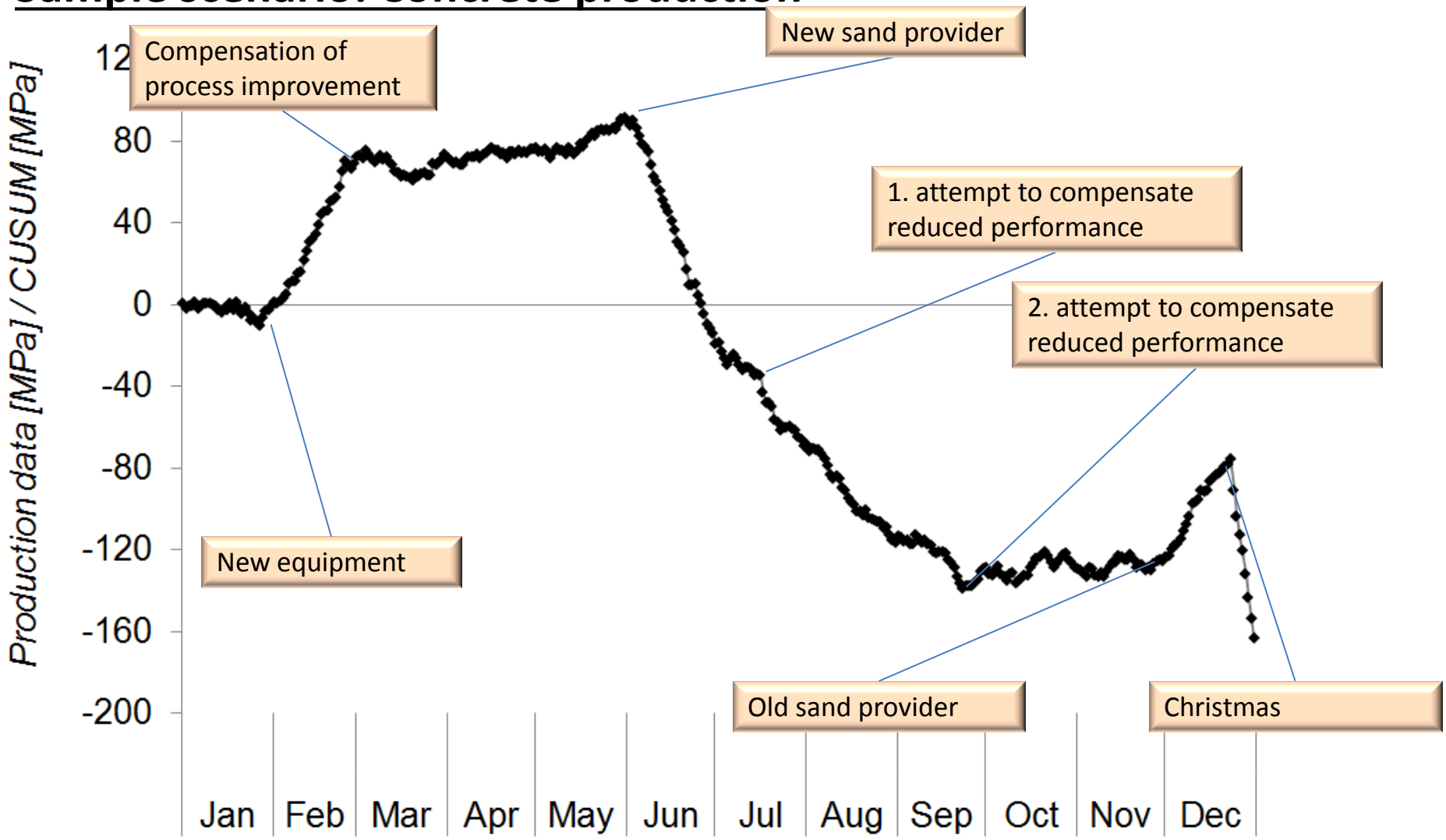
CUSUM vs. steady process data control





- **Possible disadvantages of CUSUM:**
  - Relatively unknown method. Needs training/education.
  - Higher computational effort.
  - Interpretation is more difficult.

Sample scenario: Concrete production



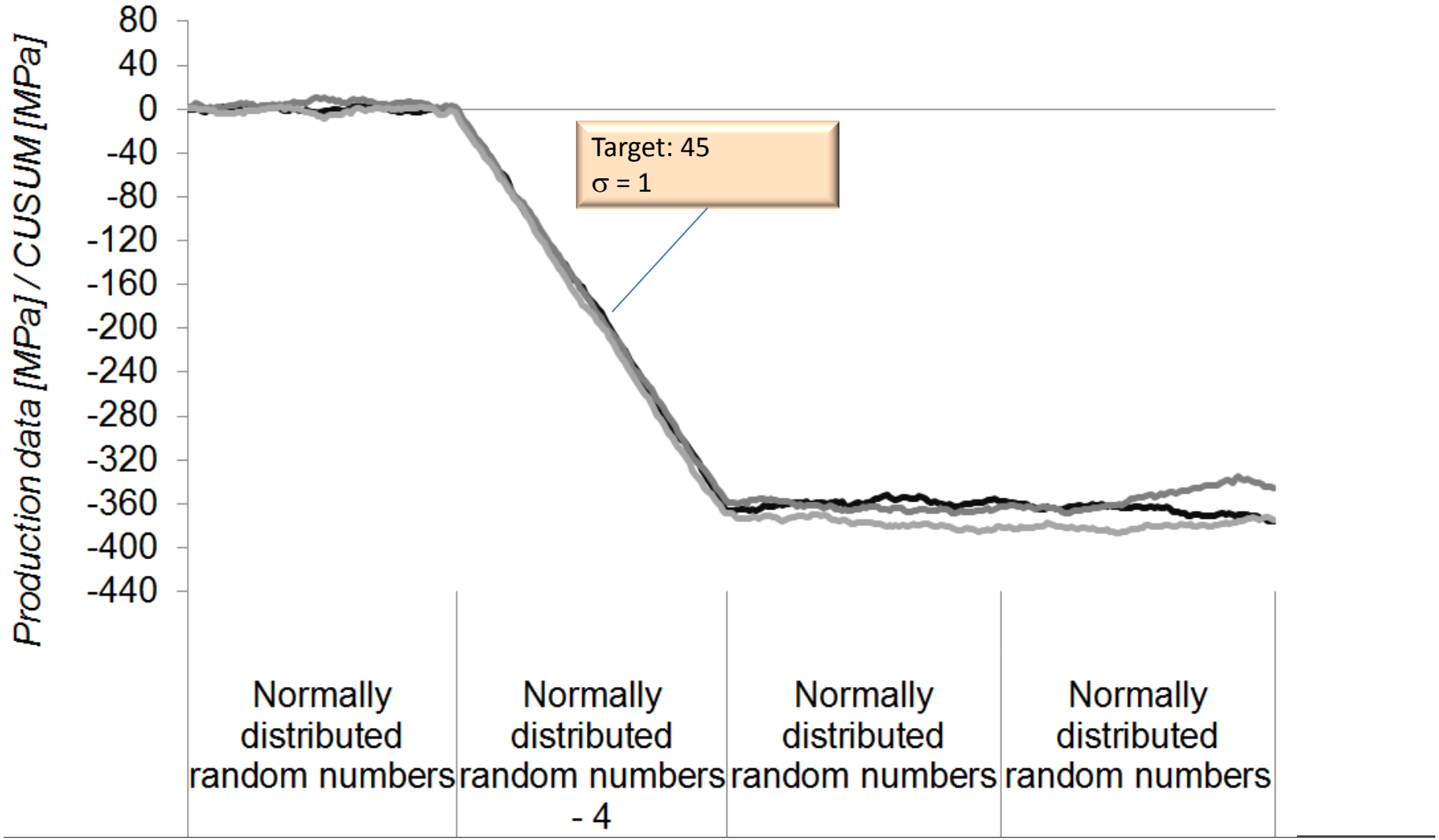
The V-mask concept

Decision making with CUSUM

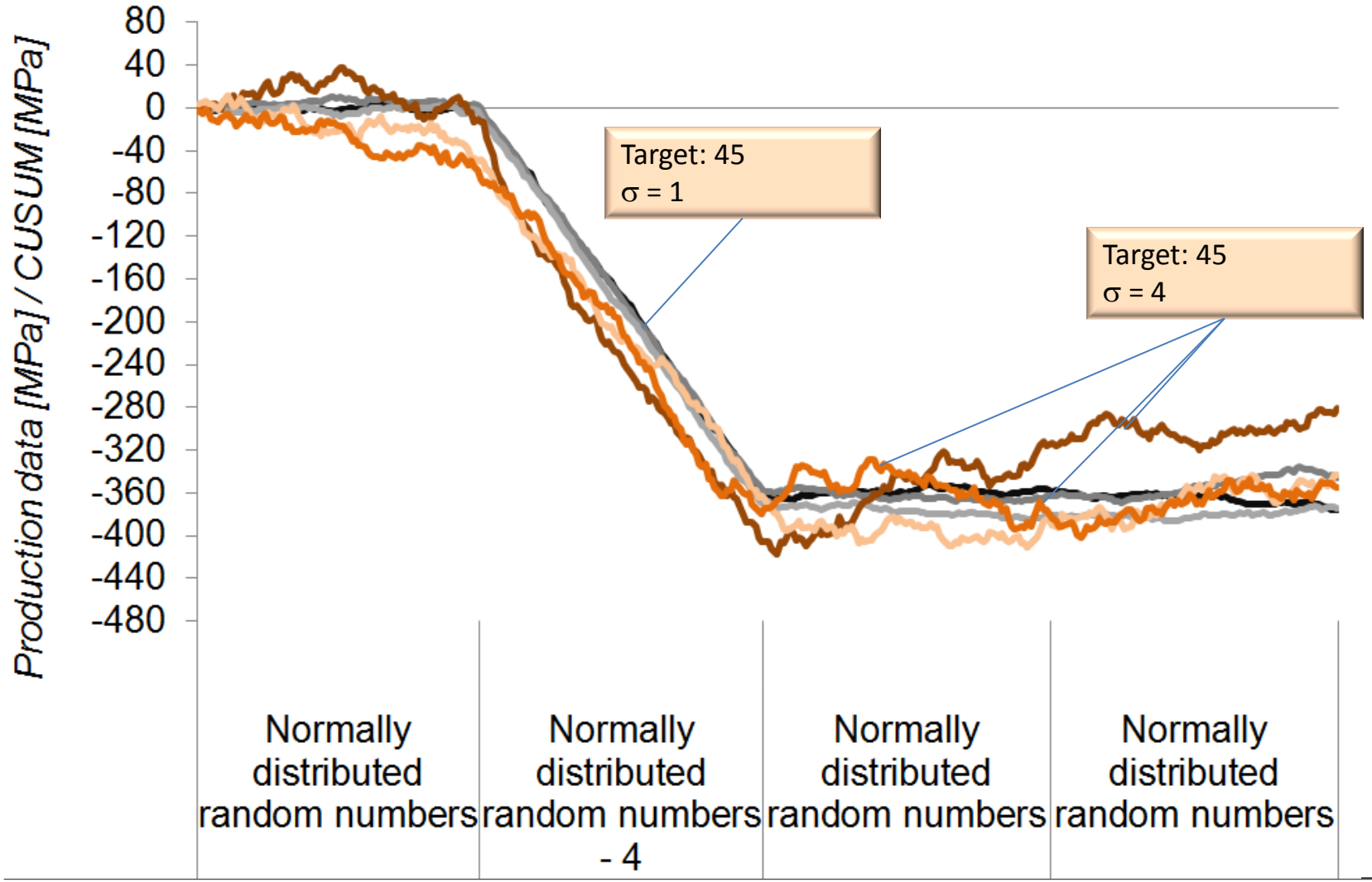
- CUSUM observes the slope of the curve:
  - Horizontal slope → OK!
  - Upward drift → Production above target
  - Downward drift → Production below target

- Curve trends are not always easily identifiable.
  - If differences are small, the slope may be to small to be identified easily
  - Increasing standard deviation increase the scatter of the CUSUM

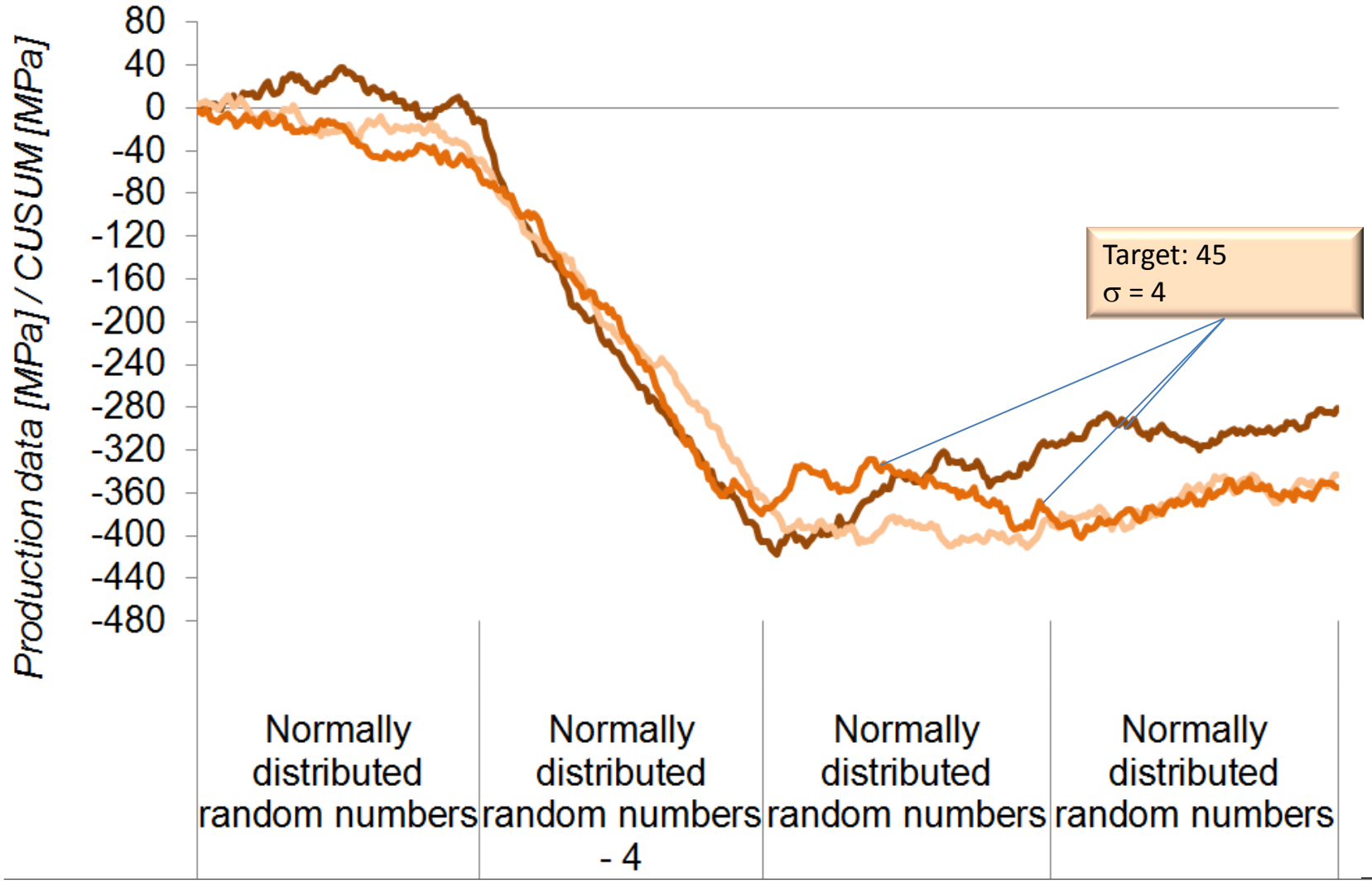
Decision making with CUSUM



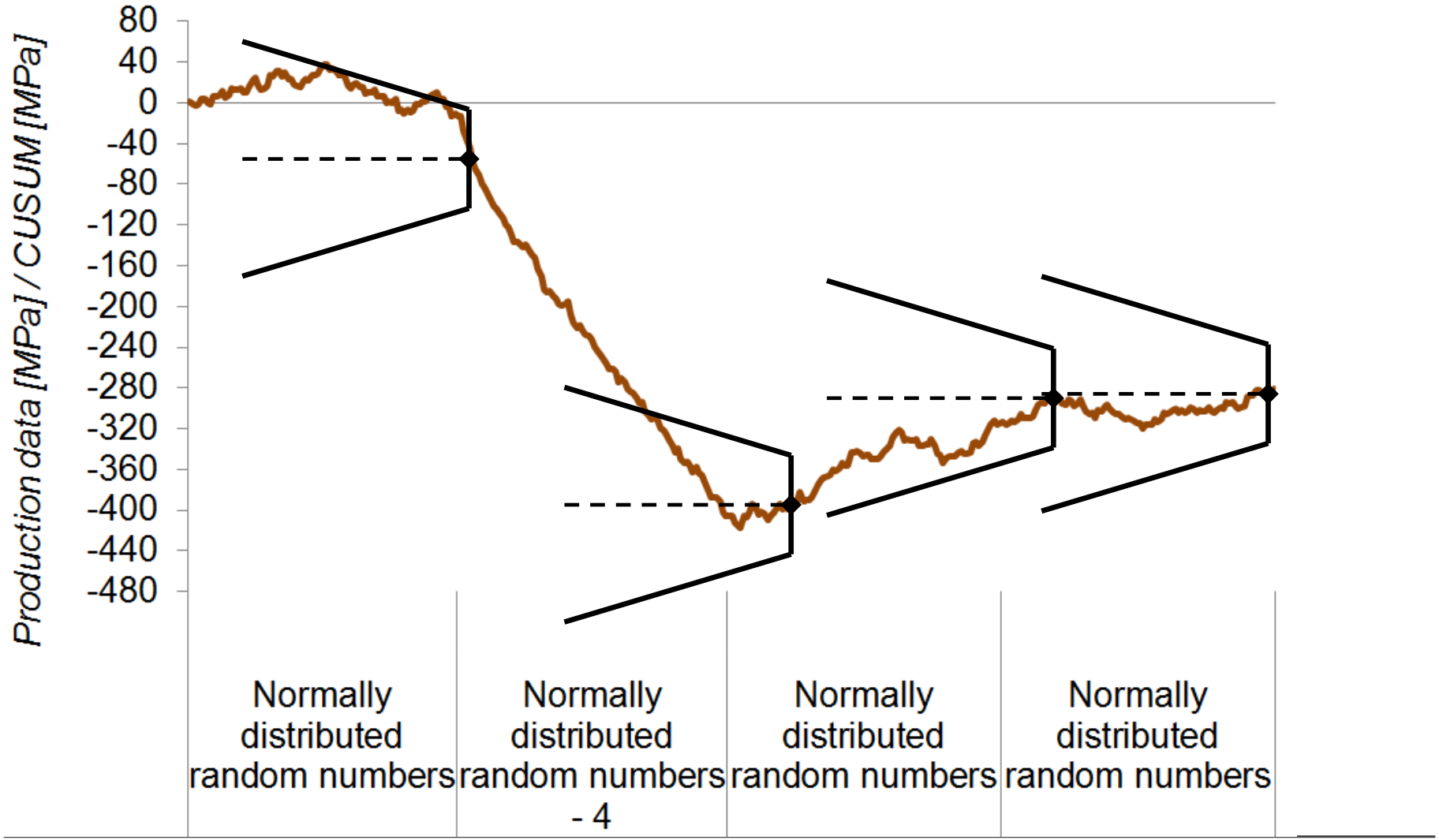
Decision making with CUSUM



Decision making with CUSUM

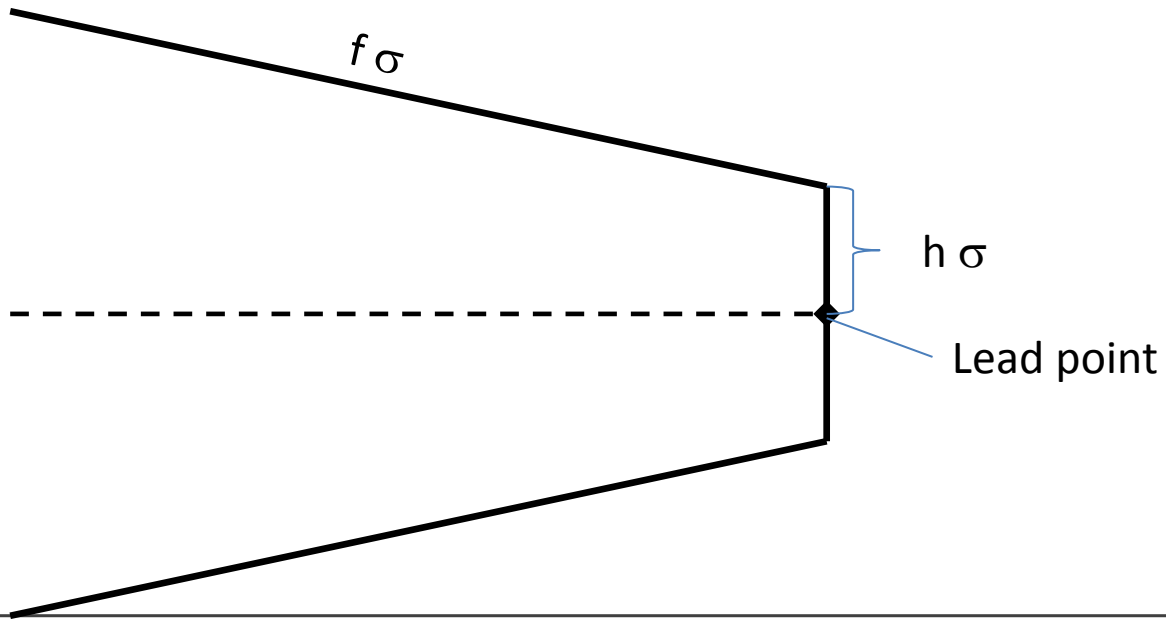


Decision making with CUSUM



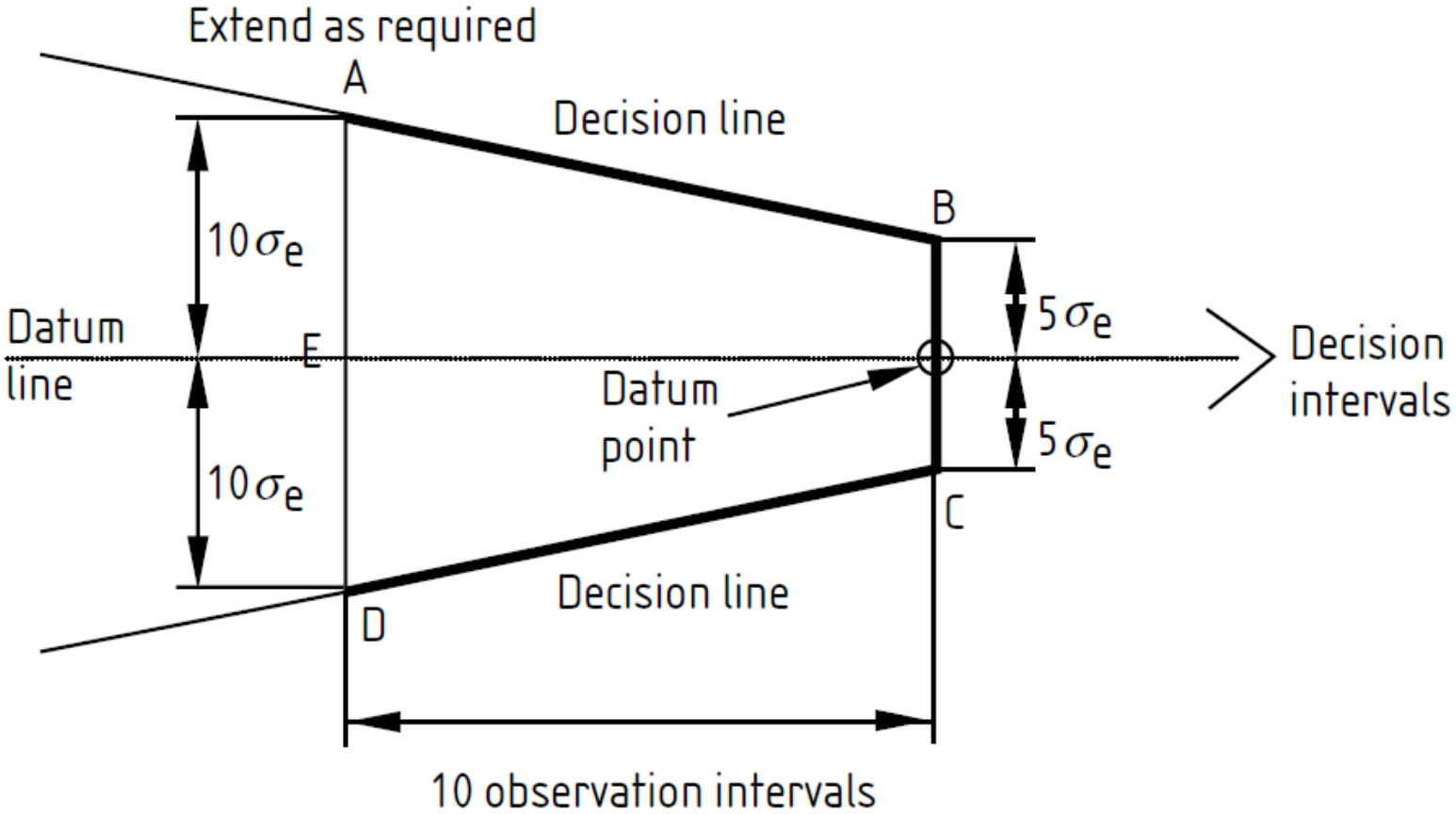
Geometry of the V-mask

- The geometry of theV-mask should depend on the standard deviation
  - The lead point can be put on any process value of the CUSUM
  - The half mask height is a measure of the reliability of the detection.
  - The slope is a measure of the size of change to be detected.



The general purpose, standard, truncated V-mask

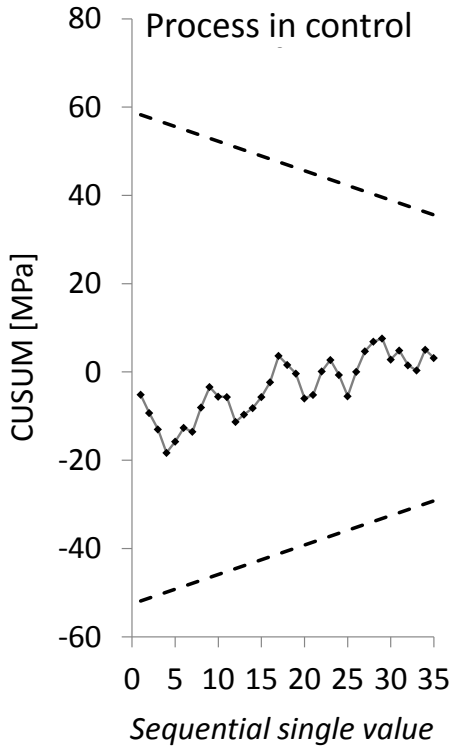
- h = 5
- f = ½



Interpretation of the V-mask

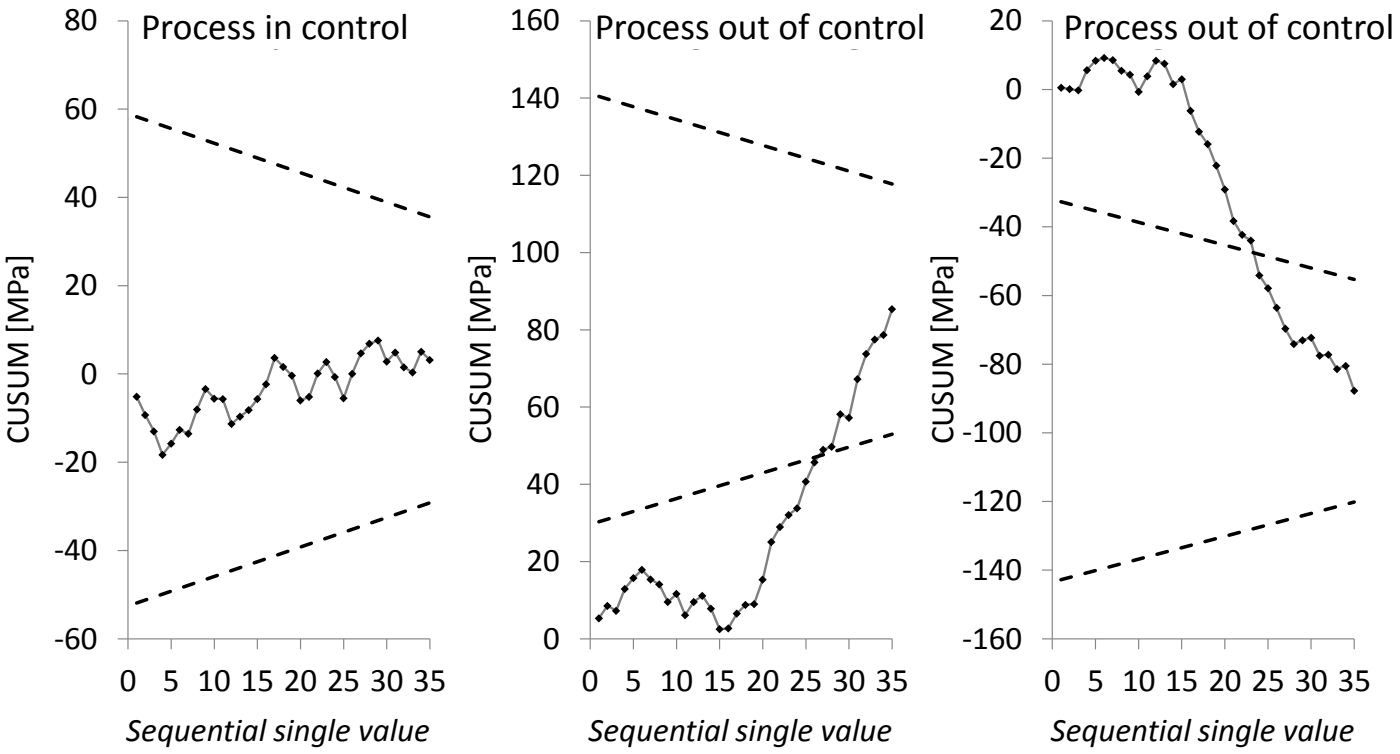
- As long as the CUSUM runs between the limbs of the mask there is no reason to interfere

  → this avoids „over-control“



Interpretation of the V-mask

- Crossing limbs indicates that the process is out of control



Using CUSUM and V-mask to control the fresh concrete properties of SCC

Experimental

Aim of the study

- Changes in the rheology of self-compacting concrete can depend upon multiple factors.
- Typically, it is not easily possible to identify the origin of changes in rheology:
  - Different cement quality/age?
  - Superplasticizer?
  - Water content of aggregates?
  - Fillers?
  - ….
- Is CUSUM a feasible method to maintain a steady slump flow regardless of the influencing factor, based only on:
  - the addition of superplasticizer (PCE), when too small, and
  - the addition of stabilising agent (Starch), when too wide?

Reduced flowability

Increased flowability

Reference mix,
Target consistence
s_F = 243 mm

s_F = 165 mm

s_F = 282 mm

PCE

STA

s_F = 236 mm

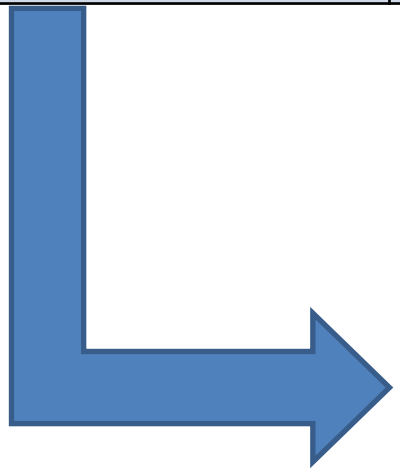
s_F = 230 mm

Reference mixture composition

	Spec. Gravity [-]	Mass/m³ [kg/m³]	Vol./m³ [l/m³]
OPC (CEM I 42.5 R)	3.125	458.0	146.6
Limestone filler	2.735	369.7	135.2
Water	1.0	259.0	259.0
PCE superplasticizer	1.07	8.2	
Sand 0.1/0.5	2.60	298.5	114.8
Sand 0.5/1.0	2.60	298.5	114.8
Sand 1.0/2.0	2.60	298.5	114.8
Sand 2.0/4.0	2.60	298.5	114.8

Variations: Effects that increase the slump flow

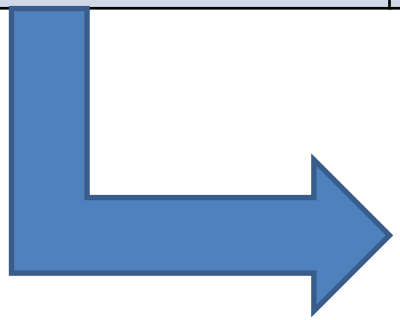
Manipulation	Specification
Reference	Target value after 15 minutes: 237.7 mm
More water	+10% of water
More coarse sand	+50% sand 2.0/4.0 and -50% sand 0.1/0.5
Less cement	-10% of cement
Less limestone filler	-10% of limestone filler



Addition of stabilising agent required to achieve target value of 237.7 mm

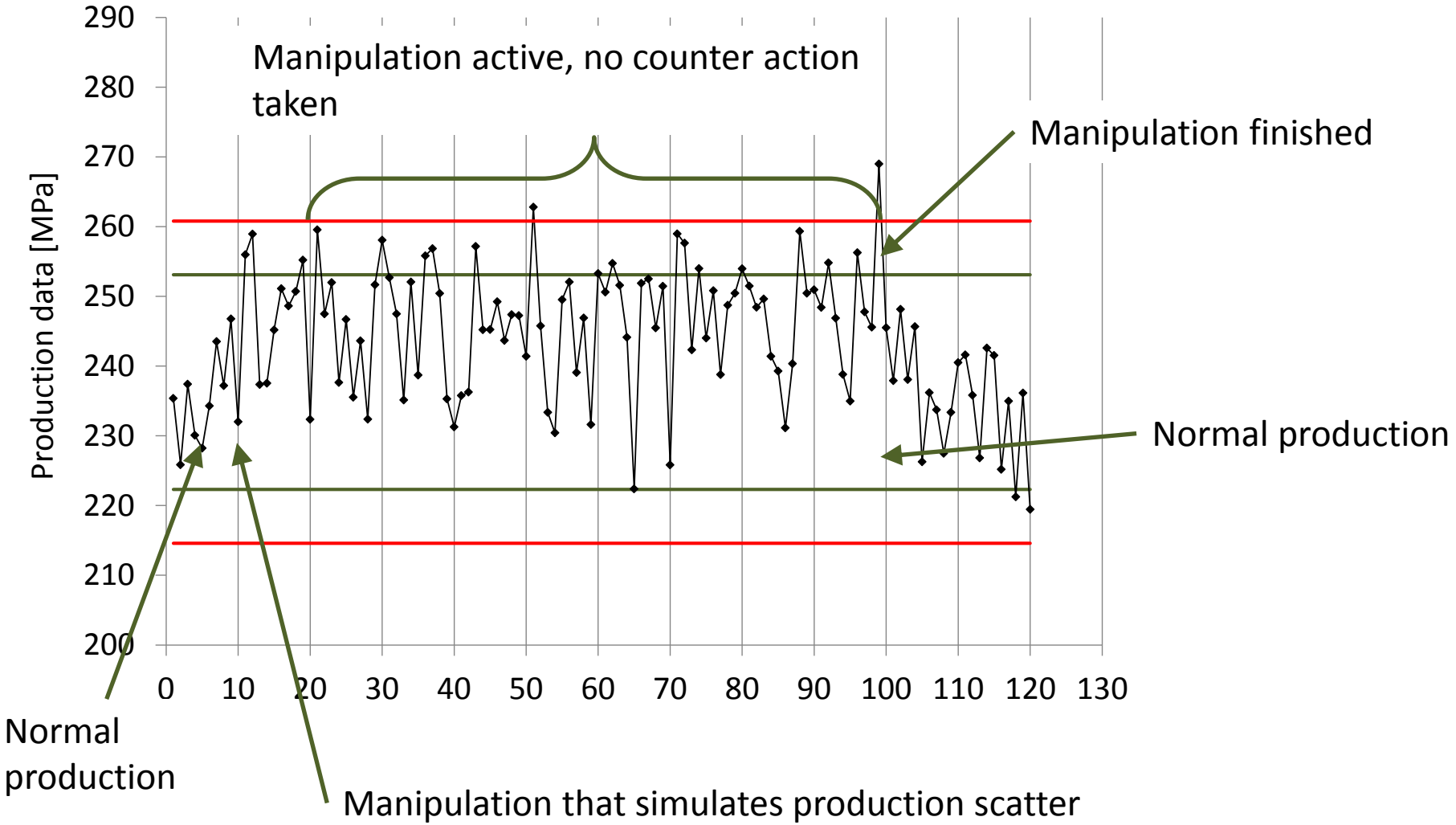
Variations: Effects that reduce the slump flow

Manipulation	Specification
Reference	Target value after 15 minutes: 237.7 mm
Less water	-10% of water
Crushed sand	Coarse quartz sand fraction replaced by crushed sand
Gypsum addition	+0.35% of cement
More fine sand	+50% sand 0.1/0.5 and -50% sand 2.0/4.0
More cement	+10% of cement
More limestone filler	+10% of limestone filler

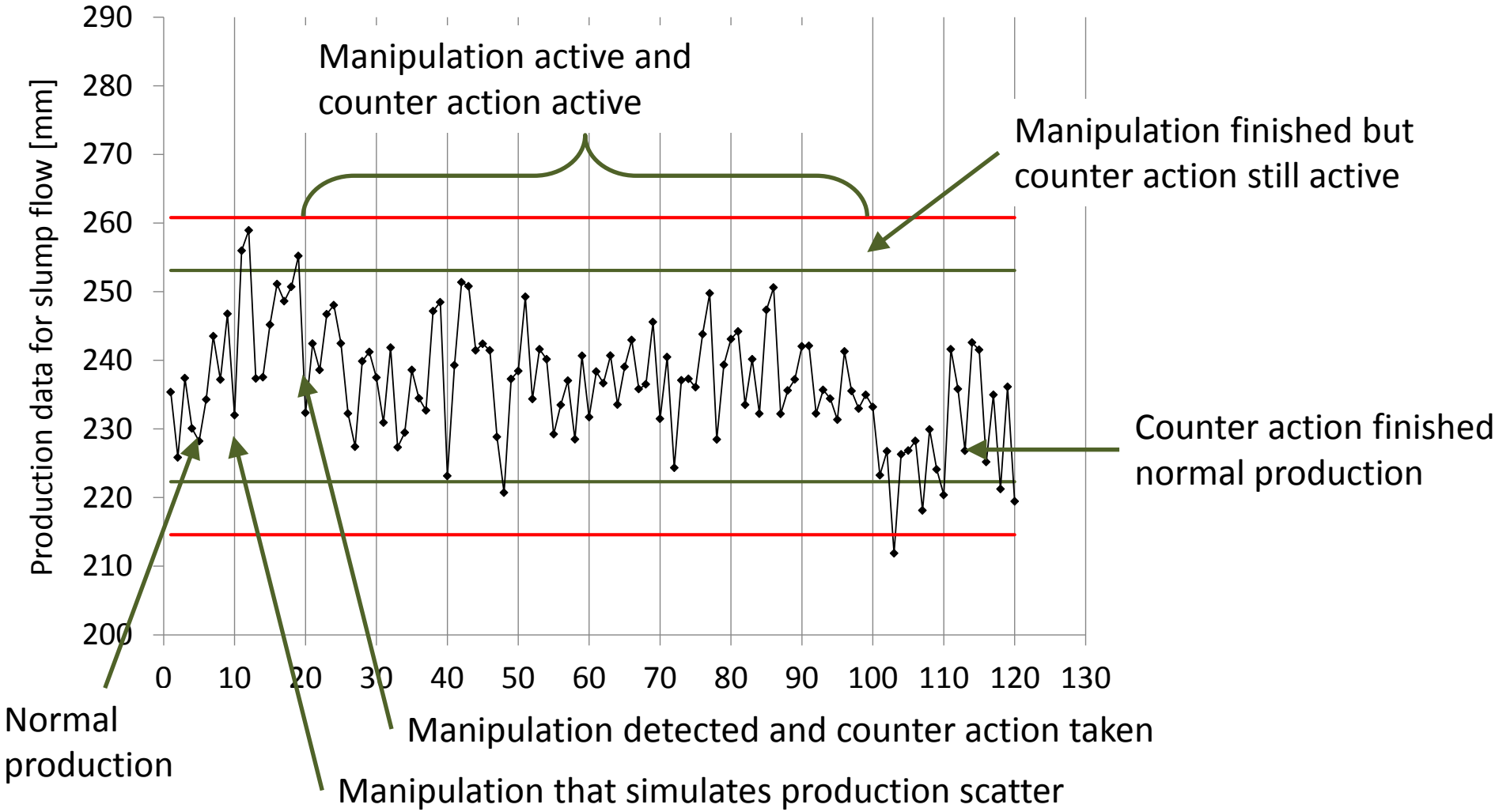


Addition of extra superplasticizer required to achieve target value of 237.7 mm

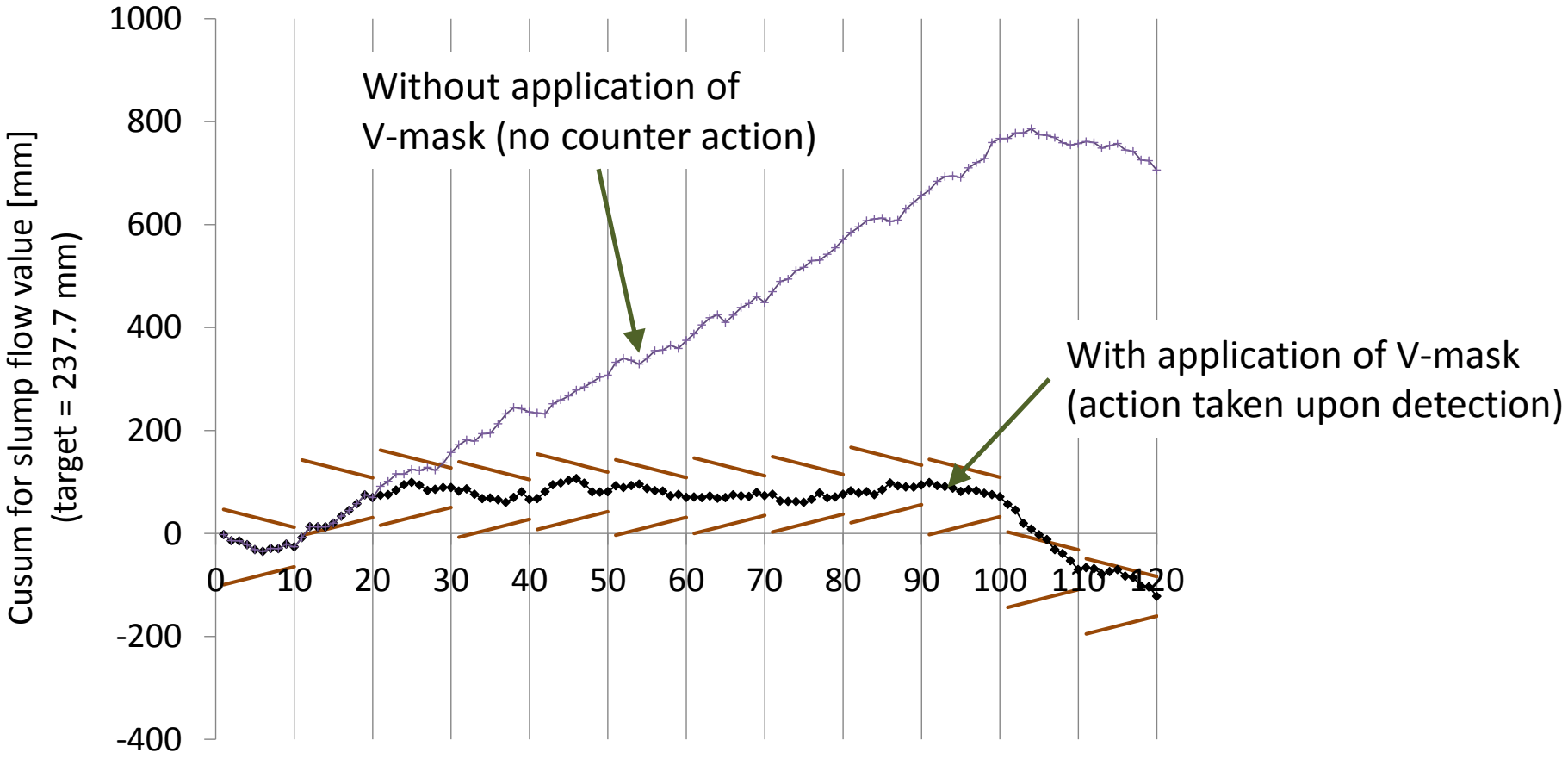
Scenario


Manipulation active, no counter action taken
Manipulation finished
Normal production
Normal production
Manipulation that simulates production scatter
Production data [MPa]
290
280
270
260
250
240
230
220
210
200
0
10
20
30
40
50
60
70
80
90
100
110
120
130

Scenario for V-mask observation

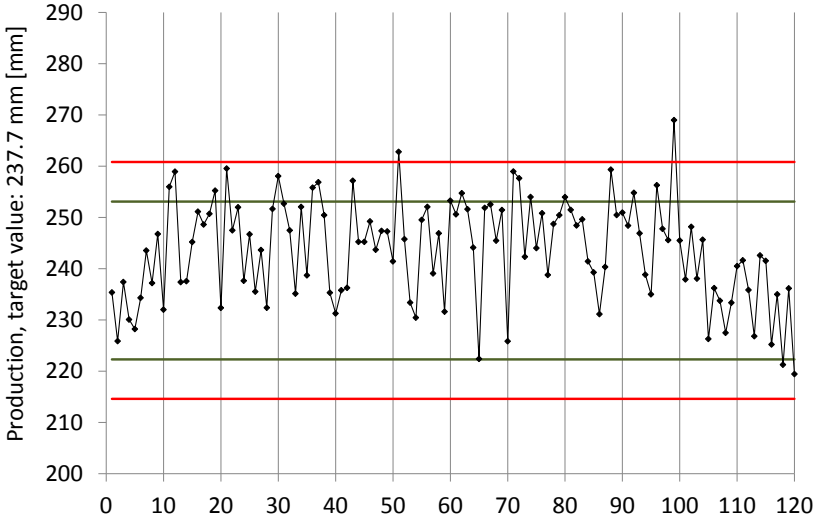


Scenario: Cusum without and with application of V-mask

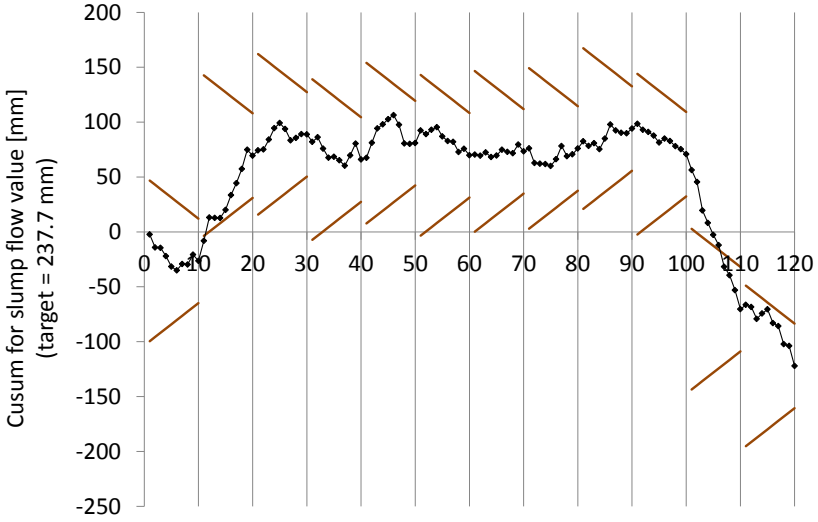


Scenario

Without application of V-mask control (no correction)



With application of V-mask control (correction upon V-mask indication)



	without V-mask	with applied V-mask
Target value after 15 min. [mm]	237,7	237,7
Mean value [mm]	245,4	238,4
Standard deviation [mm]	9,3	7,5
Deviation from target [mm]	7,7	0,7
Deviation from target [%]	3,2%	0,3%

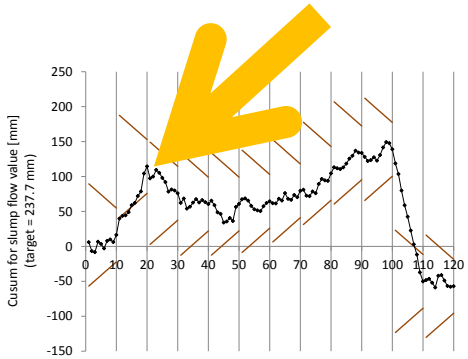
Experimental

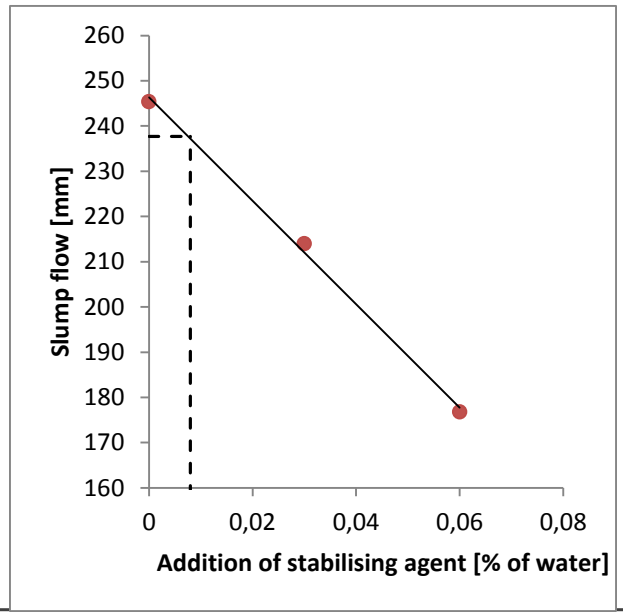
- Reference mixture: Mean value and standard deviation from 5 repetitions.
- Manipulated mixtures: Mean value and standard deviations from 3 repetitions.

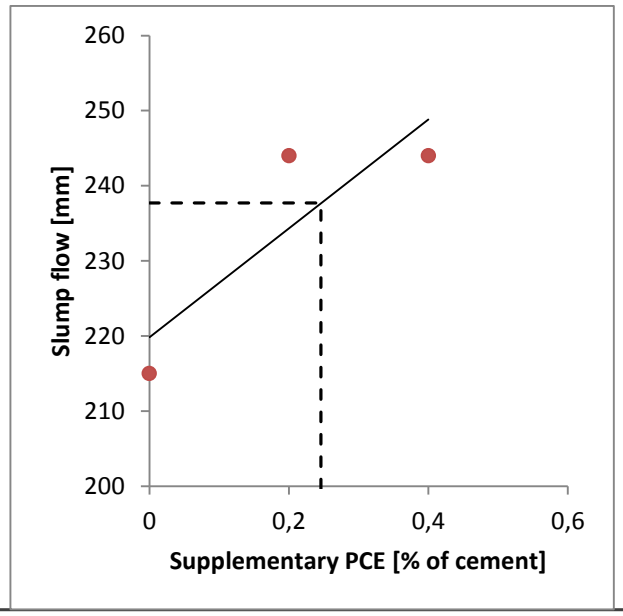
- Simulation of production data according to scenario described before:
  - Based on normally distributed random values
  - with the mean values and standard deviations from the experimental investigations.

Experimental

- Prediction of counter actions:
  - Experimental determination of manipulated samples:
    - +0%; +0.2%; +0.4% superplasticizer
    - +0%; 0.03%; 0.06% stabilising agent
- Simplified assumption: Linear correlation:

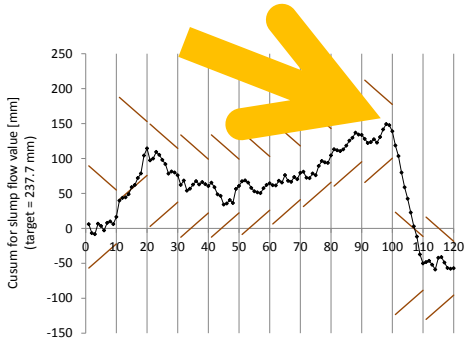


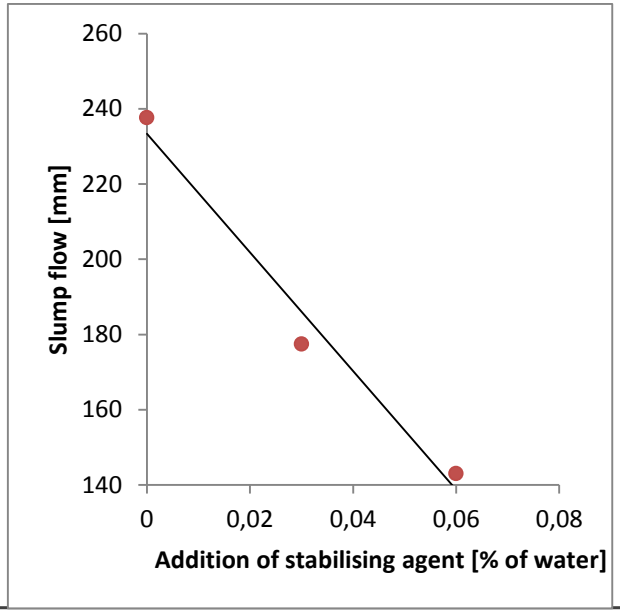


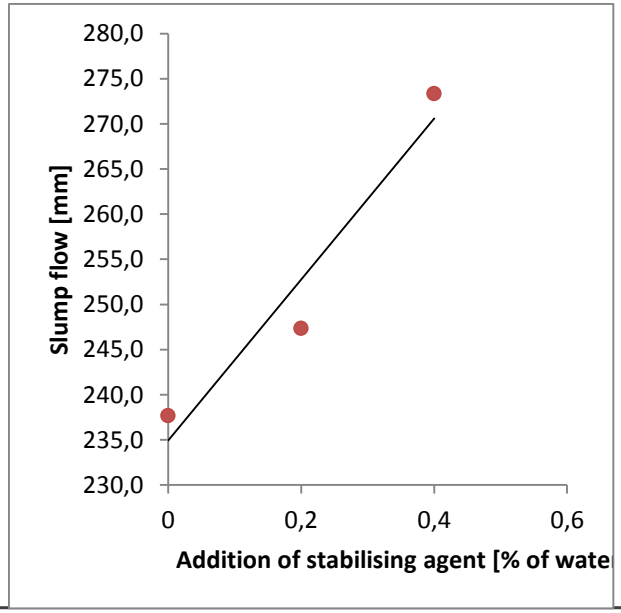


Experimental

- Prediction of flow when manipulation is stopped but counteraction still active:
  - Experimental determination of manipulated samples:
    - +0%; +0.2%; +0.4% superplasticizer
    - +0%; 0.03%; 0.06% stabilising agent
- Simplified assumption: Linear correlation:

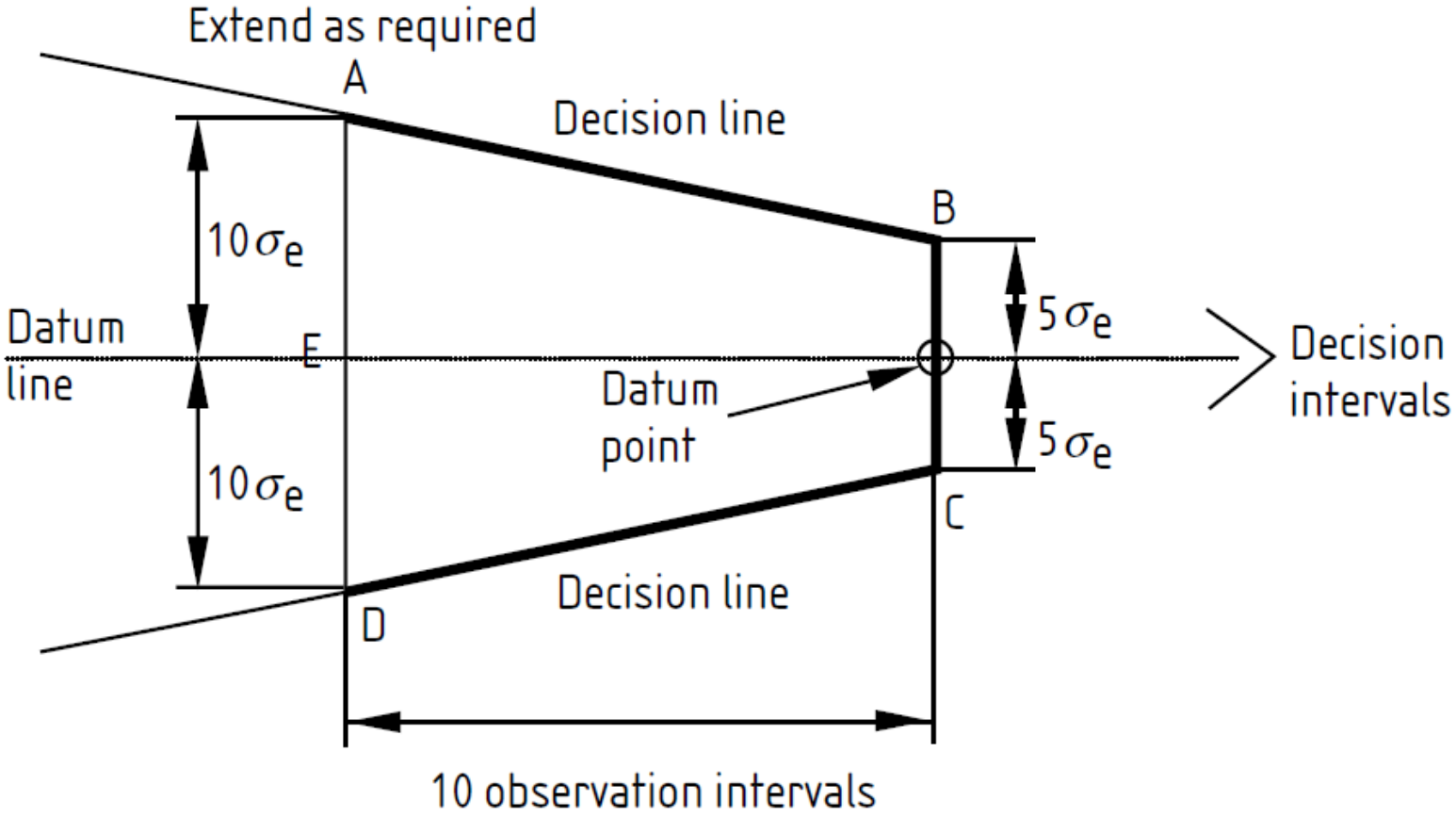






Experimental

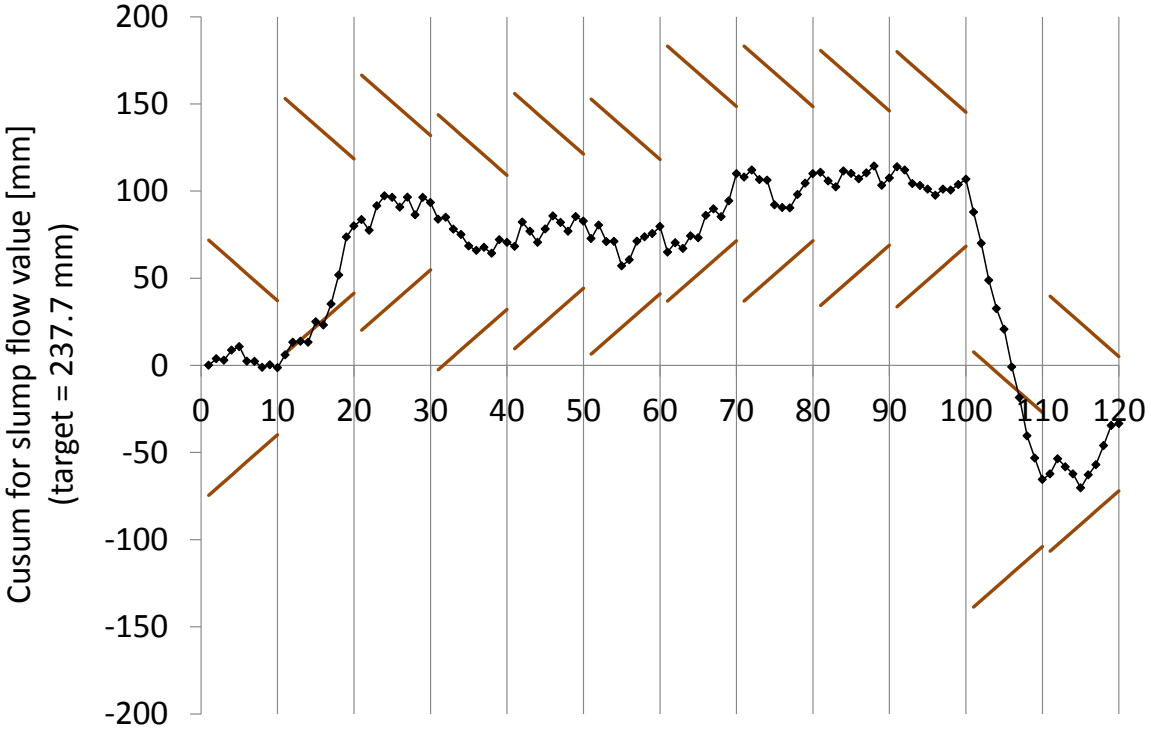
- h = 5
- f = ½



Using CUSUM and V-mask to control the fresh concrete properties of SCC

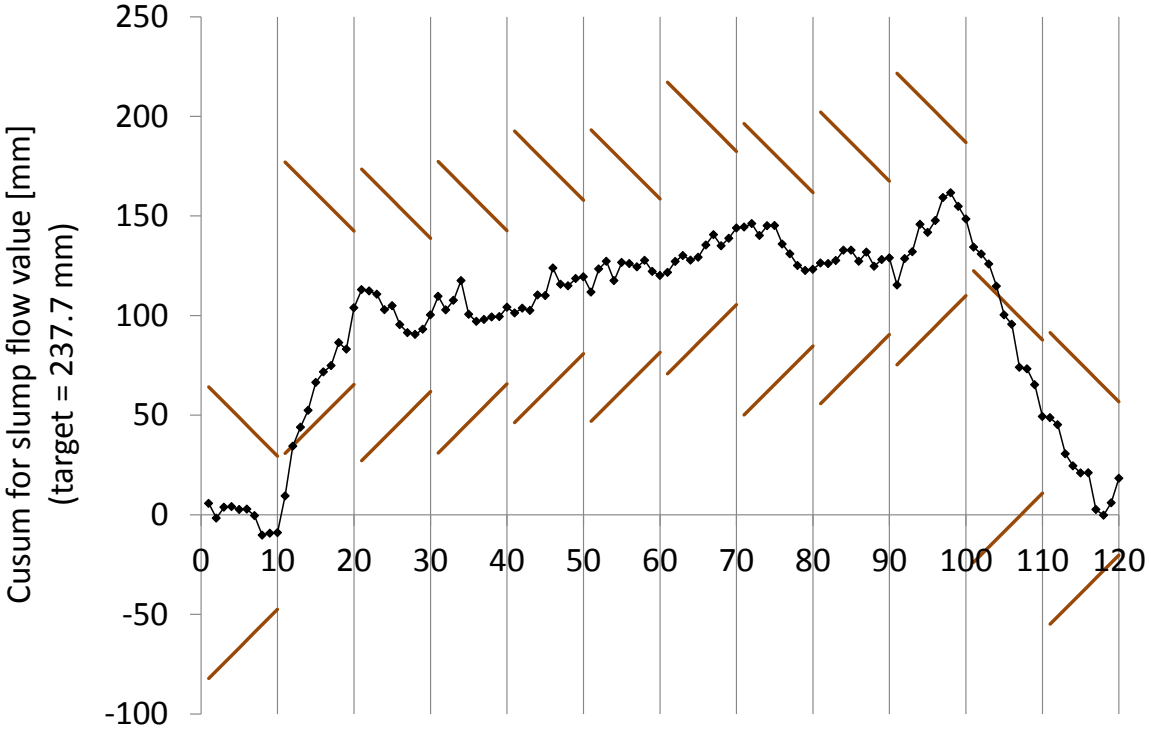
Results and discussion

Results: Extra water



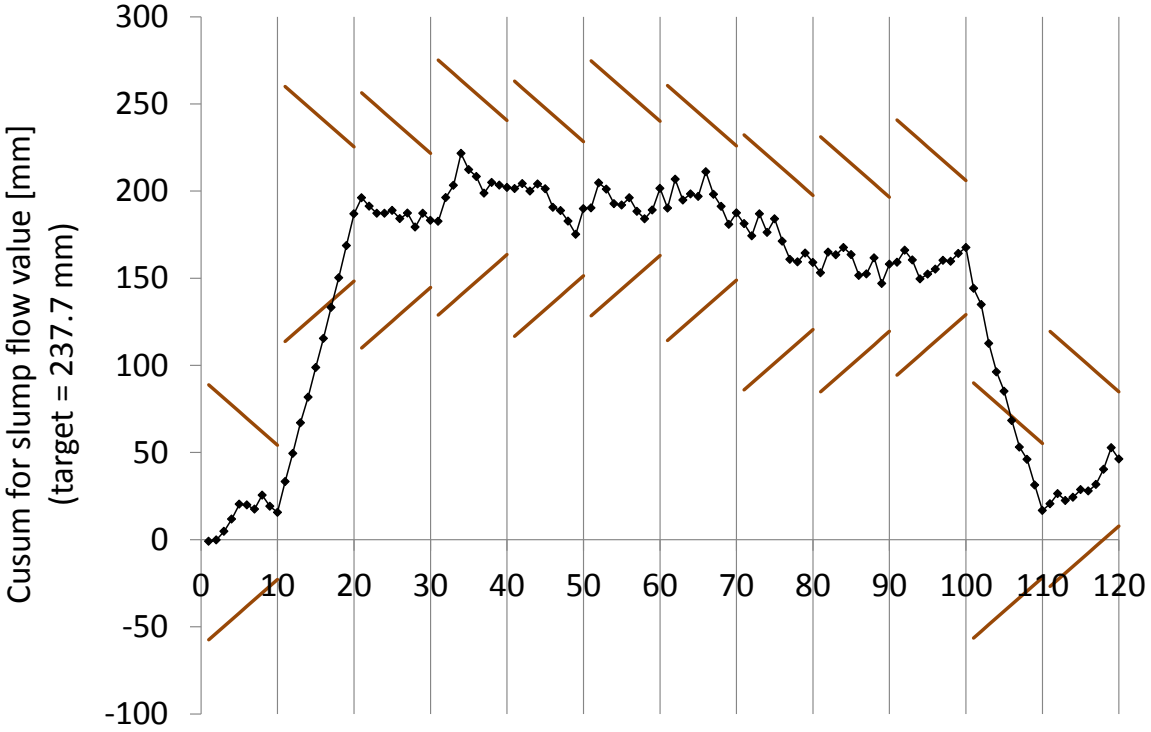
	without V-mask	with applied V-mask
Target value after 15 min. [mm]	237,7	237,7
Mean value [mm]	243,9	238,8
Standard deviation [mm]	8,5	7,0
Deviation from target [mm]	6,2	1,1
Deviation from target [%]	2,6%	0,4%

Results: Higher content of coarse aggregate



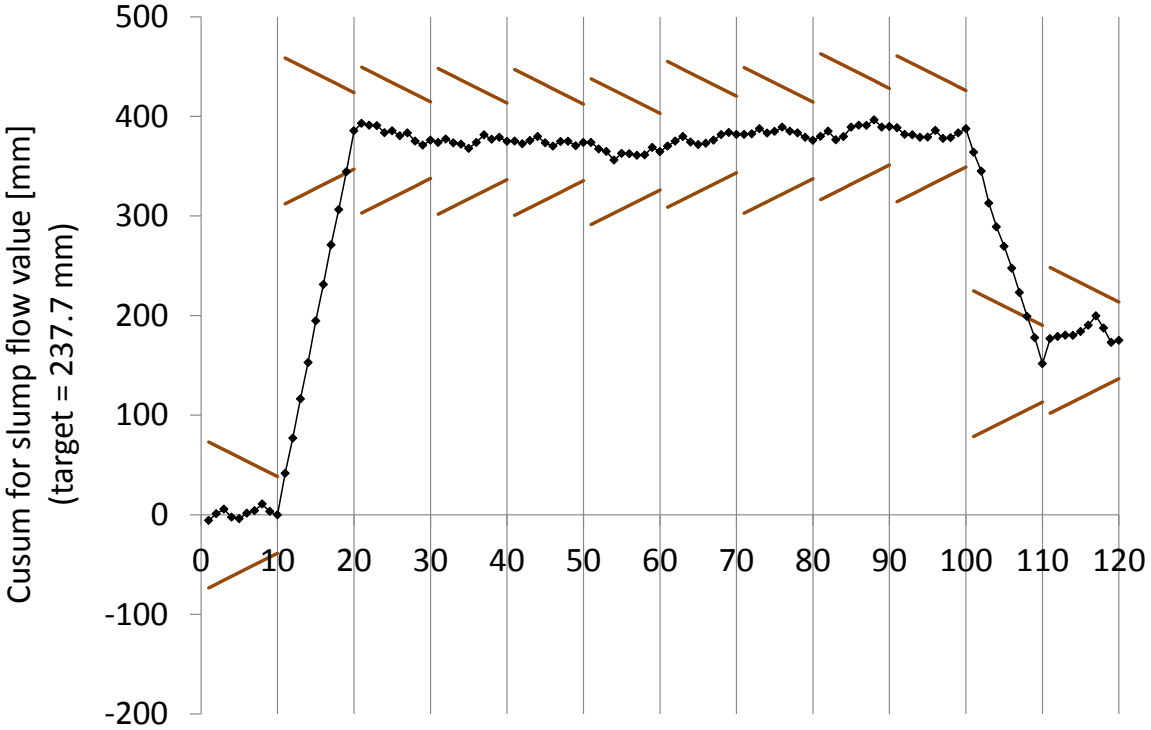
	without V-mask	with applied V-mask
Target value after 15 min. [mm]	237,7	237,7
Mean value [mm]	245,3	239,2
Standard deviation [mm]	9,9	7,1
Deviation from target [mm]	7,6	1,5
Deviation from target [%]	3,2%	0,6%

Results: Lower cement content



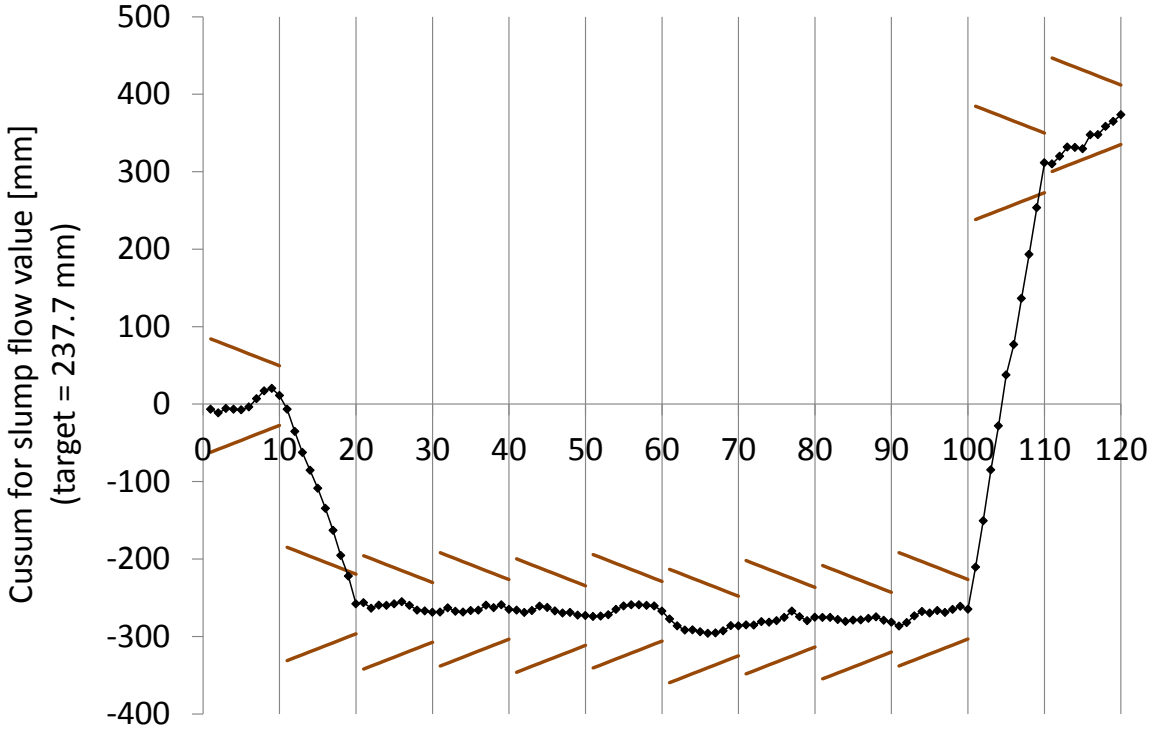
	without V-mask	with applied V-mask
Target value after 15 min. [mm]	237,7	237,7
Mean value [mm]	253,2	239,4
Standard deviation [mm]	5,2	9,0
Deviation from target [mm]	15,5	1,7
Deviation from target [%]	6,5%	0,7%

Results: Less limestone filler



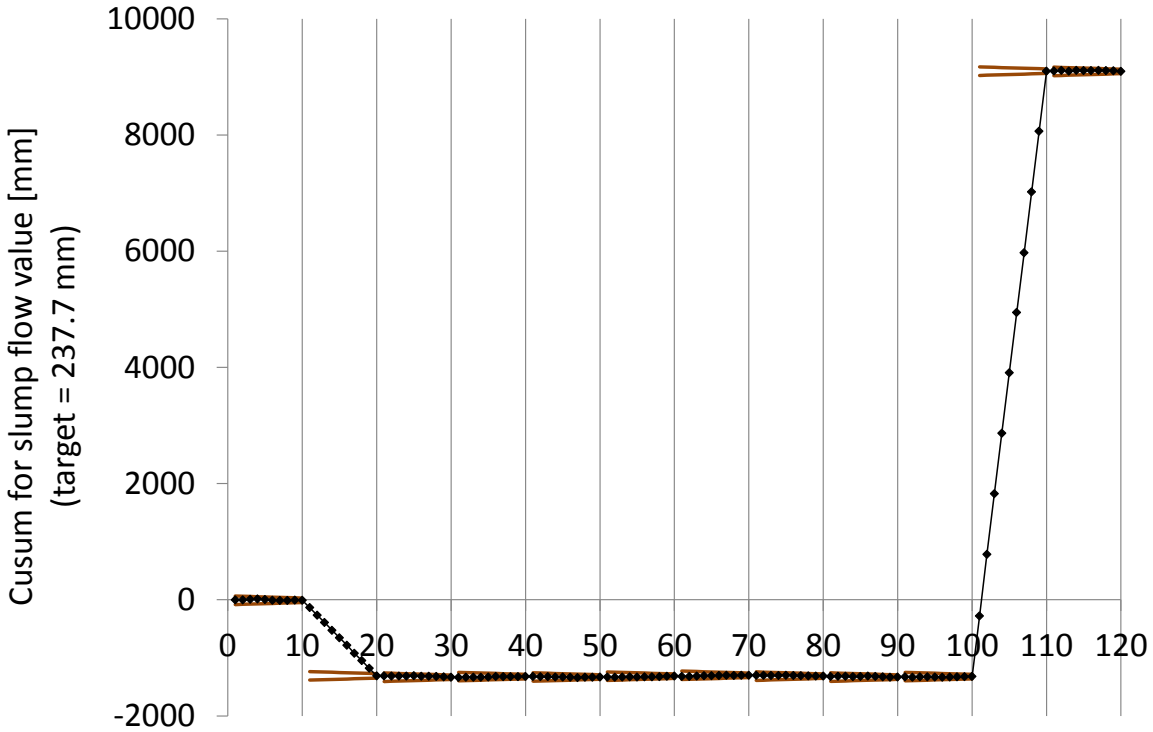
	without V-mask	with applied V-mask
Target value after 15 min. [mm]	237,7	237,7
Mean value [mm]	274,7	241,6
Standard deviation [mm]	12,9	12,5
Deviation from target [mm]	37,0	3,9
Deviation from target [%]	15,6%	1,6%

Results: Less water



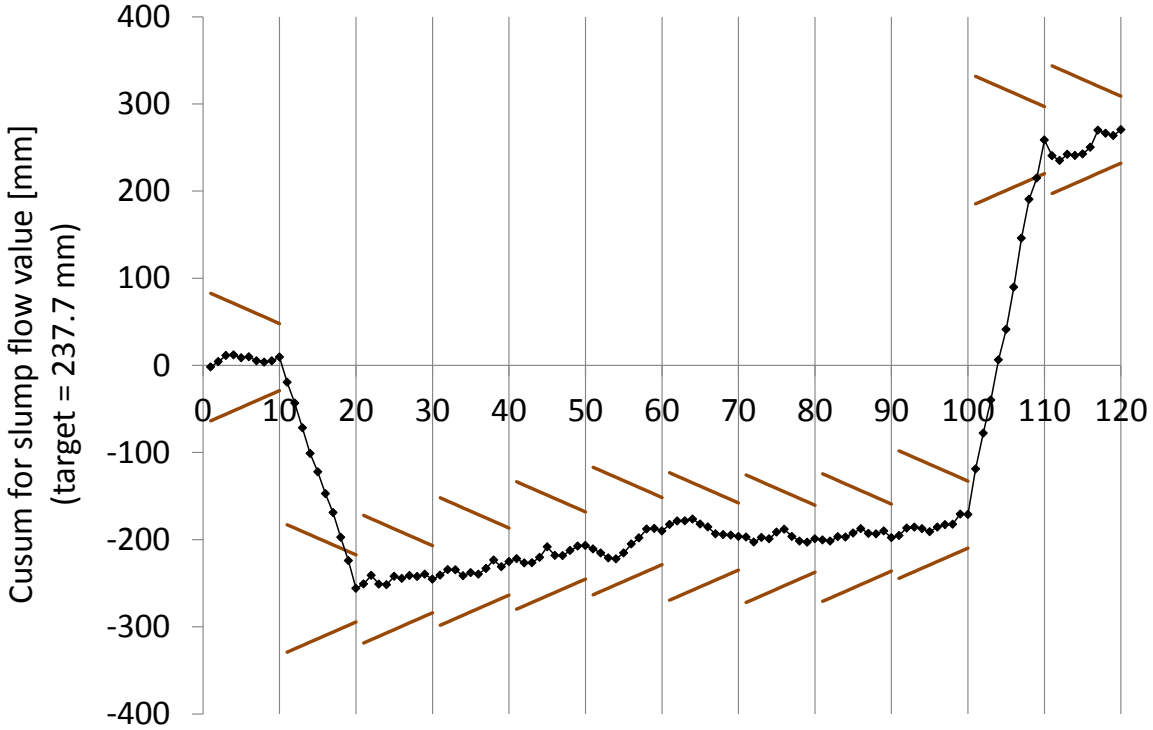
	without V-mask	with applied V-mask
Target value after 15 min. [mm]	237,7	237,7
Mean value [mm]	216,9	235,1
Standard deviation [mm]	9,0	9,2
Deviation from target [mm]	-20,8	-2,6
Deviation from target [%]	-8,7%	-1,1%

Results: Crushed sand



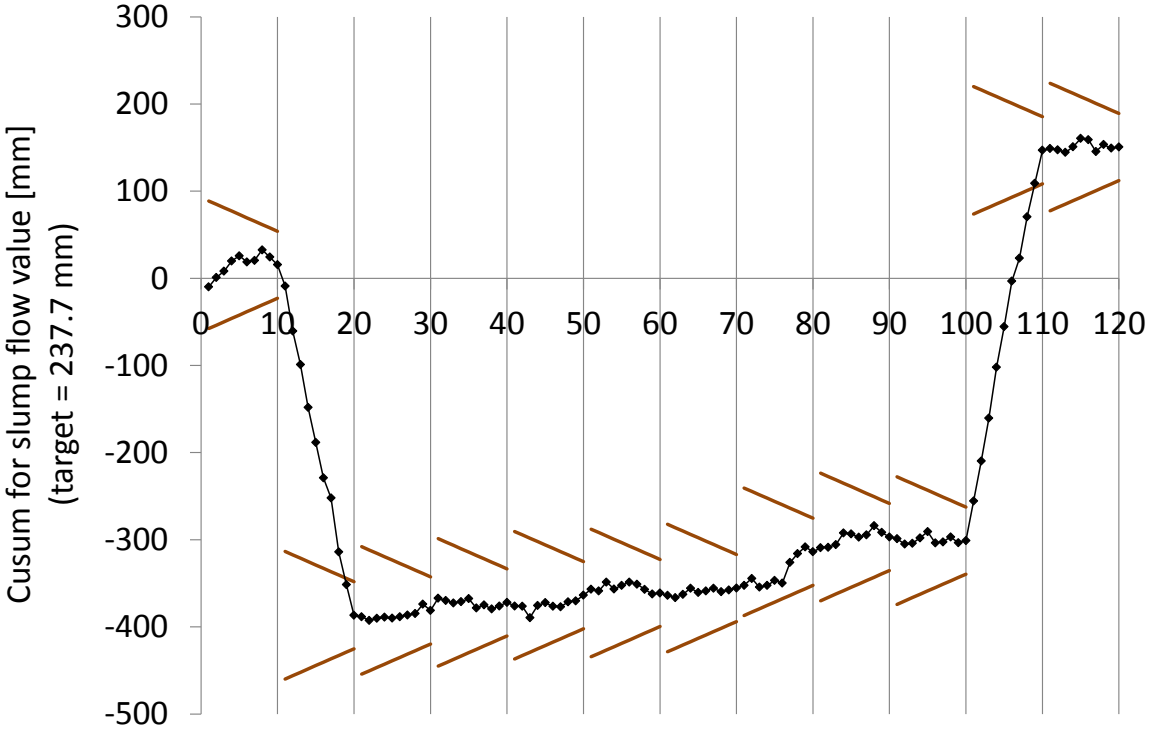
	without V-mask	with applied V-mask
Target value after 15 min. [mm]	237,7	237,7
Mean value [mm]	121,6	224,5
Standard deviation [mm]	38,7	39,4
Deviation from target [mm]	-116,1	-13,2
Deviation from target [%]	-48,9%	-5,6%

Results: Extra gypsum



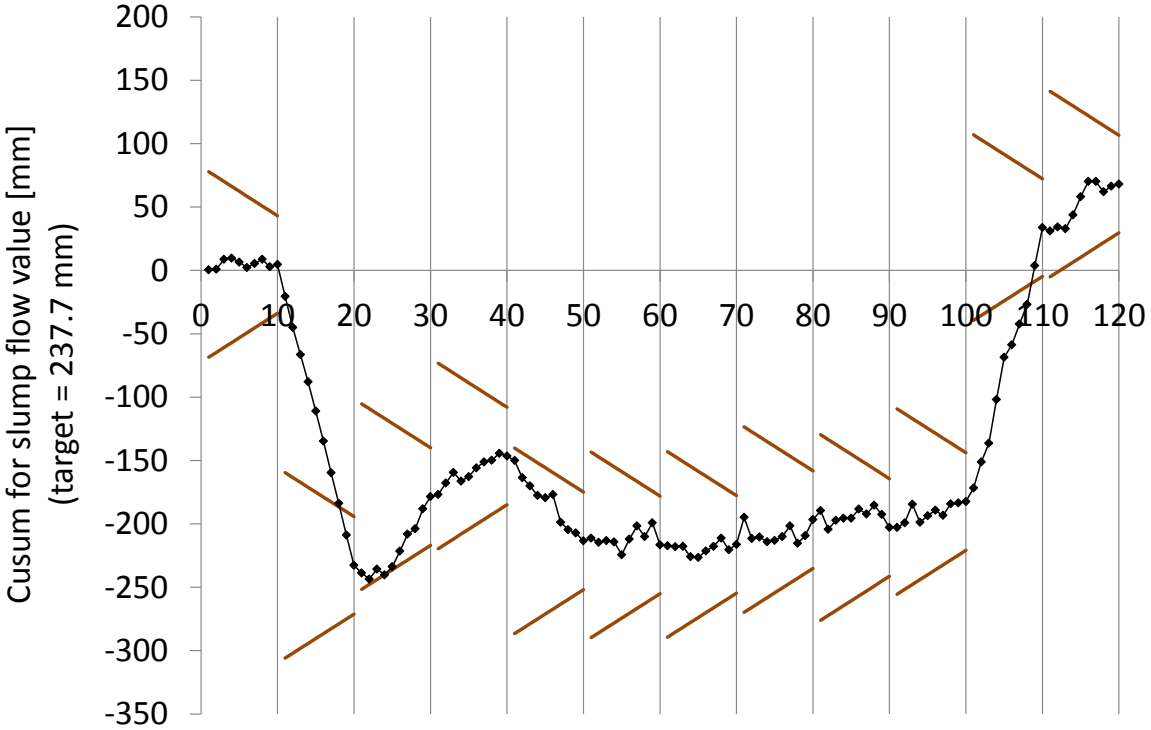
	without V-mask	with applied V-mask
Target value after 15 min. [mm]	237,7	237,7
Mean value [mm]	215,8	236,0
Standard deviation [mm]	9,1	9,7
Deviation from target [mm]	-21,9	-1,7
Deviation from target [%]	-9,2%	-0,7%

Results: Higher content of fine sand



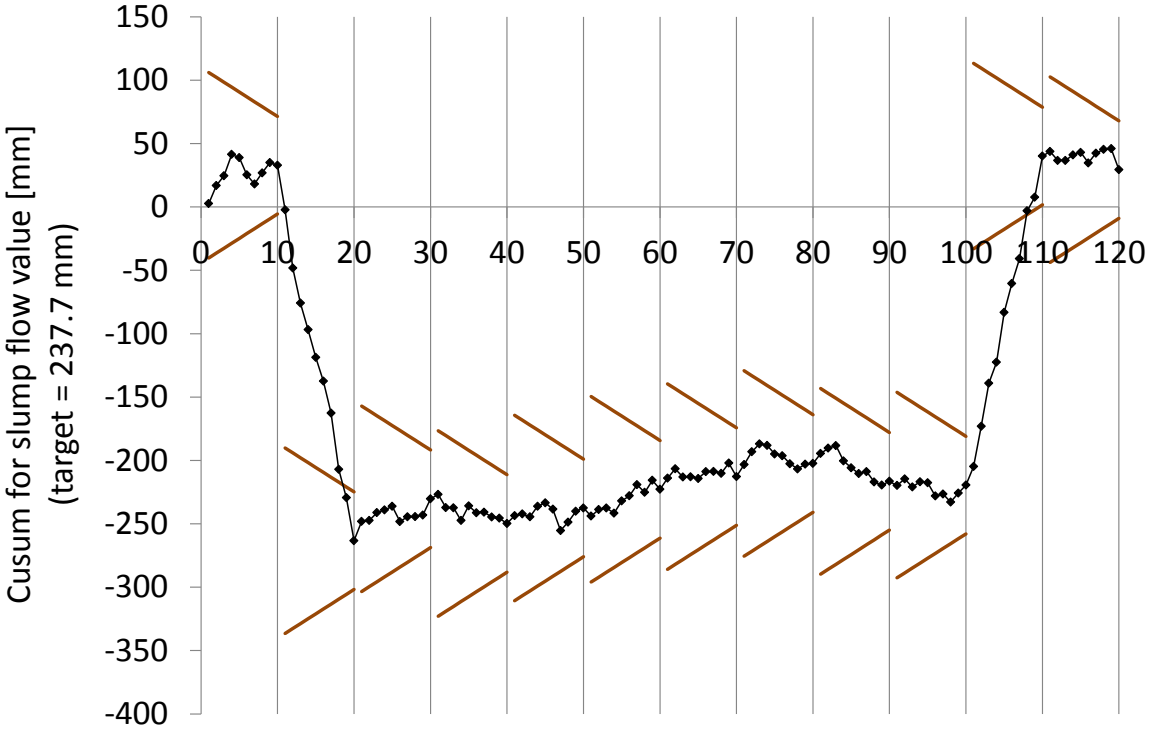
	without V-mask	with applied V-mask
Target value after 15 min. [mm]	237,7	237,7
Mean value [mm]	203,3	234,7
Standard deviation [mm]	15,3	14,4
Deviation from target [mm]	-34,4	-3,0
Deviation from target [%]	-14,5%	-1,3%

Results: Higher cement content



	without V-mask	with applied V-mask
Target value after 15 min. [mm]	237,7	237,7
Mean value [mm]	217,3	235,9
Standard deviation [mm]	7,2	10,6
Deviation from target [mm]	-20,4	-1,8
Deviation from target [%]	-8,6%	-0,8%

Results: Extra limestone filler



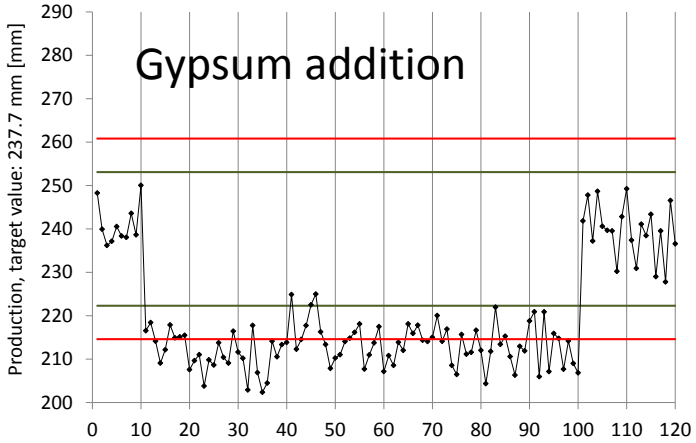
	without V-mask	with applied V-mask
Target value after 15 min. [mm]	237,7	237,7
Mean value [mm]	210,0	235,5
Standard deviation [mm]	14,9	11,7
Deviation from target [mm]	-27,7	-2,2
Deviation from target [%]	-11,6%	-0,9%

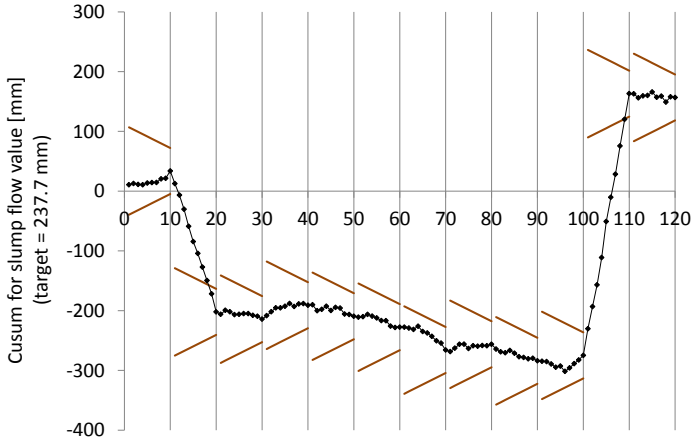
Discussion

- In all cases, the V-mask was able to immediately detect systematic effects that negatively affected the production.
- The counteractions successfully created stable processes on target:
  - Additon of supplementary PCE, when slump flow decreased.
  - Addition of stabilising agent, when slump flow increased.
- In all cases the production mean could be maintained close to the target value and the standard deviation of the production was lower than without detection of the systematic error.
- The V-mask could also immediately indicate when the systematic production influence ended and standard production could be continued.

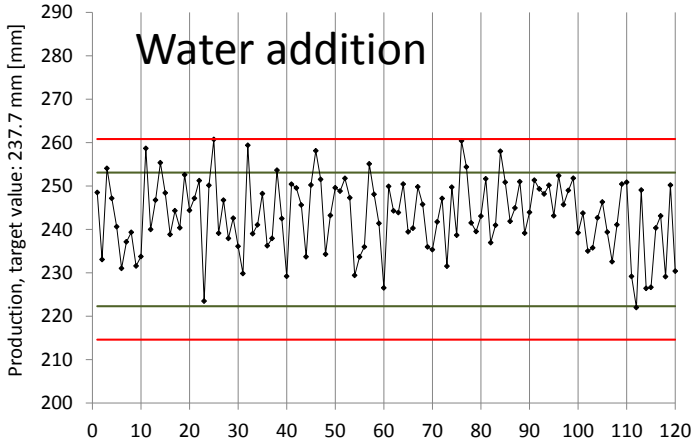
Discussion

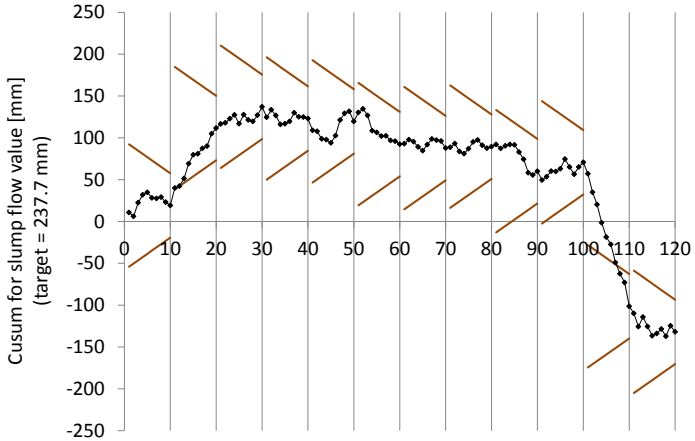
- Nevertheless: often a „simple“ Shewhart chart would have indicated the same.





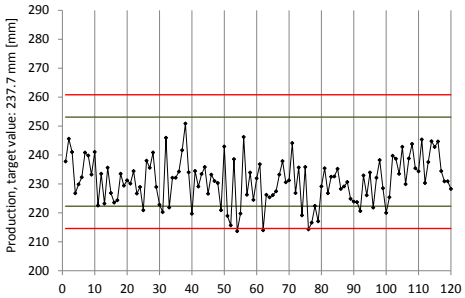
- However, particularly at small changes, cusum is stronger.

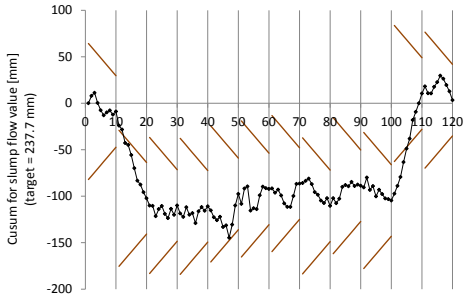




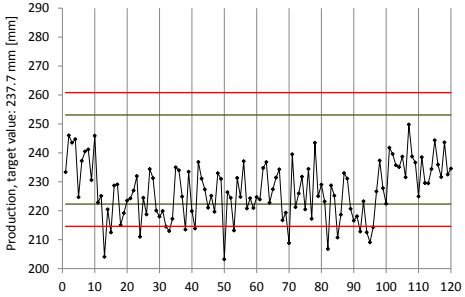
Discussion

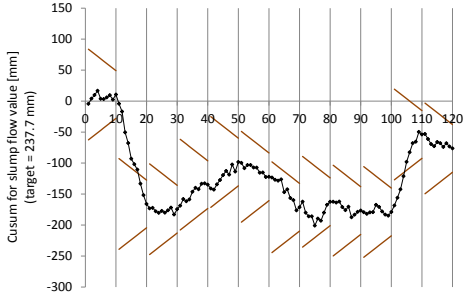
- Example: 3%
  deviation from target:



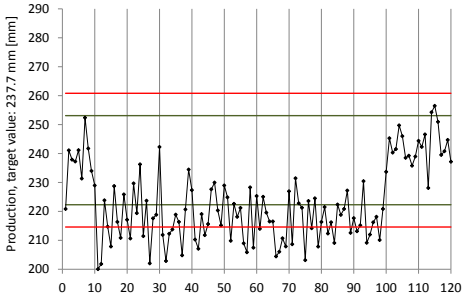


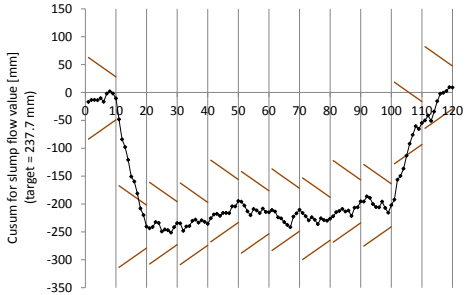
- Example: 6%
  deviation from target:





- Example: 9%
  deviation from target:





Conclusions

- Investigations on the use of cusum control charts in combination with a standard V-mask for the production control of the fresh concrete properties of SCC were conducted.
  - In case of a higher slump flow, stabilising agent was added to achieve target slump flow diameter.
  - In case of a smaller slump flow, supplementary superplasticizer was added to achieve target slump flow diameter.
- The cusum system in combination with a standard V-mask identified in all cases systematic effects that caused deviations from standard production.
- Different from reading process values (Shewhart chart) the cusum system is much more sensitive and identifies changes immediately.
- Cusum in combination with a V-mask ist therefore a strong tool to improve the robustness of the casting of flowable concretes.

ACCTA

International Conference on Advances in Cement and Concrete Technology in Africa

January 27 to 29, 2016 - Johannesburg

http://www.accta2016.com

Thank you very much for your kind attention!