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Sustainable Water Management in the City of the Future

Integrated Project
Global Change and Ecosystems

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Assessing future uncertainties associated with urban drainage using flexible systems – the COFAS method and tool

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SWITCH Deliverable Briefing Note

SWITCH Document: D 2.1.4 Assessing future uncertainties associated with urban drainage using flexible systems – the COFAS method and tool
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Audience: This document is targeted at those who want to compare different planning alternatives using multi criteria assessment and flexibility assessment. It is especially useful for (but not limited to) those involved in urban stormwater management planning, wastewater management planning und urban development planning e.g. policy makers, engineers and planners (from private companies or from local/state/federal government) etc. as well as researchers working in this field.
Purpose • To provide a software tool (named **COFAS**) for the multi-criteria assessment and flexibility assessment of the future uncertainties associated with urban drainage systems (download links are available in the deliverable document and can be accessed on SWITCH intranet) • To provide guidance and background information on the use of the COFAS tool • To provide a comprehensive literature review on flexibility measurement
Background: Switching a city's stormwater management strategy from a "disposal mentality" towards a more sustainable, source control oriented approach is a difficult task. Currently decision makers tend to focus on single problems rather then the whole picture. They tend to think "one dimensionally", i.e. considering one solution for one problem and then optimizing this solution with respect to the identified problem. Instead, it is advocated that the whole picture should be considered, by being aware of (all) the objectives and hence developing and comparing multiple solutions to optimally use synergies and find sustainable solutions. The COFAS-Tool promotes this way of thinking and acting. Another issue already worked out earlier in D 2.1.1 is, that stormwater management measures are exposed to changing boundary conditions (e.g. climate change, population dynamics, new laws, etc.) many of them impossible to predict. The best way of dealing with these uncertainties are flexible systems. COFAS can assess flexibility and incorporate flexibility into the decision process.
Potential Impact: The COFAS tool facilitates multi criteria assessment and flexibility assessment and the comparison of different planning alternatives. The application of the tool is considered to have the following main impacts: • Promotion of the development and comparison of different planning alternatives as a prerequisite for finding sustainable and efficient solutions

- Providing a multi criteria assessment approach which supports multi objective thinking, thus utilizing synergies and finding sustainable and efficient solutions
- Enabling a flexibility approach which allows the development of systems that can cope with many different future trends and facilitates long time functionality.

Recommendations:

In order to use synergies and to come up with sustainable solutions it is essential to evaluate different alternatives with respect to all objectives. It is recommended that the COFAS-software provided with this deliverable should be used for this task.

Our environment is constantly changing and many of the changes are unpredictable. Flexible urban drainage systems can cope with this trend. It is recommended that the COFAS-software should be used to account for flexibility when comparing different solutions.

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1 Summary

Several change drivers like population dynamics or global warming affect the design and operation of urban stormwater management systems. However, for most of the drivers it is not possible to quantify the effects today. For urban stormwater management systems, these future uncertainties are particularly important because they are long-term investments with an average lifetime of more than 50 years. Thus, the design and operation of urban stormwater management systems is confronted with a dilemma. On the one hand, it is foreseeable that change drivers will affect the basic conditions of the urban stormwater management system. On the other hand, with the design of urban stormwater management systems long-lasting decisions have to be made. Bearing these influences in mind, strategies to consider the future uncertainties in the design and operation of urban stormwater management systems are required. A solution for this dilemma could be the flexible design of urban stormwater management systems. Flexibility facilitates the design of urban stormwater management systems despite of future uncertainties.

Precondition for the implementation of flexible designs are approaches for the measurement of flexibility. However, profound insights about the quantification and assessment of flexibility for urban stormwater management systems were missing. Goal of the deliverable is to develop and present suitable approaches for the measurement of flexibility for urban stormwater management systems.

The deliverable is divided in two complementary parts. In chapter 2 the COFAS Software as an approach for the measurement of flexibility of urban stormwater management systems is presented and the application of the tool is described. In chapter 3 the scientific background of different approaches for the measurement of flexibility is documented and the theoretical foundation of the COFAS method is presented.

Chapter 2 starts with a description of different future change drivers, which may affect the design and operation of urban stormwater management systems. The need for a flexible design for urban stormwater management systems is illustrated. The foundation of the COFAS method in system theory as well as decision analysis is presented. The high importance of diversity within systems as an approach to achieve flexibility is illustrated. Furthermore, the utility value analysis as a classical method in multi-criteria assessment is described. The flexibility of a system to adapt to future changes is not considered by classical utility value analysis. With the COFAS method, an approach to consider flexibility within the framework of utility value analysis is presented.

The COFAS method is described in detail. It assesses the flexibility of urban stormwater management systems based on the indicator 'homogeneity of performance'. A system with a high homogeneity is more robust and flexible against future change drivers than a system with a low homogeneity, because it shows equally good performance against all criteria. The COFAS-Software features utility value analysis and the calculation of the homogeneity. The measurement of flexibility is supported by a visualisation with sector diagrams as well as a sensitivity analysis. An application of the COFAS method for the municipality Kupferzell in Southwest Germany is presented. Finally, a manual for the application of the COFAS-Software is provided. It includes another example and a step-by-step guidance. It also points out important issues and common mistakes in the application of the COFAS method.

In chapter 3 the scientific foundation for the measurement of flexibility is presented. In several disciplines, but particularly in engineering science and business management clear concepts of the measurement of flexibility exist. On the contrary, in urban stormwater management the quantification and assessment of flexibility is still at its infancies. In a literature review, different generic measurement approaches are presented and the transferability of these generic approaches to the field of urban stormwater management systems is analysed. The different measurement approaches are grouped according to their theoretical background in indicator-based measurement, approaches from preinvestment analysis, approaches from decision analysis, approaches from system analysis and simulation methods.

Based on the profound literature review two approaches for the measurement of flexibility for urban stormwater management systems are developed. On the one hand, with the COFAS method is a pragmatic approach for the measurement of flexibility is presented. The measurement can be performed with a limited amount of effort. The method is in particular suitable for project assessment in real world planning situations. On the other hand, an approach for a more detailed measurement of flexibility is presented. The approach enables a precise description of the characteristics of flexibility. However, the approach requires a significant higher amount of work, so that the approach is mainly suitable for scientific purposes. Finally, it is illustrated how the COFAS Software can support the application of both measurement approaches.

Conclusions

It is recommended, to use flexibility as a decision criterion for urban stormwater management systems. Flexible design guarantees that present decisions do not affect the future capability of the urban stormwater management system to react to future alterations. The COFAS-

Software facilitates the measurement of flexibility and supports the implementation of flexible urban stormwater management systems.

2 The COFAS Method and Tool

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2.1 Introduction – Flexibility in Urban Drainage Planning

Cities and villages are dynamic systems. Especially larger urban agglomerations are ever changing regarding size and structure. Urban areas are also constantly interacting with their environments through expansion, consumption of natural resources, production of pollutants, etc.

The Ruhr-area for example had half a million inhabitants before the industrialisation. Fifty years later, 6 million people lived in the same area and the environment had changed totally: heavy air pollution, surface sealing and the conversion of natural rivers into open sewer channels were only some of the consequences. In the last decade, the population has reduced again by several percent caused by the decline of heavy industry. Until 2015, a drop of 7% has been forecast. Initially seen as a retrograde step, this structural change nowadays leads to high quality jobs, a better standard of life and a healthier environment. The revitalised river Emscher is a symbol for this process (Figure 1).

Figure 1: River Emscher around 1890, 1960 and 2000.

Similar stories are known from all over the world, e.g. from Middle England, Detroit in Michigan, USA and the former communist countries in Eastern Europe. They show very clearly that development does not always mean growth, although most of the so-called mega-cities like Beijing, Mexico City or Lagos are still in a process of rapid expansion.

It is well known that urban development has a strong impact on the water cycle:

- Increase of flood peaks and volume
- Decrease of base flow
- Hydraulic stress and morphological damage
- Water pollution

These are usually mentioned as typical consequences of urbanization, although it is not the urbanization itself which is causing these negative impacts but the way that we usually cope with the runoff from the urban areas. Traditionally, stormwater is discharged as quickly as possible to the next receiving water by pipe systems or open ditches. Negative effects are compensated – if at all – by end of pipe facilities like retention ponds or clarifiers. In recent years, alternative strategies targeting the causes are becoming more popular. These best management practices (BMP) – also called 'SUDs ' or LIDs - provide the same drainage comfort as traditional sewer systems but also sustain the urban water cycle and control pollution at source.

It is obvious that changes in the urban development ("urban dynamics") can have an influence on the design and operation of urban stormwater management systems (USWMS) – traditional or source control approach. For example, an increase of sealed surfaces due to urban sprawl results in more runoff. For this higher hydraulic load sewers have to be enlarged or new BMPs have to be built. Another example is the higher pollution of road runoff caused by a higher traffic load.

In addition to urban dynamics, stormwater management systems will be affected by climate change. Global warming is an accepted fact but a prediction of its impact on USWMS is difficult because of several reasons:

- Predictions of global warming are based on socio-economic scenarios. Even the best climate model is only an "if-then" prediction.
- Linkage of global warming with a change of precipitation patterns has uncertainties.
- Design of USWMS requires high temporal resolution of local precipitation whereas the common climate models lack this resolution and are on a global or regional scale.

Therefore, climate change will have an effect on stormwater management in the future, but is not possible to quantify this effect today.

The same applies to many other drivers that may have an influence on USWMS in the future.

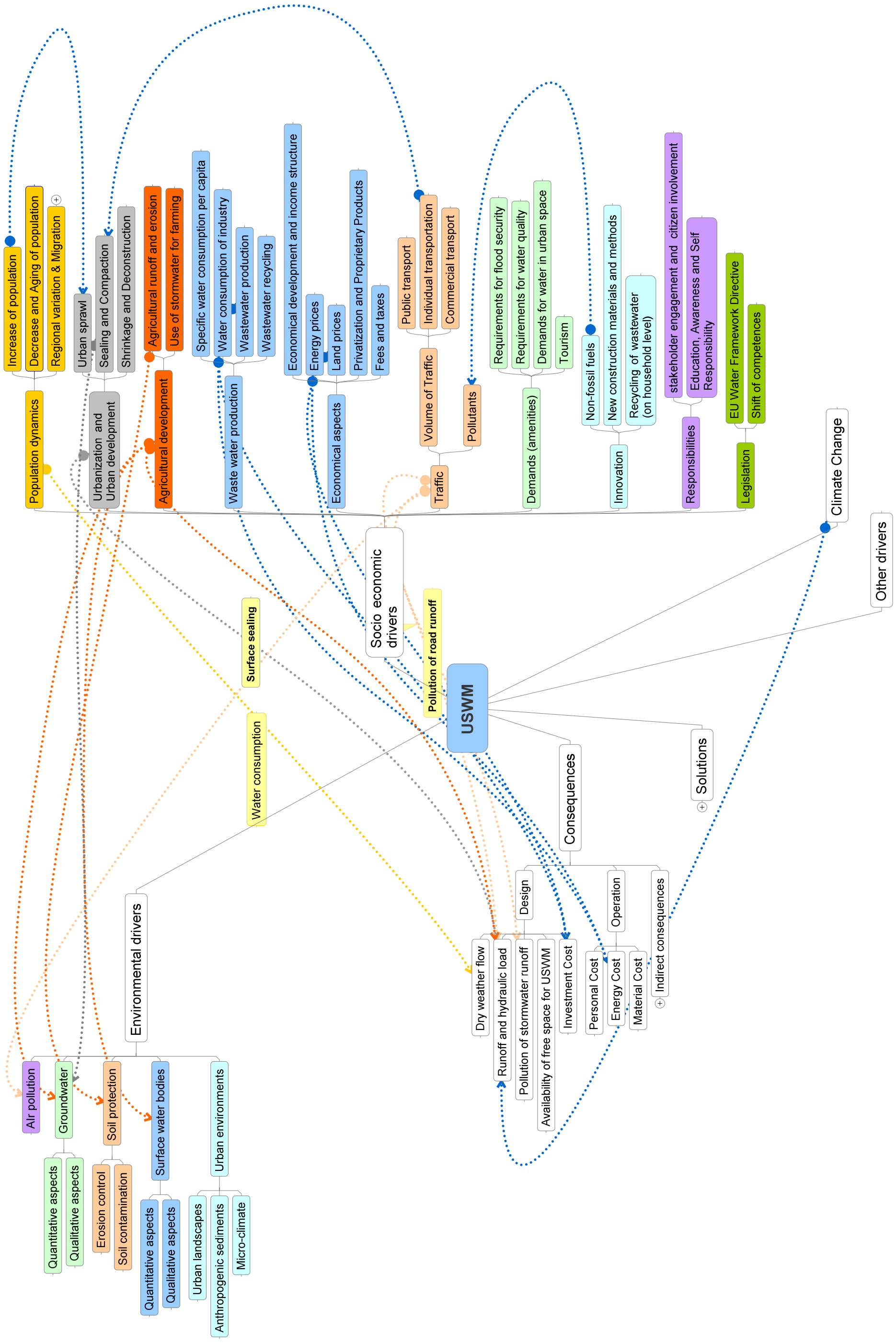


Figure 2: Overview chart of socio economic environmental drivers and their interactions (Scholes et al. 2006)

Figure 2 shows a mind-map of socio economic environmental drivers for urban stormwater management and their interactions.

Bearing these influences in mind, strategies for the design and operation of USWMS should consider future changes. This is particularly important because USWMS are usually long-term investments. Compared to other parts of a cities infrastructure (e.g. telecommunication or power supply systems) the average lifetime of a sewer system is relatively long. Major parts of an urban drainage system, for example the sewer system or retention tanks, have a life cycle of more than 50 years. In Germany, tax deduction for concrete sewer pipes has to be assessed over approximately 80 years and in many sewers in city centres are more than 100 years old. Nevertheless, the typical time horizon for an urban drainage master plan (UDMP) is usually between 25-30 years. A review of several UDMPs in Germany (Sieker 2000) has shown that:

- Usually only an increase of urban area and water consumption is taken into account with regard to future changes. Other possible drivers like changes in stormwater pollution, demands for higher security against flooding or new regulations are generally not considered.
- Even in cities where a decrease of population is already observed and future reduction is predicted, the urban drainage master plan still assumes an increase of surface sealing.
- Design storms are usually derived from historical records of rainfall. Future changes in rainfall pattern caused by climate change are not taken into account.
- Cost comparisons are done on the base of life cycle cost assessments. With this tool, long lasting alternatives are generally preferred. Flexibility and adaptiveness are not considered as decision criteria.

Several negative examples of this common practice can be observed in East Germany. Following the fall of the iron curtain in the early nineties, many East German cities set up new urban drainage master plans. With the euphoria of that time, enormous growth rates had been assumed. The consequences were over-sized drainage systems and treatment plants resulting in very high wastewater tariffs.

An ideal UDMP would have tried to base future scenarios for the socio-economic development on expert knowledge. If a prediction of the socio-economic development was unclear or if scepticism was not opportune politically (which was the case in East Germany in the early nineties) then flexibility and adaptiveness should have been taken into account as decision criteria.

2.1.1 Flexibility in System Theory

Form a system perspective each system is part of a hierarchy where systems of higher levels are made up of subsystems from lower levels, but not in the sense of a top-down sequence of authoritative control. Rather semi-autonomous levels are shaped from the interactions among a set of variables that share similar speeds. Each level communicates a small set of information or quantity of material to the next level. In this way the flexibility of a system depends on its capacity to adapt and its resilience to recover from perturbations. Therefore, the resilience of a system refers to its ability to maintain structure and self-organization of the subsystems at each level, if the whole system is confronted with external stress (Holling 2001).

Renewal and readjustment are essential elements of this process. Renewal of components helps a system to persist. Therefore, for a system to be sustainable, its subsystems must have the possibility to go through renewal cycles. As long as the system can adapt in this way, it is sustainable. Since every process of adaptation is only a temporary solution to changing conditions, it is of high importance to maintain diversity within the system. Diversity represents a repertoire of alternative options and increases the possibility that altered conditions can be successfully responded to. The consequence of implementing large infrastructures is that high costs make systems extremely inflexible (Tillman et al. 2005). One way to avoid this scenario and implement diversity, is through the utilisation of small scale modular design. In this way diversity:

- Avoids the dissipation associated with the link-up of processes
- Enables adaptation to regional conditions (special environmental requirements, different social acceptance of technologies, etc.)

Small scale modular diversity exponentially increases the amount of possible configurations that can be achieved from a given set of inputs. This increases the flexibility of a system and provides for the characteristics of a complex adaptive system. The system is equipped with internal degrees of freedom and distributed control. As a result, it has a higher resilience in relation to both: socio-economic and natural environments. This allows diversity to contribute to long term stability through adaptive flexibility. Special regional conditions can more efficiently be met by choosing exactly that measure for each special issue that fulfils the spatial profile appropriately. This approach allows for using the best practices to fulfil different criteria. The aggregated value of a system made of different small scale modular components replaces a value of greater homogeneity because low accomplishments in different criteria that might occur in a large scale system can be bypassed in a system consisting of small scale modular subsystems, in order to meet the special requirement profile. In this way

the homogeneity of value of a certain measure symbolizes the adaptive flexibility of a system.

2.1.2 Utility Value Analysis

Utility value analysis is a classical method in multi-criteria assessment (MCA) (Peters et al. 2005). To overcome the difficulty of comparing alternatives regarding based on different aspects, the assessment for an indicator (e.g. cost, emissions or water quality parameter) is standardized by using so called utility functions (Figure 3).

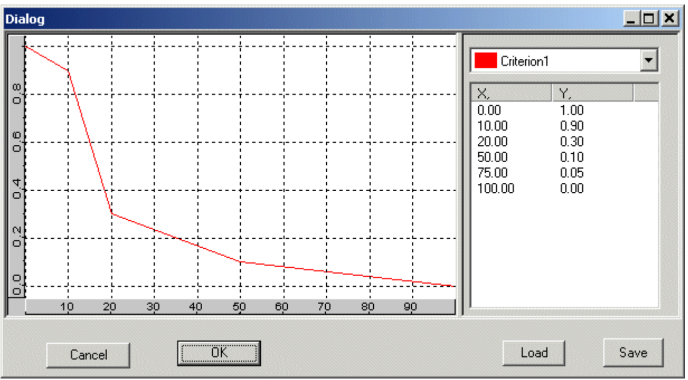


Figure 3: Example for a utility function

By adding up the utility values, weighted for each indicator, different alternatives can be compared. A typical result is shown in Figure 4. Formerly criticized as a nontransparent, academic method, this type of MCA is nowadays seen as a useful tool for group decision making (Sieker et al. 2005). The same principle is used in consumer magazines to compare different products. Also some decision support systems have used this concept (Ellis et al. 2005). By using modern software tools, it is possible to quickly change weighting factors or utility functions, carry out sensitivity analysis and to present the result is transparent way.

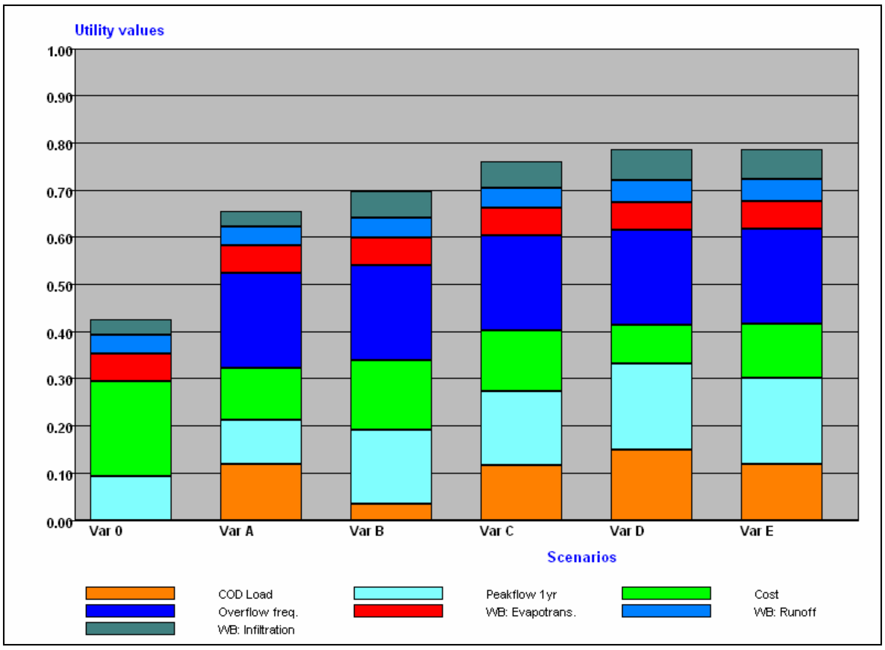


Figure 4: Result of a utility value analysis

However, the flexibility of a system to adapt to future changes is not considered by classical UVA. Only one aggregated system value is used to compare different scenarios and introducing "flexibility" as another indicator is a very subjective way to assess adaptability.

2.1.3 The COFAS method

The classical UVA approach uses only one aggregated system value to compare different scenarios. The COFAS method (COFAS: Comparing the Flexibility of Alternative Solutions) involves applying statistical methods to the level of variation associated with the utility values under different conditions.

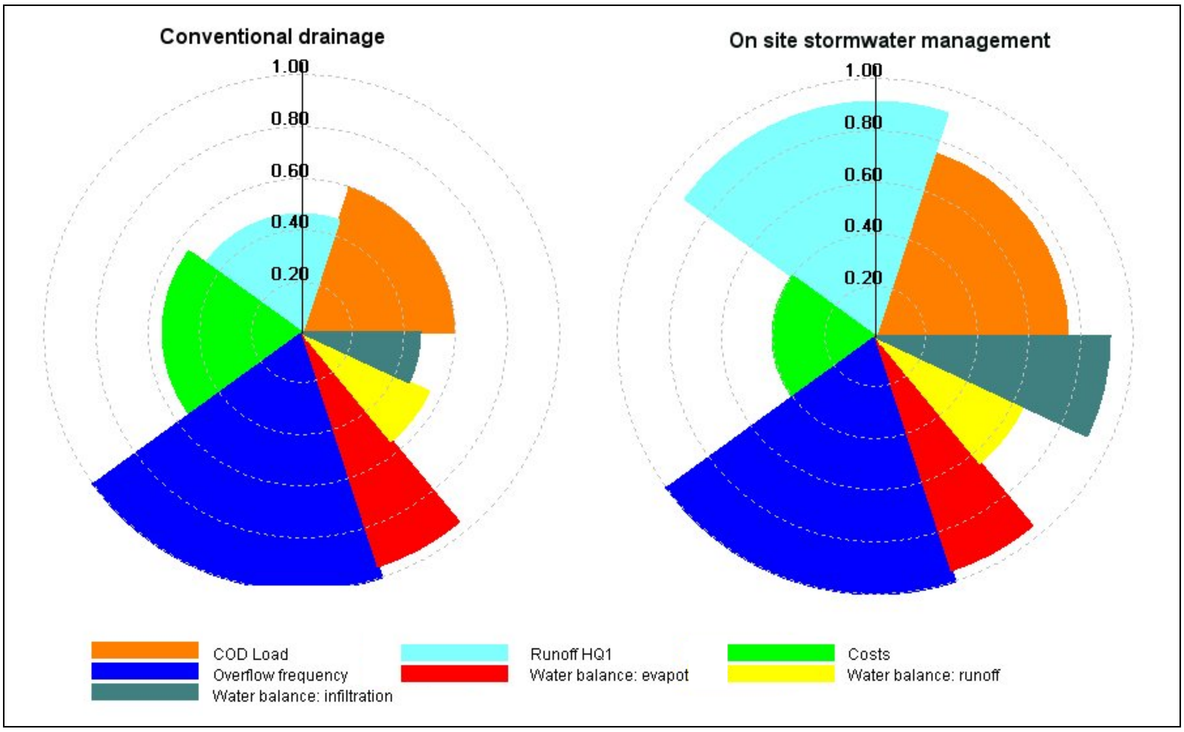


Figure 5: Sector diagram for weighted utility values

A useful way to visualize this variation is in a sector diagram (see Figure 5). In this diagram, the radius of a sector represents the utility value while the aperture angle shows the weighting factor. In the example shown in Figure 5, it is clear that the variations in the utility values associated with the conventional drainage solution (left-hand chart) are greater than those associated with an on-site stormwater management solution (right-hand chart). This type of chart can be created with the COFAS-Software presented in this deliverable.

In order to measure the variation of the utility values the "internal homogeneity" Hom is introduced. It is calculated from the weighted standard deviation of the (partial) utility values. Different authors use slightly different methods to calculate the internal homogeneity (e.g. compare Helm et al. (2007) and Schlottmann et al. (2007)). In the COFAS-tool the internal homogeneity is calculated according to the following equations:

$$Hom = \begin{cases} 1 - \dfrac{\sigma}{tUV} & where\ \sigma \leq tUV \\ 0 & where\ \sigma > tUV \end{cases}$$

$$\sigma = \sqrt{\sum_{i=1}^{n} w_i \left(pUV_i - tUV\right)^2}$$

Hom	Internal homogeneity
tUV	Total utility value (weighted mean of the partial utility values)
pUV	Partial utility value (utility value of one criterion)
σ	Standard deviation of the partial utility values
n	Number of criteria = number of partial utility values
w_i	Weighting factor for criterion i ($\sum_{i=1}^{n} w_i = 1$)
i	Index for partial utility values

Hom = 0 means minimum homogeneity, e.g. 50% of the criteria have the (partial) utility value 0 and the other 50% have the utility value 1.

Hom = 1 means maximum homogeneity, i.e. the (partial) utility values of all criteria are equal.

Combining the internal homogeneity (Hom) and the total utility value (tUV) results in the development of a "multi-dimensional Degree of Target Achievement (dDTA)" value (Helm et al. 2009; Schlottmann et al. 2007).

$$dDTA = \sqrt{tUV \cdot Hom}$$

A comparison of alternatives utilizing dDTA values has the advantage that it avoids the potential drawback of a highly negative aspect of a solution (e.g. water pollution) being compensated for by a highly positive attribute (e.g. flooding).

A system with a high (internal) homogeneity is more robust against future changes (e.g. changing conditions associated with climate change, increasing urbanization etc.) than a system with a low (internal) homogeneity, because it shows equally good performance against all criteria. Hence a variation of any of the boundary conditions would never lead to complete failure. In contrast a system with a low homogeneity may react very sensitively to changes in the boundary conditions, if the pressure on those criteria that already performed badly increases.

Thus comparing different alternatives using the dDTA leads to more robust solutions.

Chapter 0 suggests, that systems which show a homogenous performance also provide a greater adaptive flexibility.

Flexibility (Changeability) Robustness: A System can cope with different boundary conditions without modifications. (Adaptive) Flexibility: A System can easily be adapted in order to cope with different boundary conditions.

Figure 6: Flexibility, Robustness, Adaptive flexibility

However, a comparison of alternatives by dDTA is still only based on information about the actual situation.

To take into account the flexibility of alternatives regarding their ability to cope with future changes more soundly, an additional parameter exHom (external homogeneity) is introduced to the previously developed approach. For each alternative solution, utility values can be computed for different future scenarios. (If the evaluation of the future scenarios includes an adaptation of the system, the external homogeneity measures (adaptive) flexibility. If the system is not modified exHom measures robustness.)

The external homogeneity for an alternative is calculated from the standard deviation of the (total) utility values for the different future scenarios according to the following equations:

$$exHom = \begin{cases} 1 - \dfrac{\sigma_{ex}}{mtUV} & where\ \sigma_{ex} \leq mtUV \\ 0 & where\ \sigma_{ex} > mtUV \end{cases}$$

$$\sigma_{ex} = \sqrt{\frac{1}{m}\sum_{j=1}^{m}\left(tUV_j - mtUV\right)^2}$$

$$mtUV = \frac{1}{m}\sum_{j=1}^{m} tUV_j$$

exHom	External homogeneity
tUV_i	Total utility value of the alternative for future scenario i
mtUV	Mean total utility value of the alternative over all future scenarios
σ_{ex}	Standard deviation of tUV_i
m	Number of future scenarios
j	Index for future scenarios

Combining the external homogeneity with the mean total utility value and the mean internal homogeneity leads to the "multi-dimensional, multi-variant Degree of Target Achievement (dvDTA)" (Helm 2007).

$$dvDTA = \sqrt[3]{mUV \cdot mHom \cdot exHom}$$

The COFAS-Software presented in this deliverable features the utility value analysis and the calculation of the internal homogeneity (Hom). It provides numerous charts, including the sector diagram previously introduced. It also comes with a sensitivity analysis that is supported by a chart.

The COFAS-Software supports the calculation of exHom and dvDTA. The user is able to create one COFAS project for each future scenario and then copy the result tables to an Excel-workbook to calculate exHom and dvDTA.

2.1.4 Example Kupferzell

The municipality Kupferzell in Southwest Germany (Helm, 2007; Sieker et al. 2008) has been investigated to determine which type of urban drainage systems represent the highest flexibility options to cope with future uncertainties.

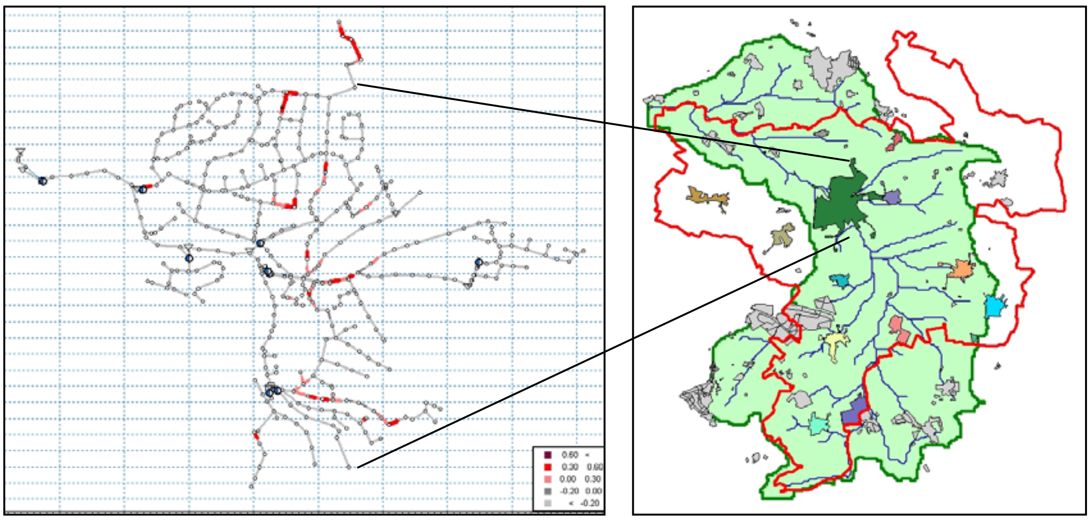


Figure 7: Mouse-model for the drainage system (left), STORM-model for the catchment of the river Kupfer (right)

The possible future developments are described as future scenarios for the year 2050. Tendencies for change in the environmental and socio-economic framework are identified through a literature survey. Four scenarios have been developed:

- a linear scenario (extrapolation of the actual development),
- a loading case scenario (combination of the results of a sensitivity analysis with plausible extremes for the boundary conditions),
- a growth-orientated scenario (conditions for a individualistic and consumer-oriented society) and
- a conservational scenario (conditions for a society with a focus on ecology and social engagement). The scenarios represent the required flexibility for urban drainage systems.

System alternatives for the further development of the urban drainage system of Kupferzell have been developed considering the existing drainage system as well as the future infrastructure for new development areas. The system alternatives represent four strategies based on different types of urban drainage systems:

1. the continuation of the existing combined sewer system
2. the expansion of the urban drainage system through a separate sewer system.
3. all additional urban drainage systems are realised as decentralised drainage systems.
4. an extended decentralised system is aimed for with a focus on infiltration, green roofs and rainwater utilisation as well as the disconnection of 20% of the paved surface from the existing combined sewer system.

For the system alternatives, flexibility options for the adaptation of future alterations are identified. Considered flexibility options are the adaptation of the required retention volume, the upgrading and replacement of overloaded sewers and a staged design of the urban drainage system.

In a rainfall-runoff model, the effects of the different future scenarios for the performance of the system alternatives are modelled. If an adaptation of the system based on future alterations is required the flexibility options are implemented. The performance is ascertained based on a utility value analysis, which is a classical method in multi-criteria assessment. In total 27 qualitative and quantitative indicators from the field of environment, society and

economy were considered in order to take into account the need for sustainability in performance.

There are 16 combinations of future scenarios and system alternatives with in total 432 single values. To produce meaningful results an aggregation to one value per system alternative is required. Therefore the COFAS-Method was applied, including the calculation and evaluation of internal homogeneity (Hom), external homogeneity (exHom) and "multi-dimensional, multi-variant Degree of Target Achievement" (dvDTA). (The COFAS-Software presented in this deliverable was not available at that time, so the application of the COFAS-Method had to be done manually using Excel.)

Finally, the flexibilities of the different system alternatives are compared. The results of the Kupferzell example illustrate, that for the further development of the urban drainage system, both decentralised alternatives offer a significant higher degree of flexibility and therefore are more easier to adapt to future changes than both conventional system alternatives (Sieker et al. 2008). Hence the implementation of decentralised sustainable urban drainage systems is a flexibility option. This result is consistent with general statements in the technical literature. So it is expected that decentralised sustainable urban drainage systems will offer a higher flexibility than conventional drainage systems (Sieker et al. 2007; Schmitt, 2006; Sundberg, 2004).

2.1.5 Conclusions

The COFAS-method is a tool to compare the flexibility of alternative options (e.g. for stormwater management) regarding their adaptiveness to future changes.

This flexibility is very important as it is not possible to exactly predict future change for most of the drivers relevant for stormwater management (climate change, urban dynamics).

For the Kupferzell example it has been shown that decentralized solutions, such as stormwater infiltration are more flexible than conventional drainage systems. This seems to be a general fact; nevertheless it has to be proven in other applications.

A COFAS-Software is presented in this deliverable.

2.2 Manual for the COFAS-Tool

2.2.1 Introducing an Example: River Panke catchment, Berlin

The example used in this chapter is based on data from Peters (2007) and Peters (2008).

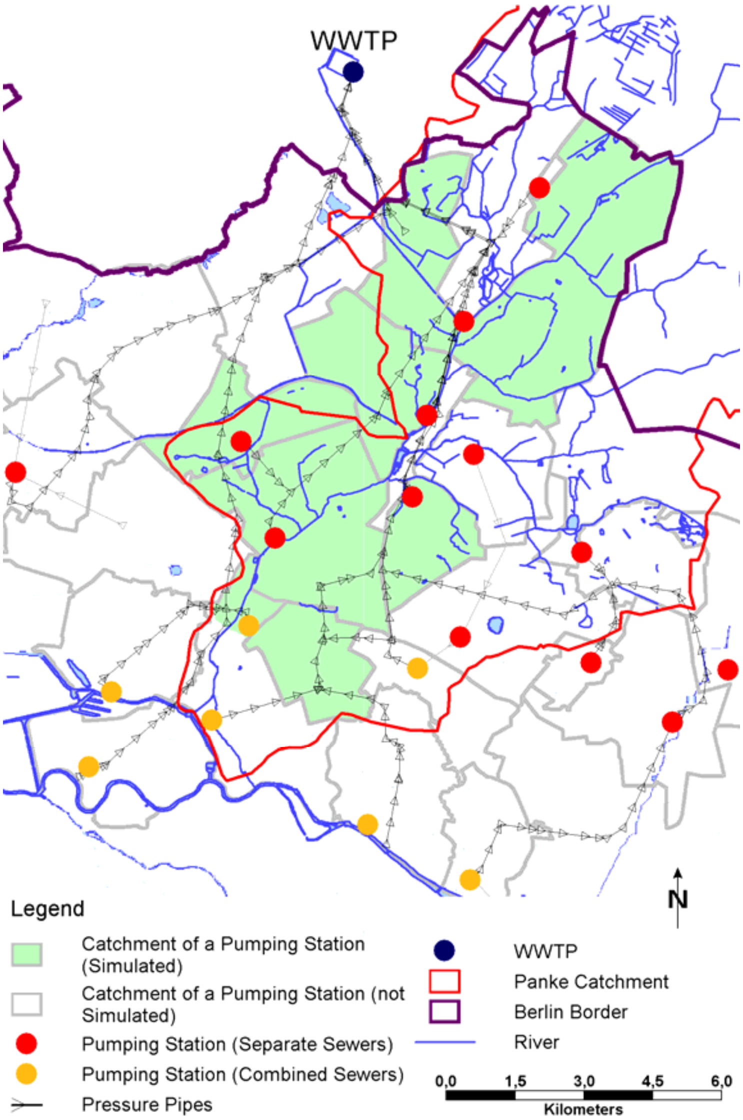


Figure 8: Example Catchment

Description of the Catchment and its Problems

The catchment area (≈ 200 km²) of the river Panke (Figure 8, red/dark grey outline) is situated in the northeast of Berlin (bold violet/black border), Germany. It suffers from hydraulic peak loads and pollutant loads from separate sewers and combined sewer overflows (CSOs). Because of the hydraulic peak loads, flood protection measures had to be implemented and thus the river Panke suffers from structural degradation (Figure 9). A high percentage of paved area results in low dry weather flows.

Figure 9: Panke in Berlin

Berlin's city centre is drained using combined sewers (Figure 8, orange/light grey dots), whereas the suburban areas utilise separate sewers (red/dark grey dots). Mainly due to incorrect connections and manhole covers, the wastewater pipes in the separate systems are also affected by stormwater. The wastewater from both systems runs to pumping stations (orange and red/light and dark grey dots) and is pumped from there through a network of pressure pipes (black arrows) to one of Berlin’s six WWTPs (dark blue/black dot). The pressure pipe network causes high peak loads to the WWTP during rainfall events; when the pumps increase the hydraulic load, it immediately reaches the WWTP, because the pipes are always completely filled with water. But the pipes still contain dry weather concentrations and it can take up to ten hours until diluted water reaches the WWTP.

Scope of the Investigations

In order to address the problems stated, an integrated simulation study is carried out, quantifying the effects of real time control, stormwater infiltration, storage and urine separation. Criteria for the assessment are developed and a multi-criteria analysis is applied.

The focus of the study was laid on the field of stormwater in combined sewers, unintended stormwater in separate wastewater sewers and the interaction between catchment, pressure pipes and the WWTP. Consequently, the model system contains the following components (see Peters (2007) for further details):

- Rainfall runoff model and sewer network model (hydrological; STORM for the catchment areas of 7 pumping stations (Figure 8):
  - 2 combined systems
  - 5 separate systems, only wastewater sewer including unintended stormwater, no storm-water sewer.
  - The model depicts 243109 inhabitants and 447 ha of sealed area.
- Pressure pipe network and pumping stations (own modules for MATLAB Simulink)
- WWTP (Activated Sludge Model No. 1, IWA 2000, SIMBA, ifak system 2001)

Long-term simulations were carried out using historical rainfall data over a period of 30 years (1965 - 1994) and a simulation step of 5 minutes.

Criteria for Scenario Comparison

Schilling et al. (1997) provide an overview of river impacts caused by urban drain-age. Peters & Mühleck (2005) and Peters (2007) describe a methodology for indicator development. Based on this and taking into account the different time scales (acute, delayed, accumulating) in which the impacts occur, the criteria shown in Table 1 were chosen for scenario comparison. The 'peak load' criterion was calculated taking into account the maximum hourly loads that are exceeded for 12 h per year.

Table 1: Criteria for Scenario Comparison

Peak Loads			Mean Loads		
Criterion		Impacts	Criterion		Impacts
Q	(m^3/h)	Hydraulic stress for biocoenosis Morphology Flood protection			
NH_4	(g/h)	Acute NH_3 toxicity	NH_4	(kg/a)	Delayed toxic effects of NH_4 Delayed oxygen depletion
COD	(kg/h)	Acute oxygen depletion	COD	(t/a)	Delayed oxygen depletion Particulate COD: Adsorbed Heavy metals and toxic organics
			P	(kg/a)	Eutrophication

Scenarios

The investigated scenarios are described in Table 2 and illustrated in Figure 10 and Figure 11. Table 2 can be considered as background information which does not have to be read it in detail to continue with the example application.

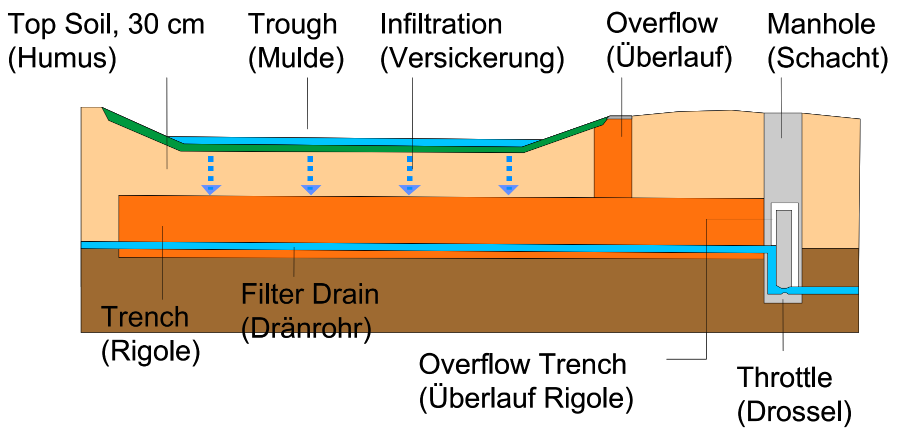
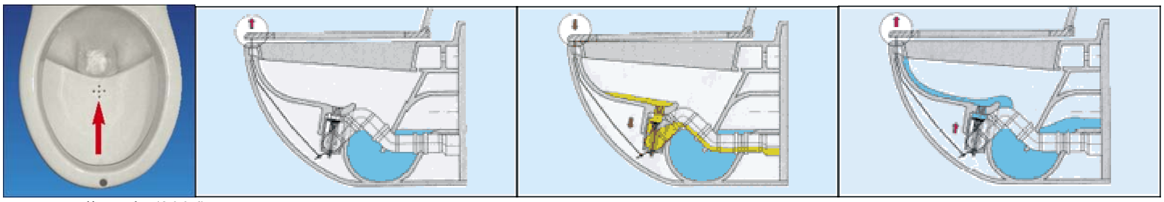


Figure 10: Trough Trench System



www.roediger.de (2006)

Figure 11: Urine Separation Toilet

Table 2: Scenario Description

	Name [Name used in Peters (2007)]	Description
St.Q.	**Status Quo** [Ist]	As described in "Investigated Catchment and its Problems" and "Scope of the Investigations"
Storage	**StS** [SpT2Qd16]	Additional storage volumes for unintended stormwater in wastewater sewers: at each of the separate system's pumping stations, infinite storage volumes are added to the model.
Stormwater Infiltration	**InfCxSy** [AbkMxTy]	x% of the impervious area in the combined systems and y% of the impervious area in the separate systems are disconnected from the sewer and the stormwater is infiltrated through troughs and trough trench systems (Figure 10).
	InfS100 [AbkT100(15)]	100 % of the impervious area that is unintendedly connected to the wastewater sewer is disconnected. As stormwater sewers are unavailable in some areas, overflow water remains connected to the wastewater sewer.
	InfC17 [AbkM17(15)]	For comparison with InfS100, the same absolute amount of impervious area is disconnected in the combined systems.
	InfMax C24S100 [AbkMax M24T100(35)]	Maximal potential of infiltration Combined systems: The maximum possible fraction of roof and paved backyard area that can be disconnected and infiltrated had been estimated on a house block scale (Ingenieurges. Prof. Dr. Sieker mbH 1999). For streets, half of this fraction is assumed, leading to a maximum of 24 % of the impervious area that can be disconnected in total. Separate systems: see InfS100
Urine Separation		Urine separation is one of the so-called new or ecological sanitation concepts mainly targeting nutrient recovery. A good introduction on the topic is given in Lange & Otterpohl (2000). Urine contains approximately 80 % of the Nitrogen and 45 % of the Phosphorus in household wastewater. It is collected separately using urine separation toilets (Figure 11) and utilised as fertilizer in agriculture. However, those benefits are not accounted for in this work, only the effects on the wastewater system are considered. Separation efficiency is assumed to be 75 %. In this work, all other household wastewater remains connected to the sewer.
	UrsC17 [UrsM17(6)]	17 % of the inhabitants in the combined systems are utilising urine separation. For comparison with InfC17
	Urs100 [Urs100(100)]	Maximal potential of urine separation. 100 % of the inhabitants in the combined and separate systems are utilising urine separation.
Real Time Control [RTC]	**Opt Vol.** [St1b cbd 1|1.1]	Overflow reduction by optimal usage of the available storage volumes (pumping stations, tanks), i.e. trying not to have overflows at one pumping station when there is still storage volume available at another.
	PL (Passing Lane) [Ue40b]	Reduction of the WWTP peak load effect caused by the pressure pipes. From each pumping station there are at least two possible paths to the WWPT (these can be parallel pipes or also completely different paths, not all used in status quo and depicted in Figure 8). PL scenarios use one pipe for wastewater and switch to the other during stormwater events. When the hydraulic load to the WWTP increases, it is not fed with highly concentrated wastewater like in status quo, but with water from the stormwater pipe that contains diluted water from the last stormwater event.
	Comb. [St1b cbd 1|1.2 Ue40b]	Combination of Opt Vol. and PL

2.2.2 Evaluation using the COFAS Method

Installation

Download the COFAS-Software from the SWITCH intranet.
http://www.switch.watsan.net/page/4748

Unzip the file to a folder of your choice, e.g.: C:\Program Files\COFAS\

Right click on “EntscheidungsMatrix.exe”, create shortcut. Move the shortcut to your desk-top. Double-click the shortcut to start the program.

Download the examples from the SWITCH website and save them in a folder of your choice.

Entering Data, Weighting Factors and Utility Functions

Open “COFAS_Example_0.mtx” (File -> Open).

Click “Input Data” in the tree.

Click and fill the dialog according to Figure 13 (left). Click “OK”. This will create a criteria-group “P”.

Click again and fill the dialog according to Figure 13 (centre). Click “Colour” and enter the HSV (Hue, Saturation, Value) values according to Figure 13 (right). Click “OK”. This will create the criterion “P Mean WWTP”. Repeat to create the criterion “P Mean Overflow” (Colour HSV: 200, 240, 80).

Open the group P in the tree by clicking the +. You can use the arrows to move criteria and groups up and down.

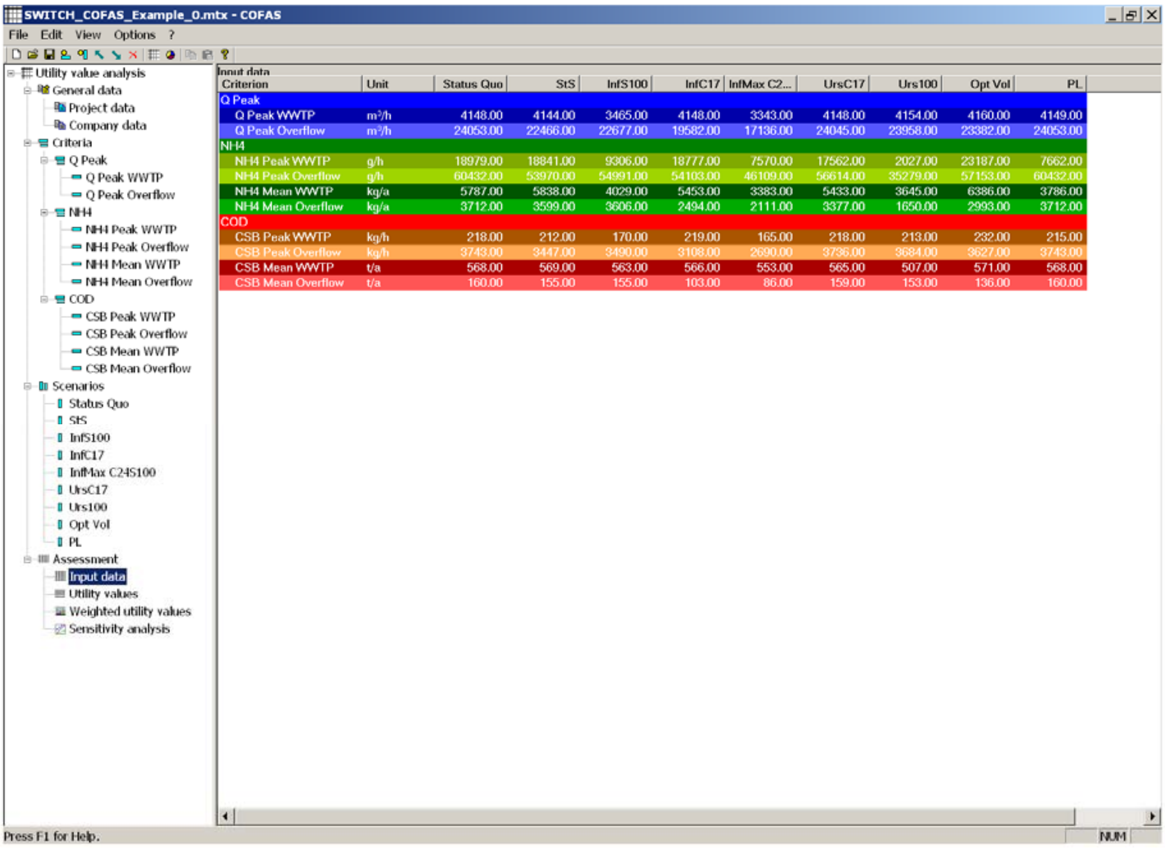


Figure 12: COFAS example after loading

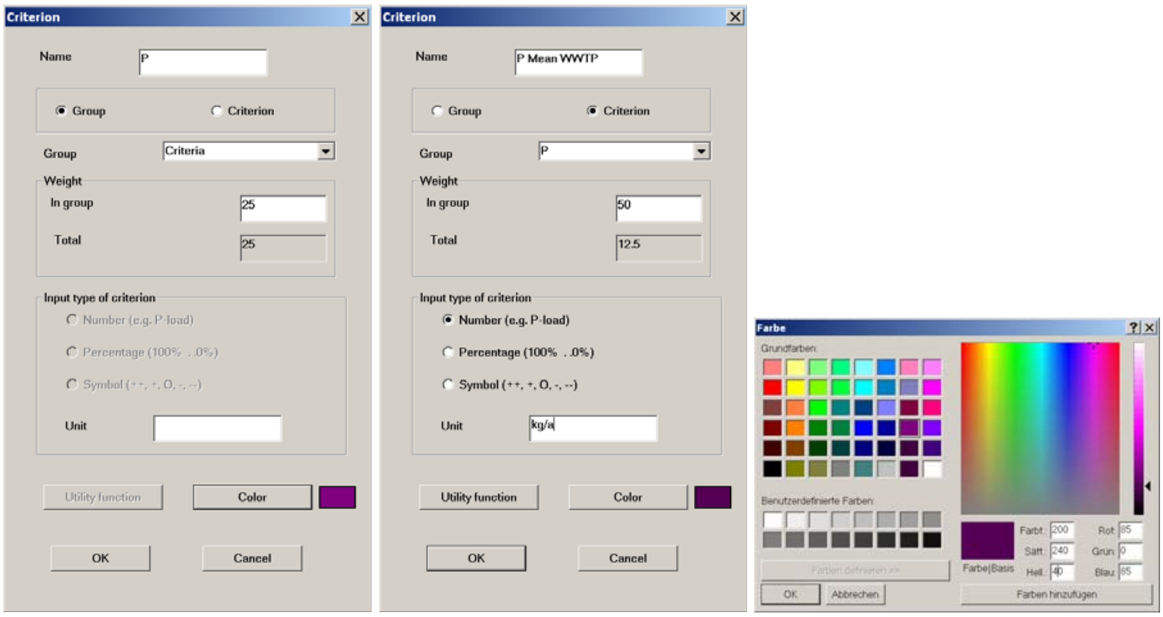


Figure 13: COFAS, adding criteria

Click , and enter the name "Comb.".

Save file as "COFAS_Example_1.mtx" (File -> Save as…)

Your screen should look now as shown in Figure 14.

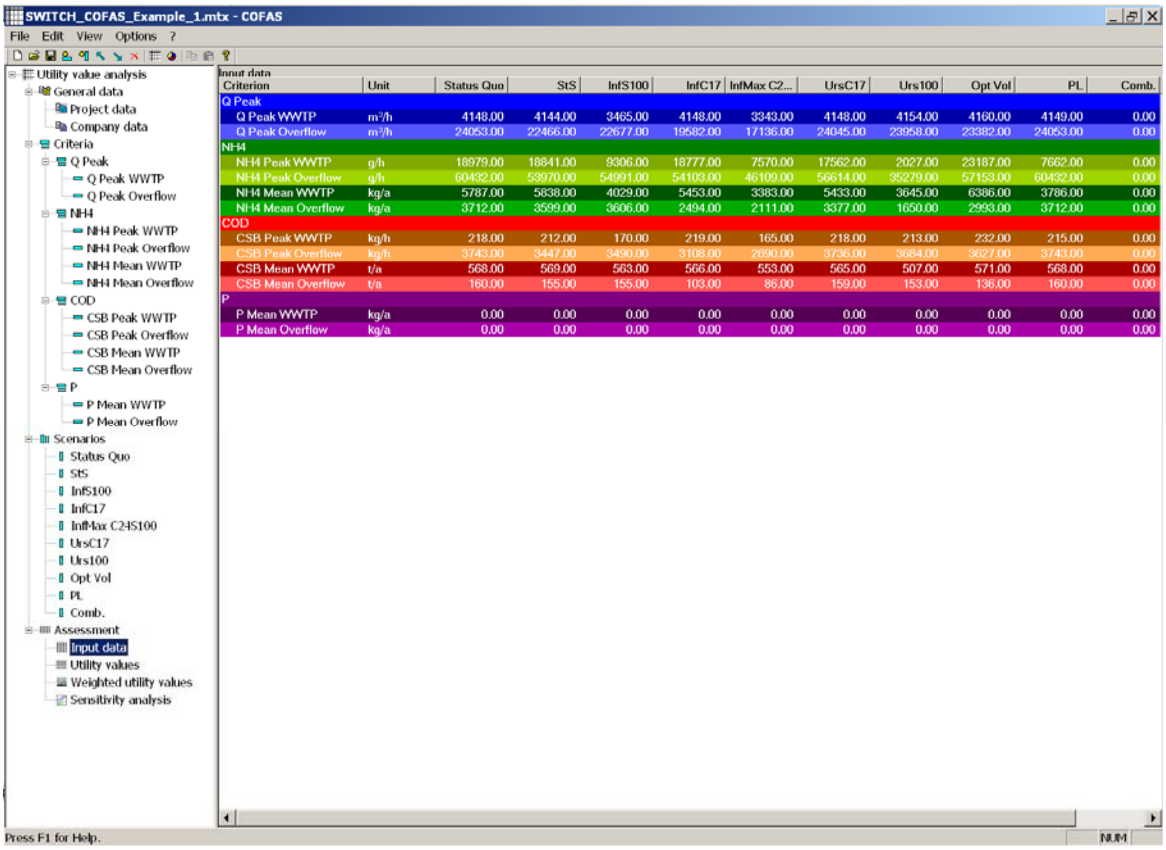


Figure 14: COFAS example after adding criteria and a scenario

Enter the missing values according to Figure 16 by double-clicking the values in the matrix.

It is also possible to copy the values from Excel. To do so, single click the top left item in the Matrix (Q Peak). Click . Open an empty Excel document. Activate the top left cell. Press CTRL-V. The result is depicted in Figure 15 (top). Now you can enter the values or copy and paste them from any other source (Figure 15, bottom). Now select the range according to Figure 15 (bottom), press CTRL-C, activate the COFAS-Software and click . Now the COFAS-Window should look like Figure 16.

Save file as "COFAS_Example_2.mtx".

Figure 15: COFAS, copying to Excel

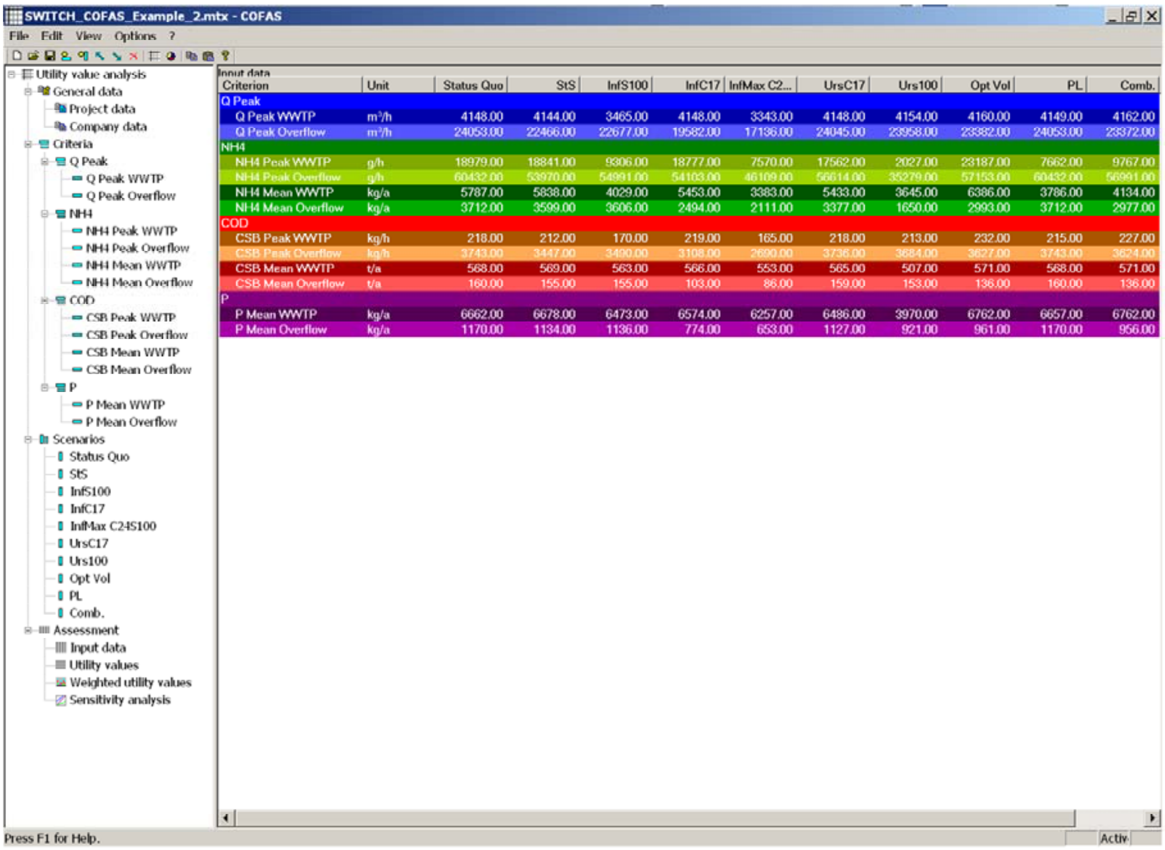


Figure 16: COFAS after entering the input data

Now we have to enter the Utility functions for the new criteria.

Double-click “P Mean WWTP” in the tree or in the matrix. Click “Utility function”. Enter the values according to Figure 17. Click “OK”. Change weight in group to 85 (%).

Do the same for “P Mean Overflow” using the following values: Weight in Group: 15 (%), UV(0) = 1, UV(2339) = 0.

Phosphorous problems in status quo were considered moderate thus an UV of 0.5 was assigned for this. Zero emissions was assigned UV = 1. UV = 0 represents 2 times the emissions of status quo. The weighting factors within the group were assigned in a way, that the reduction of 1 kg/a leads to the same improvement in the tUV for both, WWTP and overflow emissions (13324/(2339+13324) = 85%, 2339/(2339+13324) = 15%).

Please read chapter 2.2.3 for general advice on utility functions!

Save file as “COFAS_Example_3.mtx”.

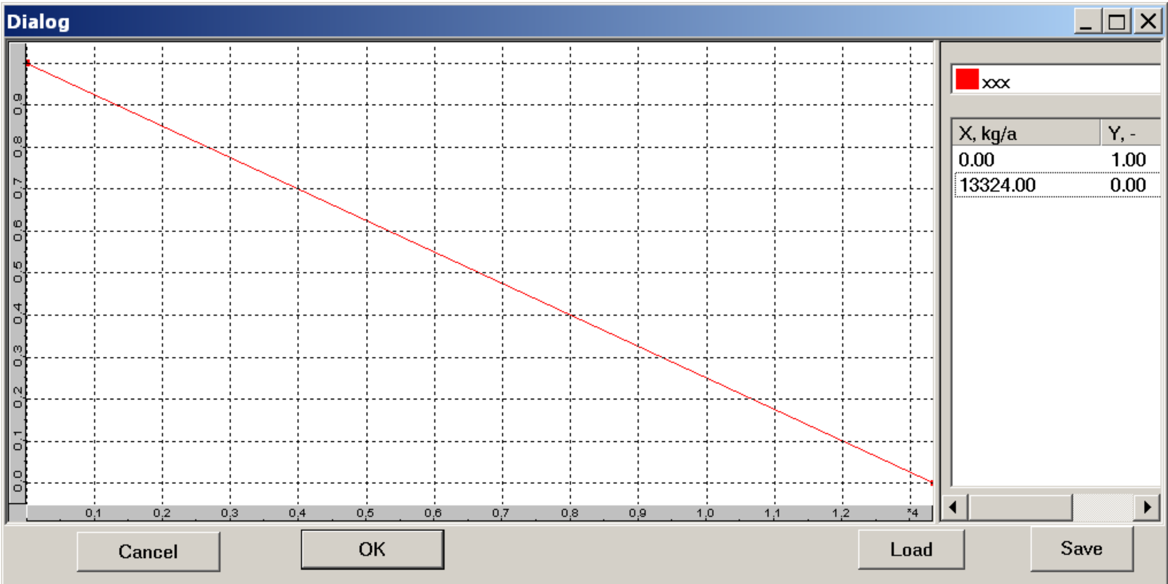


Figure 17: COFAS utility function

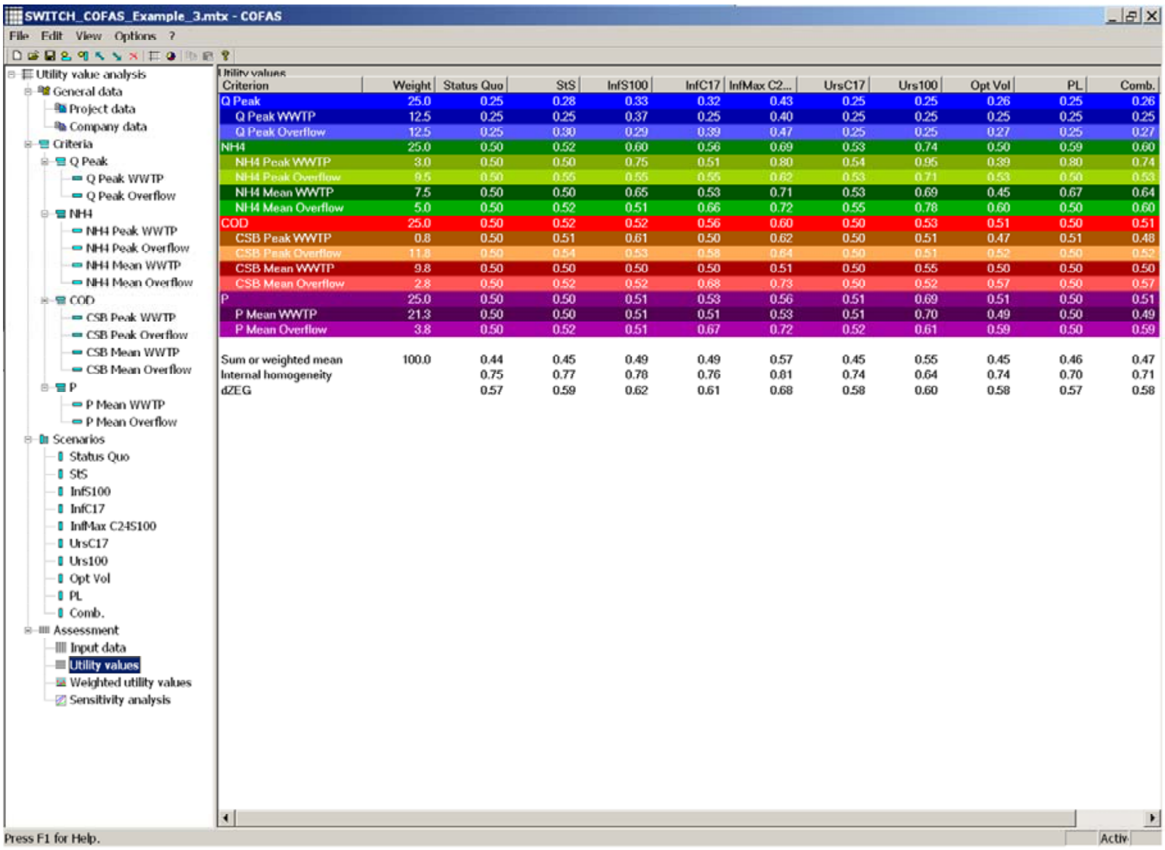
Evaluation

Click “Utility Values” in the tree. Instead of the input data and the units, the partial utility values (pUV) and the weighting factors can now be seen (Figure 18). The row “Sum or weighted mean” shows in the left column the sum of the weighting factors. This must be 100. In the following columns, it shows the weighted mean of the pUVs thus the total utility value (tUV). The following lines show the internal homogeneity and the dDTA (see chapter 0).

The Scenario InfMax C24S100 exhibits the highest tUV and homogeneity, subsequently the highest dDTA. Thus, it is the preferred one according to the preferences of the user (utility functions and weighting factors).

For most of the items in the COFAS tree, a table-view and a graph-view are available. It is possible to switch between these views using the and buttons.

Click to enter the graph-view (Figure 19). Each column represents a Scenario. The height of a column represents the total utility value (tUV). The sectors of a column represent the weighted partial utility values (w*pUV).



Criterion	Weight	Status Quo	StS	InfS100	InfC17	InfMax C2...	UrsC17	Urs100	Opt Vol	PL	Comb.
Q Peak	25.0	0.25	0.28	0.33	0.32	0.43	0.25	0.25	0.26	0.25	0.26
Q Peak WWTP	12.5	0.25	0.25	0.37	0.25	0.40	0.25	0.25	0.25	0.25	0.25
Q Peak Overflow	12.5	0.25	0.30	0.29	0.39	0.47	0.25	0.25	0.27	0.25	0.27
NH4	25.0	0.50	0.52	0.60	0.56	0.69	0.53	0.74	0.50	0.59	0.60
NH4 Peak WWTP	3.0	0.50	0.50	0.75	0.51	0.80	0.54	0.95	0.39	0.80	0.74
NH4 Peak Overflow	9.5	0.50	0.55	0.55	0.55	0.62	0.53	0.71	0.53	0.50	0.53
NH4 Mean WWTP	7.5	0.50	0.50	0.65	0.53	0.71	0.53	0.69	0.45	0.67	0.64
NH4 Mean Overflow	5.0	0.50	0.52	0.51	0.66	0.72	0.55	0.78	0.60	0.50	0.60
COD	25.0	0.50	0.52	0.52	0.56	0.60	0.50	0.53	0.51	0.50	0.51
CSB Peak WWTP	0.8	0.50	0.51	0.61	0.50	0.62	0.50	0.51	0.47	0.51	0.48
CSB Peak Overflow	11.8	0.50	0.54	0.53	0.58	0.64	0.50	0.51	0.52	0.50	0.52
CSB Mean WWTP	9.8	0.50	0.50	0.50	0.50	0.51	0.50	0.55	0.50	0.50	0.50
CSB Mean Overflow	2.8	0.50	0.52	0.52	0.68	0.73	0.50	0.52	0.57	0.50	0.57
P	25.0	0.50	0.50	0.51	0.53	0.56	0.51	0.69	0.51	0.50	0.51
P Mean WWTP	21.3	0.50	0.50	0.51	0.51	0.53	0.51	0.70	0.49	0.50	0.49
P Mean Overflow	3.8	0.50	0.52	0.51	0.67	0.72	0.52	0.61	0.59	0.50	0.59
Sum or weighted mean	100.0	0.44	0.45	0.49	0.49	0.57	0.45	0.55	0.45	0.46	0.47
Internal homogeneity		0.75	0.77	0.78	0.76	0.81	0.74	0.64	0.74	0.70	0.71
dZEG		0.57	0.59	0.62	0.61	0.68	0.58	0.60	0.58	0.57	0.58

Figure 18: COFAS utility values (table)

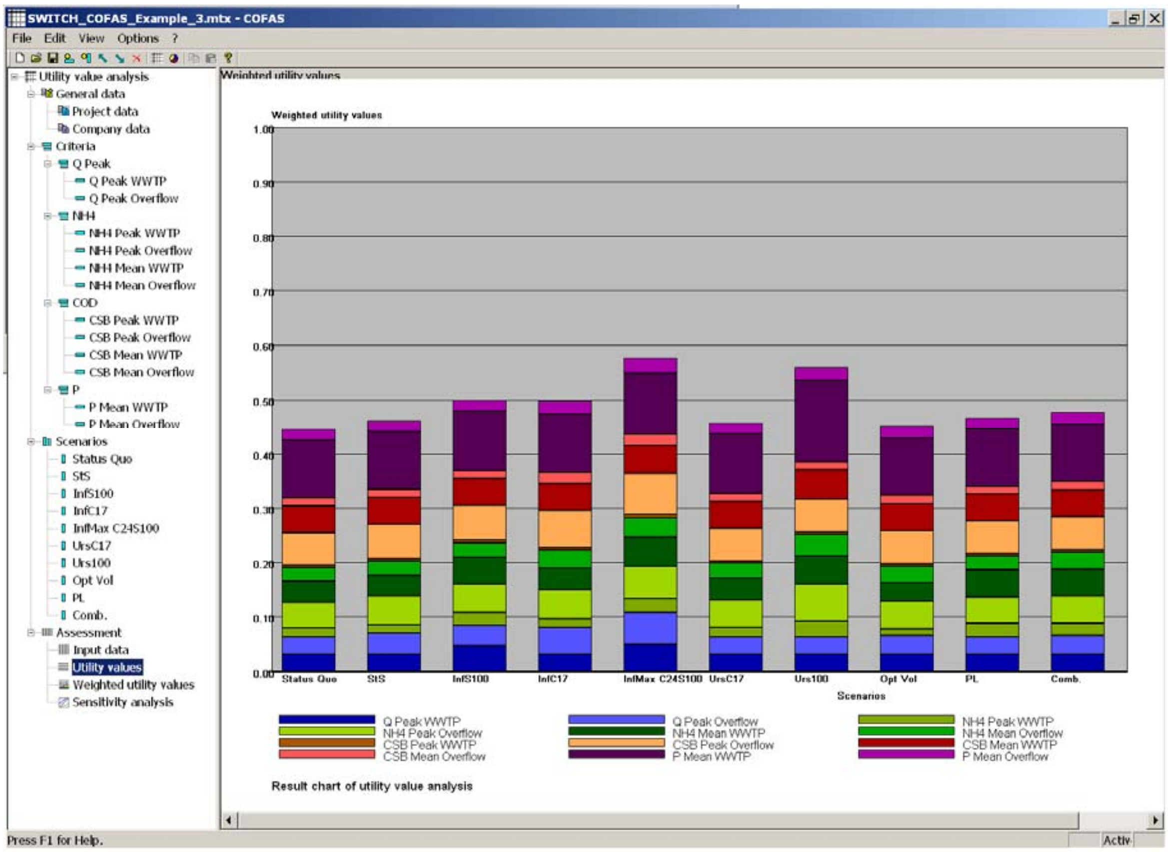


Figure 19: COFAS utility values (graph)

The symbols (-) and (+) in the tree can be used to minimise and expand the criteria groups. This will also appear in the table- and graph- view (Figure 20).

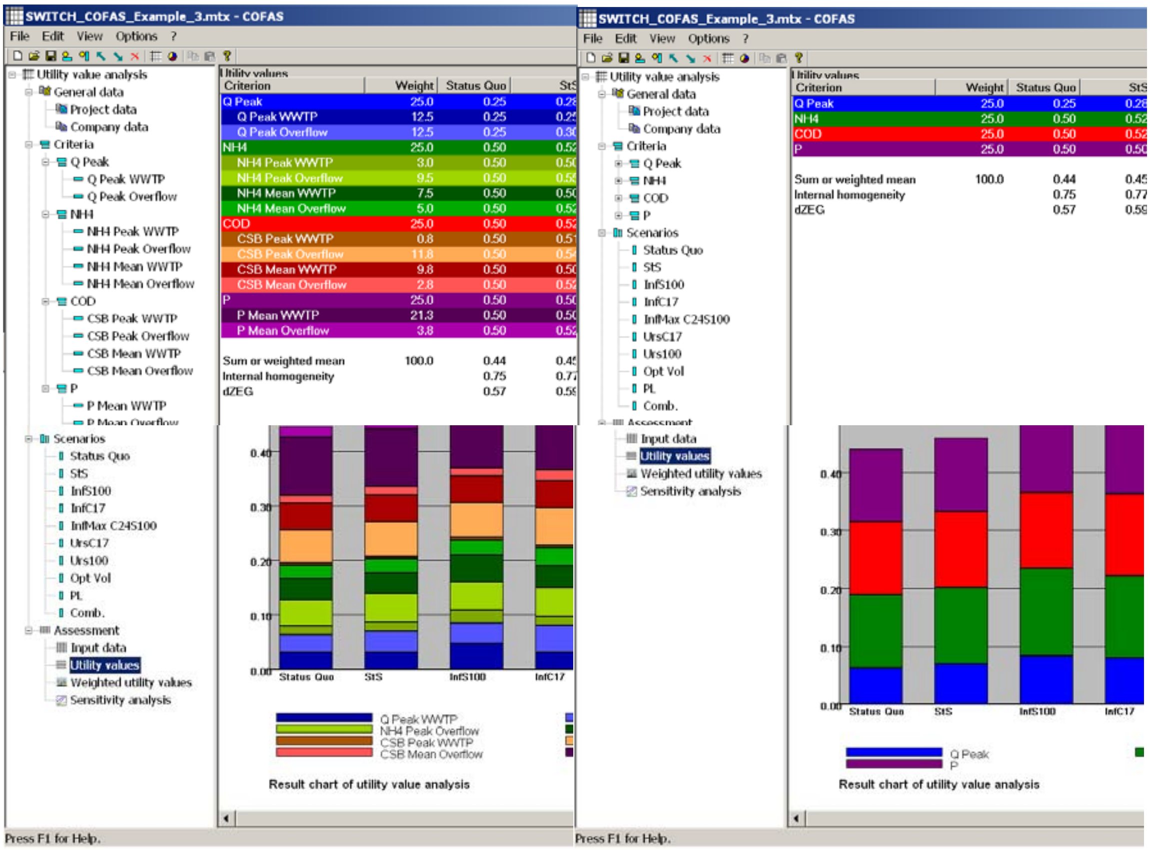


Figure 20: COFAS usage of criteria groups

Clicking on the scenarios in the tree (graph-view) shows the pie chart (Figure 21). The radius of a sector symbolizes the pUV. The aperture angle symbolizes the weighting factor. This chart gives a visual impression of the homogeneity.

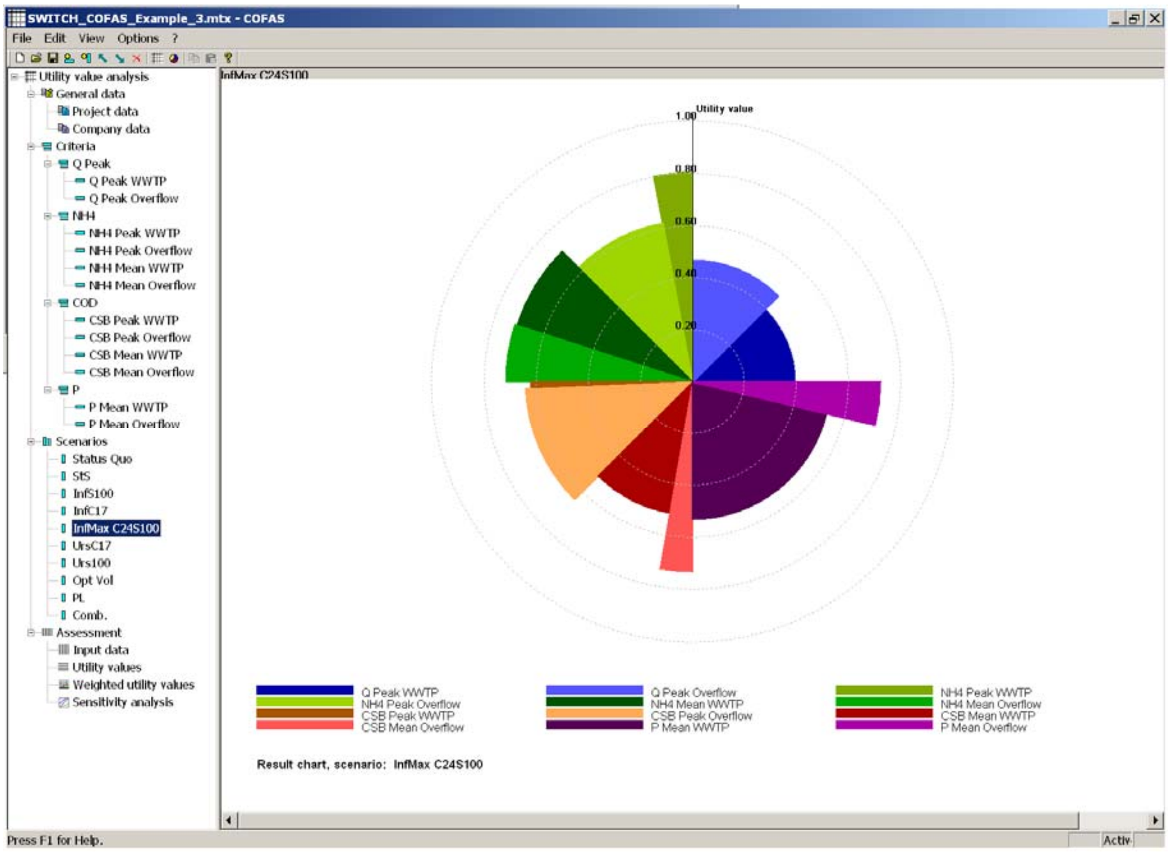


Figure 21: COFAS pie chart

The purpose of this chapter was to provide a tutorial for the COFAS-Software. To obtain a more detailed interpretation of the results for the particular example, please see (Peters 2007) and (Peters 2008). Note that (Peters 2007) uses a different multi criteria analysis method with slightly different preferences.

2.2.3 Important Issues for the Definition of the Utility Functions and Common Mistakes

In UVA, the weighting factors in conjunction with utility functions depict the preferences of the decision makers. Utility functions measure the utility of an alternative with respect to a criterion. Depending on the type of measure scale, different interpretations of the utility value are permitted.

Using an Absolute Scale

This principle is for example generally applied in consumer test magazines (e.g. the German "Stiftung Warentest"). Using absolute scales is preferable because their interpretation is the most intuitive. On the other hand, the definition of the utility functions is most difficult. They must be defined in a way that UV = 0 always represents "very bad" (--) and UV = 1 always represents "very good" (++). Although this sounds trivial, it is not. For example what is "very bad" with respect to phosphorous emissions or hydraulic peak loads has to be determined specifically for each catchment. (Peters 2007)

Only if absolute utility functions are defined it is possible to discuss the weighting factors without worrying about utility functions. And only then can the results of the UVA be interpreted with an absolute scale, i.e. only then a total utility value tUV = 1 represents "very good" (++) and tUV = 0 represents "very bad" (--). Statements like alternative A is twice as good as alternative B are permitted, i.e. it is permitted to form ratios of UVs. When using an absolute scale for the utility functions the "internal homogeneity" defined in chapter 0 is a meaningful result.

If you are using an absolute scale you can emphasise this in the COFAS-Software using the display type "Symbol (++, +, O, -, --)" for the utility values (Options -> General preferences).

Using Interval Scales

Using interval scales, utility functions can be defined arbitrarily. For example the user could define UV = 0 as the highest phosphorous load from all considered alternatives and UV = 1 as the lowest.

The previous chapter discussed the use of an absolute scale. This chapter discusses interval scales, because every criterion has its own scale. For example if all alternatives perform "medium" to "good" with respective to phosphorous-loads, according to the principle stated above the user would define a utility function where UV = 0 represents "medium" and UV = 1 represents "good". Another criterion's utility function might range from "very bad" to "bad", etc.

The advantage of using interval scales is that we do not have to know for example what a "very bad" phosphorous load is, when defining the utility functions. However, the disadvantage is that we are now not allowed to discuss weighting factors independently from utility functions. Instead, we have to assign them according to the "trade of" principle.

This principle is illustrated using Figure 22 which shows an example with two utility functions. Reducing the ammonium peak loads load by 120865 g/h increases the corresponding pUV from 0 to 1. Multiplying with the weighting factor of 10% results in increasing tUV by 0.1. Reducing hydraulic peak loads by 24053 m³/h increases the corresponding pUV by 0.5. Multiplied with the weighting factor of ~20% increases tUV by 0.1 as well. Thus, the user values reducing ammonium peak loads load by 120865 g/h the same as reducing hydraulic peak loads by 24053 m³/h.

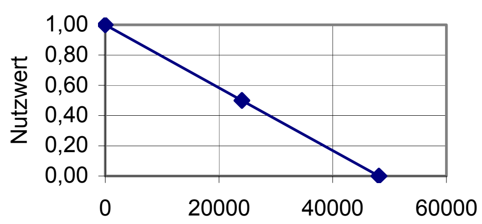
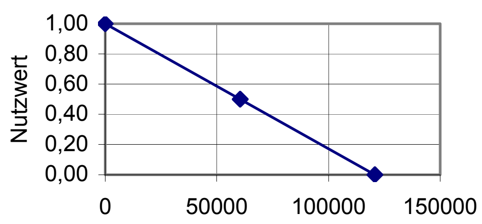
Nr.	Kurzbez.		Einheit	Gewich-tung	Nutzenfunktion
02.	Q S Ü Q Spitze, Überläufe		m³/h	21% 8,5	
	x	y	x	y	
	0 24053 48107	1,00 0,50 0,00			
04.	NH4 S Ü NH4-N Fracht, Spitze, Überläufe		g/h	10% 3,8	
	x	y	x	y	
	0 60432 120865	1,00 0,50 0,00			

Figure 22: Utility functions, example

Using interval scales, one has to interpret the results of a UVA much more carefully then when using an absolute scale. A total utility value tUV = 1 generally does not represent "very good", neither does tUV = 0 represent "very bad". The absolute number of a utility value is

meaningless. Statements like alternative A is twice as good as alternative B are not permitted, i.e. it is not permitted to form ratios of UVs. Valid interpretations are: alternative A is better then alternative B. Also valid would be: The improvement of alternative A compared to alternative X is twice the improvement of alternative B compared to alternative X, i.e. ratios like (tUV(A)-tUV(X))/(tUV(B)-tUV(X)) are meaningful.

The “internal homogeneity” defined in chapter 0 is generally not meaningful when using interval scales.

Often UVA is applied in a way that the user defines utility functions using interval scales, but then discusses weighting factors and interprets results as if they had an absolute scale. This is wrong!

3 Measurement of Flexibility

Jochen Eckart, University of Birmingham

3.1 Introduction

The decision about the design of urban drainage systems is characterised by alternative solutions, multiple objectives as well as uncertain future drivers. Because of the high complexity associated with decision making, intuitive decisions becomes increasingly difficult. Hence methods for a structured decision-making process are required in the face of numerous uncertain future drivers like climate change, spatial development etc for example in urban drainage systems. To cope with decisions under uncertainty flexibility is presented as a new decision criterion. However, a knowledge gap exists in relation to how flexibility could be used for the design of urban drainage systems.

To support a structured decision making process for urban drainage systems and to support the implementation of the flexibility as a decision criterion in the SWITCH project, a software tool 'Comparing the Flexibility of Alternative Solutions' COFAS has been developed. In the following the scientific foundation for the measurement of flexibility is presented. The paper attempts to answer the question ‘How can the flexibility of urban drainage systems be measured?’

Chapter 3 is an extract from the ongoing PhD Thesis titled 'Flexible Urban Drainage Systems' prepared within the SWITCH project. It is based on a thorough literature review of the different methods for the measurement of flexibility. In several disciplines, but particularly in engineering science and business management, a clear concept of flexibility exists, whereas in the field of urban drainage there is still a knowledge gap. In urban water management the discussion about flexibility is still in its infancy. Only few and mainly simplified approaches for definition and measurement of flexibility for urban drainage systems exist. Hence in this section both specific approaches for urban drainage systems as well as generic approaches for the measurement of flexibility are presented. As a result a framework for the measurement of flexibility for urban drainage systems is illustrated.

The following aspects are discussed:

- An introduction based on a framework for a structured decision-making process for urban drainage systems is presented. The basic terms of the decision process such as

objectives, alternatives and future scenarios are introduced and the specific requirements for decision-making for urban drainage systems are illustrated. As a result it is outlined, why for a decision with numerous objectives as well as uncertain future drivers the decision criterion flexibility is required.

- The decision criterion flexibility is further substantiated. The term is defined and distinguished from other comparable decision criteria. Furthermore the effects of flexibility on the life cycle of urban drainage systems is described.
- Different approaches for the measurement of flexibility are presented. Based on the existing technical literature a structured survey about the different methods for the measurement of flexibility is illustrated. As a result approaches for the measurement of flexibility for urban drainage systems are developed.
- Finally, a short guidance for the implementation of the COFAS tool is presented.

3.2 Decisions Support for the Design of Urban Drainage Systems

3.2.1 Decision Analysis Framework

Several alternative solutions, multiple objectives as well as uncertain future drivers characterize the decisions for the design of urban drainage systems. Such complex decisions have to be supported by a structured and formalised decision analysis. According to Eisenführ et al. (2003) decision analysis is a formalization of common sense for complex decision problems. In other words it is *'a systematic procedure for transforming opaque decision problems by a sequence of transparent steps'*. The objective of decision analysis is to produce rational decisions. Goodwin et al. (2004) or Eisenführ et al. (2003) offer an overview over the numerous literature about decision analysis.

The basic assumption of decision analysis is, that a better and easier solution of complex decision problems is possible when the problem is divided into single aspects to reduce the complexity of the problem. According to (Eisenführ et al. 2003), decision analysis provides a general framework for decision-making (see Figure 23). This framework is suitable for general decision analysis as well as for specific decisions about flexibility and includes following steps:

- Objectives of the decision maker: The objectives and preferences of the decision maker have to be ascertained. The objectives influence the selection of alternative solutions and serve as a benchmark for the modelling of the effects.

- Environmental influences: The system external influences, which are relevant for the decision, have to be considered. Depending on the quality of information the future prognosis is classified in certainty, risk and uncertainty. The future system environmental influences can be presented as future scenarios.

- Alternative solutions: For many decisions, reasonable alternatives are unknown and it is part of the decision problem to generate such possible solutions. The final decision is, to select the best action alternative from the possible alternatives.

- Consequences of the alternative solutions: The combined effects of the alternatives and the environmental influence are ascertained by modelling the effects. The consequences of the decisions are identified.

The COFAS tool supports the application of this decision framework. In the following sections the specific requirements of urban drainage systems are described.

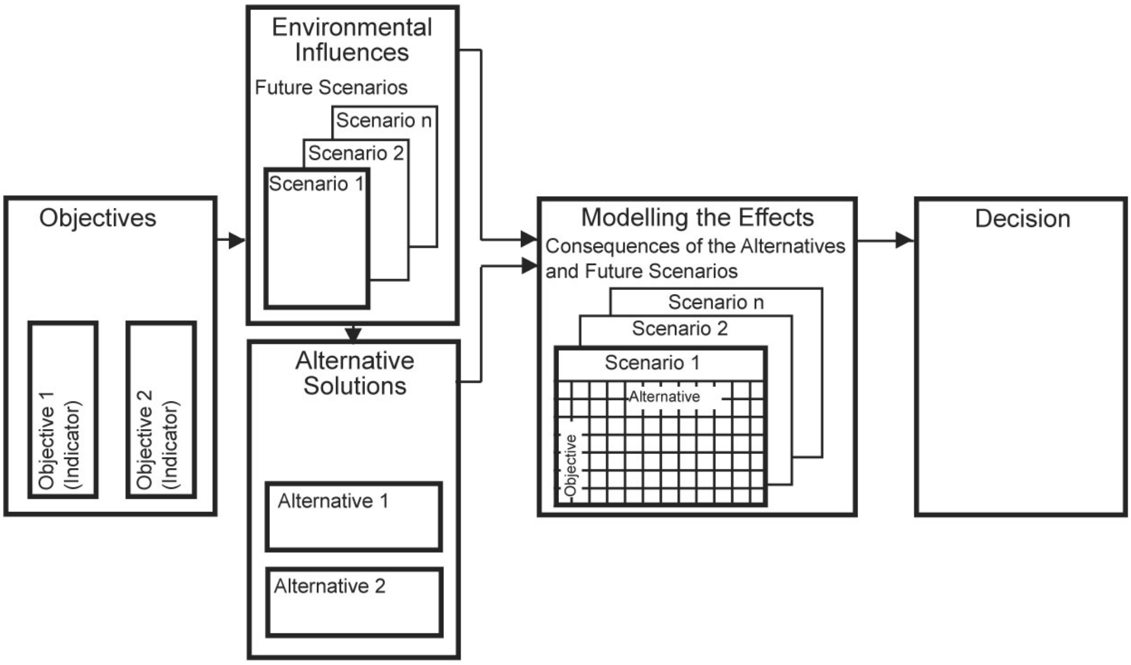


Figure 23: Framework Decision Analysis

3.2.2 Alternative Solutions

For the design of urban drainage systems several alternative solutions are available. A decision between conventional drainage systems and sustainable urban drainage systems or a combination of both is required. Conventional systems are combined sewer systems, where the sewage and the storm water are carried in the same sewer. In separate sewer systems, the sewage and storm water are collected and transported in different sewers. In contrast, sustainable urban drainage systems focus on a decentralised retention, evaporation and infiltration of stormwater. There are several design alternatives for sustainable urban drainage systems and different levels of centrality or decentrality. This means that the runoff may be managed on each single plot of land or the sustainable urban drainage system could extend to include the whole settlement. Different levels of connection between the management elements are possible and management elements with or without surface retention volume, with or without subsurface retention volume can be included in the system. Part of the decision process for urban drainage systems is to decide between the numerous alternatives.

The various alternatives for urban drainage systems are characterised by different performance levels. All urban drainage systems should guarantee the same level of security against flooding. However, for other objectives such as the minimization of the disturbance of the natural water cycle or the guarantee of a good quality of the receiving surface water bodies, there are obvious differences between the different alternatives. In terms of decision analysis the performance of the alternative solutions differentiates them from each other. In simple decision support methods, factors such as cost comparison cannot be used.

3.2.3 Objectives

The question of the desired objectives for urban drainage systems is essential for the decision process. There is no general agreed set of objectives for urban drainage systems as these are quite often customised depending on location etc. Furthermore, in recent years objectives have changed from only being focused on the drainage of the settlement to being focused on a broader concept of goals including water pollution control, urban water management, and social, ecological and cultural requirements. A detailed description of the suitable objectives for urban drainage systems can be found in the relevant technical guidelines (e.g. German guidelines for integrated urban drainage DWA A 100) or the objective catalogues discussed in the technical literature (Sieker et al. 2007a), (Peters et al. 2005) or (Peters 2008).

For decision analysis, it is imperative that urban drainage systems are not only limited to a single objective but also to consideration of numerous objectives. Hence, an assessment method is required, that is suitable for assessing multi-objectives. For the assessment of multi-objective performance of urban drainage systems, the 'value benefit analysis' is a tried and tested approach (Sieker et al. 2006), (Sieker et al. 2007) or (Peters et al. 2007). According to (Fürst et al. 2008) the value of benefit analysis includes the following steps:

- Development of an objective system: Based on the single objectives a hierarchical system of objective categories and sub-objectives is developed. The hierarchical objective system should facilitate the assessment of the contribution of a single objective to the overall performance of the system. Furthermore, measurable and predictable indicators can substantiate the objectives.
- Weighting factors for objectives: Because not all objectives have the same importance and hence do not have the same contribution to the overall performance of the system weighting factors for the different objectives and their related indicators should be considered.

- Development of utility functions: Utility functions are developed which represent the relationship between a value of the indicator and the level of achievement of the objectives. The utility function presents how far an objective is achieved by different values of the indicator.

- Aggregation: Based on the objectives, the weighting factors, and the utility functions, the benefit values are calculated. These values represent the performance of the system.

For the application of the utility value analysis different requirements have to be considered.

- Effectivity of performance: It is possible to distinguish between indicators describing the effectivity and the efficiency of the system. Effectivity represents the level of performance of the system (level of flood protection, amount of pollutants etc.) whereas efficiency describes the effort required to achieve a certain performance (life-cycle-cost, resource consumption etc.). For the measurement of flexibility it is recommended to differentiate between both these categories. In the chosen method for the measurement of flexibility particular indicators for the efficiency are considered.

- Substitute of objectives: A precondition for the calculation of an overall combined value of benefit for different objectives is that the single objectives can substitute each other. The different objectives should compensate each other so that they can be replaced. Hence, a low value for objective A should be compensated by a high value for objective B. (Eisenführ et al. 2003).

- Independence of objectives: The different objectives should be independent from each other. In particular a functional independency is required. The value of benefit of the different objectives should not depend on the same attributes or drivers. Otherwise, the common attribute is systematically overvalued in the assessment (Eisenführ et al. 2003).

- Suitable indicators: For the established objectives indicators have to be substantiated. Indicators are used to verify a parameter, which could not (or only with a very high effort) be measured directly. There should be a causal relationship between the objective and the used indicator itself. Furthermore, the indicators should have the capability to be modelled for the future. (Fürst et al. 2008).

- Cardinal scale for utility function: To calculate statistical characteristics like arithmetic mean or variance a cardinal scale for the utility function is required (for details see Friedrichs 1980). In the cardinal scale the ranking as well as a fixed interval between

the different values is known. Furthermore, an absolute scale with a defined zero point is required to compare the results from different scales (Friedrichs 1980). For all objectives and indicators always the best and the poorest value of benefit has to be defined (Peters 2007).

3.2.4 Uncertain Environmental Influences

The performance of urban drainage systems is affected by several basic conditions such as rainfall patterns, paved surface, pollution load etc. Different future drivers like climate change, spatial development, general social value change etc. influence these basic conditions. These future alterations of the basic conditions can cause a varying performance during the operational life span of the urban drainage system. In the SWITCH project the consequences of these future drivers on the performance of urban drainage systems has been analysed in the report ' Review of the adaptability and sensitivity of current stormwater control technologies to extreme environmental and socio-economic drivers' (SWITCH Deliverable 2.1.1). Comparable analysis of the different future drivers for urban drainage systems is also offered by the research projects DayWater (Hauger et al. 2003) and net-WORKS (Kluge et al. 2006). There is agreement from all analyses that the future development of the basic conditions of urban drainage systems are characterised by severe uncertainties. In particular the future drivers associated with spatial and traffic development (paved surface, pollution load, hydro geological conditions) and climate change (rainfall patterns, loading capacity receiving water bodies) can cause huge future uncertainties and affect the performance of urban drainage systems.

As a consequences of these uncertainties the planning and development of urban drainage systems faces dilemma. On the one hand, it is foreseeable that uncertain future drivers will change the basic conditions of urban drainage systems during their long operational life span with effects on the performance as well as the costs of the systems. However, the influencing drivers cannot be currently forecast with a high degree of accuracy. At present no sufficient future predictions for the operation life span of urban drainage systems from 50 up to 100 years are possible. On the other hand long-lasting decisions about urban drainage systems have to been taken, even if it is expected that the basis for these decisions will change. It is not possible to defer the decisions until the future uncertainties are reduced.

This dilemma cannot be solved using the established decision criteria of effectivity and efficiency. Effectivity and efficiency both only consider steady basic conditions so that the urban drainage system is designed for conditions from which it is conceivable that there will

change in the future. Hence, there is a danger that the performance will fail in future. Moreover, in effective and efficient systems it is not possible to use the opportunities for the improvement of performance when demand is shrinking. Because of the deficiencies of the present decision criteria to deal with the dilemma of uncertain future drivers, a new decision criterion for urban drainage systems based on flexibility is required.

3.3 Flexibility as Decision Criterion

3.3.1 Definition of Flexibility

To measure flexibility a detailed definition of the term is required. A preliminary literature review indicates that many authors base their interpretation of flexibility on the ability to respond to future alterations or the ability to improve the future performance of a system (Saleh et al. 2001). However, this results in confusion between the term flexibility and other terms related to the ability of systems to handle future alterations such as adaptability, changeability, elasticity etc. The following definition of flexibility for urban drainage systems has been developed based on an analysis of generic definitions of the term.

Flexibility is the ability of urban drainage systems, to use their active capacity to act, to respond to relevant alterations in a performance-efficient, timely and cost-effective way.

This definition names the fundamental characteristics of flexibility such as overcoming alterations, the capability to change and the characteristics of the change process. An essential characteristic of flexibility is the overcoming of future alterations.

- Overcoming alterations: Different types of relevant alterations are differentiated. The sources of alterations are categorised by (Hocke 2004) in modifications, which occur internally in the system or occur externally in the systems environment. (Frey 2005) developed a categorisation of different types of alterations for the technical infrastructure systems and distinguished between replacement, accumulation, extension and re-equipment. The replacement demand originates from signs of wear because of the age of the system. The accumulation of demand is the difference between the existing and the required performance of the technical infrastructure. The extension of demand is determined from increasing requirements. The re-equipment demand originates from altering qualitative and quantitative demands for the technical infrastructure.

- Fulfilling functionality: Flexibility should guarantee long term functionality and good performance of the system as well as altering requirements (Schneeweiß et al. 1990). This characteristic is described by (Koste et al. 1999) and (Upton 1994) as 'uniformity', the homogeneity of the systems performance for different system requirements. The emphasis of flexibility is to guarantee the systems performance and not preserve the original system structure or single system elements. According to (de Neufville et al. 2008) and (Hocke 2004) the value and performance of a system should increase by re-

acting to uncertain events by either protecting against detrimental effects or by capturing additional value for the system when beneficial opportunities occur.

Another important characteristic of flexibility is the useable capacity to act.

- Capabilities of change: To overcome uncertain future alterations a capacity to act is required (Upton 1994) and (Schneeweiß et al. 1990). The capacity to act is described by characteristic range-numbers and range-heterogeneities (Koste et al. 1999). The range-number is the quantity of different future states, which can be handled, with an existing scope of operation. The range-heterogeneity is the extent of the differences between the different future states, which can be handled by a specific scope of operation. A flexible system should include flexibility options as big as possible and should avoid unnecessary commitments and limitations.

- Initiated change: An important characteristic of flexibility is, that the change process is externally initiated (Fricke et al. 2005). Thereby, a differentiation from robustness, where the system performance is guaranteed without change, to adaptability where the adaptation is initiated from the system itself is possible. According to (Schneeweiß et al. 1990) the external initiation of the change is a pre-condition that flexibility is an objective of the planning and management process.

The ease of movement is an important characteristic to describe the change process. Several types of barriers to the use of the capability are possible. The technical literature focuses on two characteristics, namely the time and the costs of the change process (Koste et al. 1999) and (Patig 2001). The easier it is to change a system during operation the higher the flexibility.

- Costs of change: In general costs for the construction, preservation and implementation of capability for change occur (Kaluza et al. 2005) or (Schlüchtermann 1995). A trade off between the costs and the benefits of flexibility is required. The system is more flexible with smaller costs and bigger efficiency.

- Duration of change: The time period required for change is an important characteristic of flexibility. The duration of change is the period of time, which is required to adapt the system to new demands. According to (Corsten et al. 2005) the duration of change contains observation period, decision period, implementation period, effect period and control period. There are two evaluation criteria. First, a system is more flexible the

shorter the duration of change is. Second, a flexibility option should be implemented quicker than the occurrence of alteration.

3.3.2 Flexibility in the Life-Cycle of Urban Drainage Systems

A framework for the management of flexibility can be deduced from the definition of flexibility as '*the ability of urban drainage systems, to use their active capacity to act, to respond to relevant changes in a performance-efficient, timely and cost-effective way.'* Based on the first part of the definition involving 'the capacity to act' the parameter, the 'flexibility option' is developed. The term flexibility option is defined as 'the ability to modify an operating system to adapt it to future demands by either avoiding detrimental consequences or exploit beneficial opportunities'. These options should minimize the damage of future uncertainties as well as make use of the opportunities for future development. The second part of the definition involving 'respond to relevant changes' results in the parameter 'required flexibility'. The term, required flexibility, arises from the future uncertainties and are the future alterations in the system environment which affect the system performance.

Flexibility management involves balancing the flexibility options with the required flexibility of a system. A total inflexibility is suitable for the theoretical case of a static system and environment. In contrast, an excessive flexibility is problematic because flexibility options could hold negative consequences like additional costs or disturbances of the system performance. The optimal level of flexibility is described by the principle *'as rigid as possible and (only) as flexible as necessary'* (Eversheim et al. 1980). For the management of flexibility a method to measure flexibility is required. On the one hand the required flexibility caused by future uncertainties has to be described but also the flexibility offered by flexibility options has to be measured.

The implementation of flexibility options takes place within the operational life span of the urban drainage system including the stages involving planning, implementation, utilization, conversion and deconstruction. Referring to the generic life cycle of infrastructure systems, a framework for the management of flexibility for urban drainage systems can be developed (see Figure 24).

- Problem Analysis: As a basis for problem analysis the specific urban drainage system and the objectives of the urban drainage system need to be defined. Then the uncertain future drivers are ascertained and the range of possible future developments for the pe-

riod under review are described. As a result the required flexibility of the urban drainage system is identified.

- Alternative Analysis: Based on the required flexibility, the flexibility options in urban drainage systems are determined. The different flexibility options are considered as alternative solutions. Then the performance and the effort behind the different alternatives for different future states are modelled. It is necessary if a change to the system is required to react to future alterations. Based on the modelling results the flexibility of the different alternatives is measured.

- Decision: Based on the modelling of the effects, it has to be decided which alternative of the system (and associated flexibility option) can be realised in the first implementation step. The chosen alternative needs to offer the best equalization between the required flexibility and the potential flexibility.

- Implementation: In the first implementation phase the urban drainage system is realised and the flexibility options are constructed. A capacity for change is developed. Subsequently, the development of the urban drainage system and the system environment are monitored and the consequences for the system performance are evaluated. An assessment is made as to if a change of the urban drainage system is required to cope with altering basic conditions. Based on the monitoring a decision about the utilisation of the flexibility options is made. In the second implementation step, the established flexibility options are realised and the capacity for change is used. The monitoring process is continued for the whole life span of the urban drainage system.

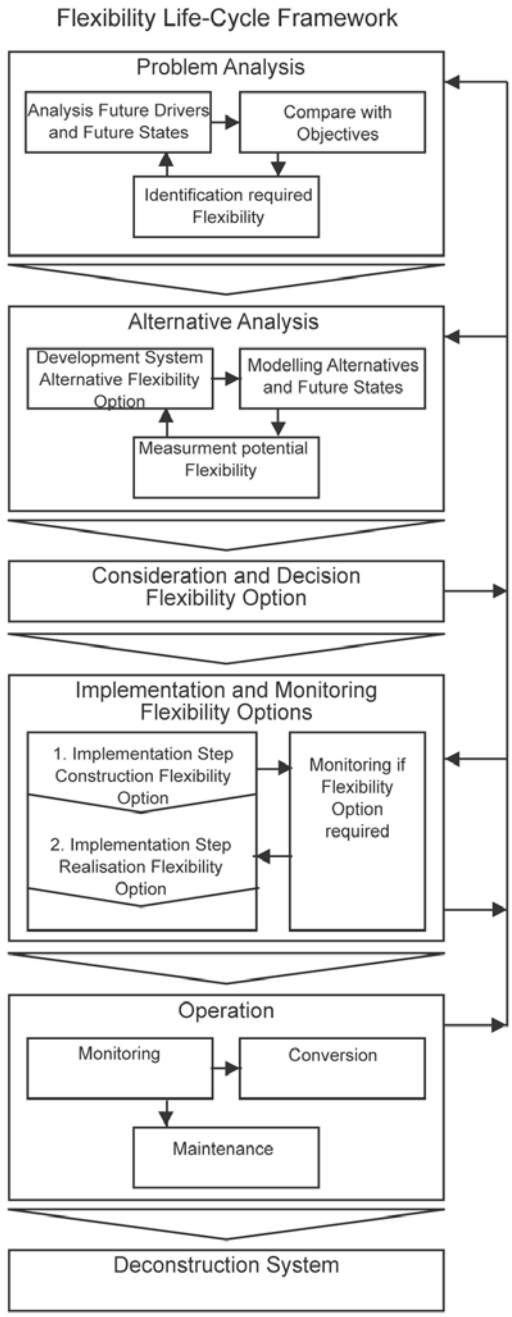


Figure 24: Life Cycle of Flexibility Management

3.4 Measurement of Flexibility

For the management of flexibility, both the quantification and measurement of flexibility are required. In the technical literature, several methods for the measurement of flexibility are discussed. Comprehensive summaries concerning flexibility measurement in business management are described by (Schlüchtermann 1995), (Pibernik 2001), (Patig 2001) and (Kühn 1989). In engineering science, (de Neufville et al. 2008) and (Shah et al. 2006) give an overview of several measurement methods. The methods for the measurment of flexibility have to consider following requirements:

- According to (Kühn 1989), the task of the method of measurement is to substantiate and operationalize the characteristics mentioned in the definition of flexibility. There is an interaction between the definition and the measurement method. On the one hand a distinct definition of flexibility is an important precondition for the measurement of flexibility. On the other hand the definition should be quantified and operationalized by the measurement method. Hence it is required to compare the measurement methods with the definition of flexibility.

- The measurement of flexibility should be applied within the framework of the management of flexibility. Two requirements of flexibility have to be considered. On the one hand, (Koste et al. 1999) clarify, that flexibility is a relative attribute, as opposed to an absolute one. Hence, it is desirable to examine the flexibility of an alternative with respect to another alternative. In contrast, the measurement of flexibility has to consider uncertain future developments. The different uncertain future states have to be taken into account in the measurement process. As a result of both demands and according to the framework for management of flexibility the measurement method should enable the consideration of different alternative solutions of the system as well as different future states. The measurement method is assessed in regard to the framework for the management of flexibility.

The measurement approaches for flexibility are subdivided into two parts.

- On the one hand, different types of flexibility metrics are presented. The metrics are the indicators, which represent the characteristics of flexibility and are used as a basis for the measurement of flexibility.

- On the other hand, different measurement procedures are illustrated. The measurement procedures describe the process of measuring flexibility. Within the process, particular

characteristics like the comparison of different system alternatives as well as the future uncertainties are considered.

In the following sections an encompassing literature review about the measurement of flexibility is presented. General measurement approaches as well as methods for the measurement of flexibility in the field of urban drainage are presented (see Figure 25).

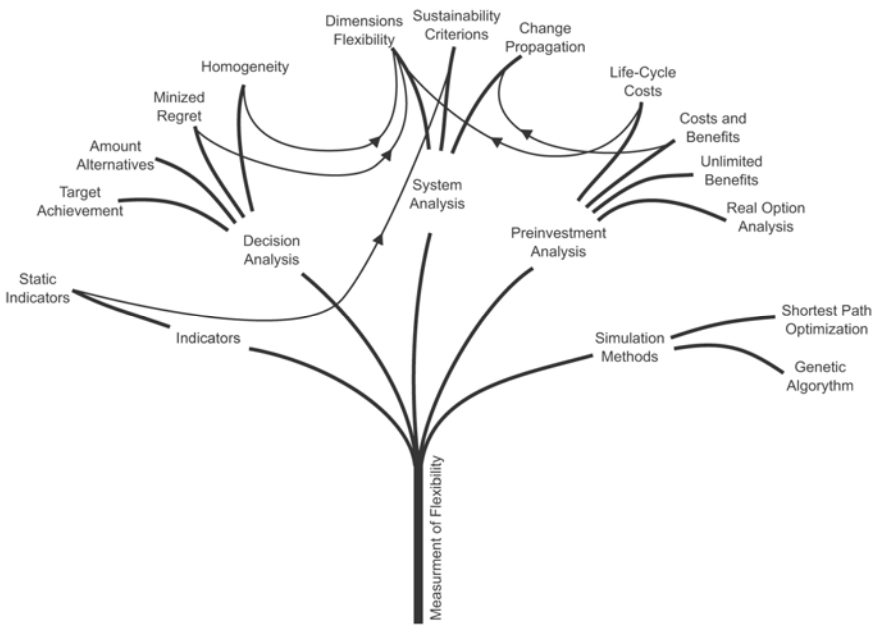


Figure 25: Survey Methods for the Measurement of Flexibility

3.4.1 Indicator Based Measurement

Most indicator based measurement methods for flexibility do not have a theoretical foundation and therefore most approaches have been developed by considering practical requirements. The basic premise is that flexibility is measured by indicators, and this offers a plausible coherence between the analysed system and the flexibility option (for example (Schlüchtermann 1995) and (Corsten et al. 2005). Flexibility is presented by single static characteristics of the system ignoring the various future states. The quality of the indicator-based approaches is determined by substantiation of the indicators. On the one hand, the relationship between the indicator and the flexibility option should be guaranteed. On the other hand, a replicable selection of indicators is required. The indicators are specialised for the regarded systems, so that a general presentation is not possible. Different examples of static indicators of flexibility for urban drainage systems will be presented.

In the research project DayWater a decision support system for urban drainage systems was developed. Besides other numerous aspects the flexibility of the system was regarded as a decision criterion. Characteristic flexibility was assessed for different elements of urban drainage systems without modelling future uncertainties. In the decision support system, flexibility was considered by the following static indicators (Revitt et al. 2003).

- An indicator for urban drainage systems needs to focus on the ability to treat heavy rain events with respect to the quantity and quality of water. The reliability of urban drainage systems should be guaranteed for the expected consequences of global climate change. Indicator is the dimension of the design freeboard of the treatment element.
- Other indicators can focus on the effort for reconstruction and adaptation of the facilities of urban drainage systems. The first indicator is the ease of retrofitting and modifying facilities measured at levels of low, medium and high. It is not substantiated which characteristics are considered in relation to retrofitting. The second indicator is the cost of retrofit and adaptation (average cost in Euro).
- A further indicator represents the ability to reuse system components of urban drainage systems. The indicator selected is the potential to recycle system components or building materials measured at the levels of low, medium and high. A substantiation of the indicator is missing.

(Woods et al. 2007) developed four static criteria for assessing the retrofitting of urban drainage systems. Although these criteria were developed for a different purpose, they have similarities to the measurement of the flexibility of urban drainage systems (see below):

1. is the type of sustainable urban drainage system suitable for retrofitting?
2. consideration of the required land-take for different urban drainage systems
3. the capital costs for the implementation of retrofitting are taken into account.
4. the maintenance requirements are listed as evaluation criteria.

Another static indicator for the flexibility of urban drainage systems is presented by (Helm 2007) also compare (Sieker et al. 2008). A static indicator for flexibility is the homogeneity of performance for different system objectives. The idea presented is that the simultaneous achievement of several objectives (a multiple use of the urban drainage system) is an important option to achieve flexibility. This indicator is supported by theoretical considerations.

According to (Winkel 1989a) and (von Weizäcker 1984) non-specialised technical infrastructure systems offer a high flexibility and robustness against uncertain future drivers. A low degree of specialisation enables a system to perform a higher diversity of functions. Hence, if the demand for a specific function decreases because of altering requirements, a non-unspecialised system can perform another function within its scope of operation. This improves the robustness of the system, because it is guaranteed that even for changing requirements the performance can be varied. Furthermore, systems with a low degree of specialisation have a high probability that the system will be suitable also for new requirements. These characteristics are described by the indicator homogeneity of performance for different system objectives. (Helm 2007) measures the homogeneity in two steps. First for a multi criteria value benefit analysis the benefit value for different system objectives is ascertained. Other than homogeneity, the value of benefit is calculated based on the standard deviation of the values. The COFAS method presented in Chapter 1of the document base on this indicator.

The measurement of flexibility by means of static indicators is a pragmatic approach with a low amount of work. But (Jacob 1989) and (Pibernik 2001) both criticise static indicators for not offering a direct coherence between the indicator and the object of studying flexibility. Static indicators neglect the required consideration of uncertain future developments. Because of the static approach, which is an essential characteristic of the framework for management of flexibility, dynamic future development is not considered. Furthermore, the presented static indicators do not properly describe the characteristics of flexibility mentioned in the definition. In the first and second approaches the indicators are focused on the effort of the change process and disregard the performance of the system. In the third approach the indicator is focused on the performance of the system but neglects the effort of the change process.

3.4.2 Flexibility Measurement Based on Preinvestment Analysis

In business management the question of flexibility is discussed within the field of pre-investment analysis. The general approach adopted within pre-investment analysis is described in numerous publications (see e.g. Kruschwitz 2005, Wöhe et al. 1993 or Schirenbeck et al. 2008). The focus of pre-investment analysis is on how different approaches evaluate the economic profitability of investment decisions. On the one hand, a conventional assessment of an investment project without the consideration of flexibility is possible. On the other hand, pre-investment analysis, complemented with additional analysis steps, could be used for the measurement and evaluation of flexibility. Pre-investment analysis is suitable in particular for answering two questions:

1. Approaches used in pre-investment analysis can determine the economic profitability of flexible systems. The costs of change are used as a benchmark for the assessment of flexibility. But the costs are only one criterion beside others to describe flexibility.

2. Approaches used in pre-investment analysis consider the uncertainties of the investment. Hence, some economical measurement methods like option analysis or the approach of unlimited benefit are customised to assess flexibility.

In the following section, different flexibility metrics as well as measuring procedures from pre-investment analysis are presented.

Life-Cycle-Costs

Life-cycle-costs are considered to be a metric for the measurement of flexibility. The life-cycle-costs approach is based on the insight that the initial capital costs often only represent a small portion of the overall costs during the whole operational life span of an urban drainage system. Hence, costs for the whole life cycle are considered as an investment decision. (de Neufville et al. 2006), (Fricke et al. 2005) and (Nilchiani et al. 2006) applied these life-cycle-costs as a metric for the assessment of flexibility. A system is more flexible than an alternative when the life-cycle-costs for different possible future states are lower.

Like all technical infrastructure systems, urban drainage systems are characterised by economic attributes like high capital expenditure, long amortization periods, large overhead costs, high persistence and indivisibility of the infrastructure (Tauchmann et al. 2006) or (Herz et al. 2002). These characteristics result in requirements, which need to be considered during pre-investment analysis. A customized method for the calculation of life cycle costs for urban drainage systems, based on the net present value method, is presented in the German guideline 'KVR Leitlinie' (LAWA 2005). The 'KVR Richtline' offers a general method and procedure, so that it could be used for the assessment of conventional rigid systems as well as for systems with different levels of flexibility.

For the economic assessment of the flexibility of urban drainage systems, special cost categories are considered (see Figure 26). The cost categories are described according to their chronological occurrence during the life cycle of the system:

- Initial construction costs for the infrastructure systems: All costs for the construction of the urban drainage system such as the costs for the land, costs for preliminary work as

well as construction costs are considered. This cost category includes the additional costs for the construction of flexibility options.

- Operational costs: Running expenses for the operation, upkeep and monitoring of the urban drainage system during the operation period are considered. According to (Siedentop et al. 2006) fixed costs (independent from the workload) as well as variable costs (dependent on the workload) have to be differentiated. For the variable costs, the cost of normal operational conditions and the special costs which occur if the system is overburdened, or under loaded have to be distinguished. In normal operation the common costs for the operation of the system occur with only minor alterations within a range of tolerance. But if a critical threshold value of workload is passed or not reached the operational costs will increase significantly. The variable operational costs are influenced by the flexibility options. So increasing operational costs could be avoided by the use of flexible options.

- Maintenance costs: Maintenance costs include measures to prevent and repair constructional insufficiencies, which occur by abrasion or aging of the urban drainage system. Maintenance costs are necessary to preserve the performance of the system. (Gutsche 2006) points to the fact that urban water management systems consist of elements with different operational life spans. Hence, reinvestment costs occur to replace the elements with a short life span during the life cycle of the overall system. For these elements a high flexibility is required.

- Change costs: (Koziol et al. 2006) consider the costs for three different types of change processes. First, the costs for adaptation measures themselves are considered. These include costs for the actual implementation of the flexibility option like construction costs etc. Second, the renewal measures at the end of the operational life span when the whole system has to be replaced. Third, the demolition costs for the decommissioning, deconstruction and disposal of the system are taken into account. Furthermore, the sunk costs (also called stranded investment) of infrastructure systems could be considered (Koziol et al. 2006), (Geyler et al. 2003) or (Schierenbeack et al. 2008).

Costs, which occur at different times of the operational life span, have a different present value. Hence, the cost positions have to be converted to equivalent economic figures referred to as the so-called cash equivalent. Therefore, the different costs are multiplied by a discount factor so that all costs are related to one point in time. Finally, the single cash equivalents are summarised to the net present value of the urban drainage system. The life-cycle-costs are calculated for different possible future states, considering varying change costs. The life-

cycle-costs for various future states are compared for different alternatives. The alternative solution, with the lowest average life-cycle-costs for different future states has the highest flexibility. The precondition for such a cost comparison is, that all alternatives have an equivalent performance. If the performance of the alternatives is different, an additional value of benefit analysis is required.

The ascertained life-cycle-costs are linked with several uncertainties because of the long operational life span of and the uncertain future drivers of urban drainage systems. In particular, the assessment of the benefits of flexibility has to consider future uncertainties. So it is uncertain, if the flexibility benefits such as prevented damage and renewal costs will be obtained. In pre-investment analysis different approaches for the consideration of uncertainties are available. Firstly, different future scenarios for the cash flow could consider the uncertainties, depending on the expectations of the occurrence of different cost categories. Secondly, the impact of uncertain future changes could be analysed using a sensitivity analysis

The measurement method based on the life-cycle-cost only represents a part of the characteristics of flexibility. The focus of the economic assessment is the costs and benefits of flexibility, whereas the other characteristics such as the capability of change or the duration change are neglected. So in the life-cycle-cost assessment method, the performance of the system is only considered indirectly e.g. as part of the operation costs. The single consideration of the life-cycle-costs is inadequate for the measurement of flexibility. However, the life-cycle-costs metric could be part of other more comprehensive approaches for the measurement of flexibility.

Costs and Benefits of Flexibility

An economic metric for flexibility is 'switching costs'. So according to (Shah et al. 2007) or (Silver et al. 2007) an accurate evaluation of the 'switching costs' is the basis for valuing the flexibility of a system. This approach is based on the basic assumption of only considering costs and benefits of flexibility options in the cost calculation (see Figure 27). Other cost categories of the life-cycle-costs are not considered. According to (Kaluza et al. 2005), (Schlüchtermann 1995) and (Pibernik 2001) the following cost categories are required for the assessment of the costs and benefits of flexibility:

- Costs for construction of flexibility options: The costs for the construction of flexibility options are part of the initial investment cost when implementing the infrastructure system. The centre of attention is the additional expenditure related to the construction of

flexibility options. These are e.g. the costs for providing an additional area required for the implementation of flexibility options.

- Costs for maintenance of flexibility options: The costs for maintaining the functionality of the flexibility options is summarised. These are the additional operation costs, maintenance costs and repair costs which emerge because of flexibility options.

- Costs for implementation of flexibility options: The costs for the utilisation of flexibility options are those which are required to adapt a system to relevant alterations. These are the construction costs for the realisation of the flexibility options as well as operational costs for required additional management measures.

- Saved adaptation costs: Adaptation costs always occur when an adaptation of the system to changing basic conditions is required. The occurrence of adaptation costs is independent of whether flexibility options are available or not. However, the amount of expenses is influenced by the available flexibility options. Therefore, flexibility options should reduce the amount of adaptation costs. It is possible to save adaptation costs by the preliminary preparation of flexibility options. These saved adaptation costs are seen as a benefit of flexibility.

- Saved damage costs: When required adaptation measures are not implemented damage costs can occur. The damage costs are expenses caused by the disturbance or breakdown of the system performance because of missing adaptation related to altering requirements. So the operational costs could increase compared to a normal operational mode. Furthermore, damages e.g. caused by flooding or water pollution are considered. With flexibility options these damage costs could be avoided. The saved damage costs are seen as a benefit of flexibility.

As a measurement procedure, the expenses and benefits of flexibility are balanced by risk analysis. A flexibility option is profitable when the benefits exceed the expenses or one alternative solution is more profitable than another. The costs of flexibility such as the construction and maintenance of flexibility options can be ascertained without any problems because they arise out of certainty. On the contrary, the benefits of flexibility such as the avoided damage or adaptation costs depend on the occurrence of uncertain future developments hence a risk calculation is required. Risk can be described as the probability of occurrence and the extent of the damage. Therefore, the benefit of flexibility is the avoidance of damage and adaptation costs and the probability that there will be relevant alteration of the basic conditions in the future. According to (Dyer 2005) the benefit of flexibility is higher

when future development is the more uncertain (the higher the probability of relevant alterations). For risk analysis, future uncertainties have to be transformed into a calculable risk. This conversion is an accepted approach of decision analysis for decisions under uncertainty (Laux 2005). Assumptions about the probability of different future states are made or according to the Laplace principal, an equal probability for all possible future states is considered. The risk calculation illustrates a dilemma for the planning of flexibility because there are certain costs for the development of flexibility options but there are only uncertain future benefits.

The cost-benefit assessment is focused recursively on economical criteria and neglects other characteristics of flexibility. Furthermore, risk analysis is criticised. Therefore, the conversion from uncertainties into risks by means of probabilities is a simplistic approach and does not meet the characteristics of uncertainty properly. The single assessment of the costs and benefits is not suitable for the measurement for flexibility. However, the results could be included in extensive measurement approaches.

Unlimited Benefits

(Marschak et al. 1962) developed a method for the measuring flexibility. The expenses and benefits of a system are presented as a cost function for different future states. A system alternative is flexible if the cost function indicates an unlimited benefit whereas the expenses are limited. Therefore, flexibility is defined as an asymmetric risk profile of a system, which enables the reduction of potential loss whereas the potential profit is preserved. However, according to (Schlüchtermann 1995) there are problems with the implementation of this approach and it is not possible to develop a valid cost function, which includes all relevant future states of a system a priori.

Real Option Analysis

Flexibility is often discussed within the scope of real options analysis. The basic idea of real options analysis is, that principles and methods of financial options can be transferred to real action alternatives and physical objects (de Neufville 2004) or (Pibernik 2001). Real option analysis considers the unavoidable uncertainties for the operation of a system and deals with it proactively by creating options, which can be used over time. Depending on the future development, options enable the alteration of the configuration of the system. So in real options analysis flexibility is understood as an option which provides *'the right, but not the*

obligation' to modify a system in operations to adapt it to this changing environment' (de Neufville et al. 2008). The option-like perception of flexibility has three consequences:

- the benefit of a flexibility option is larger the more unsteady the future development is. Therefore, there is a high probability that the preconditions of the system will change and the flexibility options will be required (Dyer 2005). As a result taking more risk creates higher benefits of flexibility.

- in real option analysis, not only the avoidance of detrimental risks but also the beneficial potentials of uncertain future developments are considered. According to (de Neufville 2004), the recognition that future alterations offer chances is key. This is an important change of perception compared to the conventional approach of risk management, which focus on the downside effects of uncertainty.

- flexibility is considered as an optimisation task (de Neufville 2000). Too much flexibility could cause problems like excessive costs for the development and management of the infrastructure whereas less flexibility could cause problems for the adaptation to uncertain future drivers. Hence both extremes have to be avoided and an optimum of flexibility has to be developed.

In real option analysis, the basis for the approach for the assessment of financial options is transferred to the analysis of real physical options. Hence, according to (de Neufville 2004) options analysis holds the promise of enabling the calculation of the value of flexibility. Financial options are the right, but not an obligation, to buy a service at a particular point of time for a price agreed beforehand. Financial options are assesssed by comparison of the option with an alternative, but comparable, investment traded on efficient stock markets. The future performance of the alternative investment is assessed and provides an indication of the worth of the option. The worth of the option is used as a flexibility metric. Real option analysis is applied in the field of engineering science. Several applications are listed by (de Neufville et al. 2006) and (Engel et al. 2006) but no implementations for urban drainage systems are known so far.

In general, options analysis enables the measurement of flexibility. However, there are also limitations to real option analysis. (de Neufville 2004) and (Schierenbeck et al. 2008) list several problems assocoiated with the transfer of the approach from business management to engineering science. The financial analysis assumes that the options are traded in efficient markets with complete information and historical statistics. However, for engineering systems neither profound historical data (in particular for uncertain future drivers) nor efficient

markets exist. There are practical problems for the development of appropriate alternative investments for engineering systems. In addition, (de Neufville et al. 2006) mention the difference, that financial options analysis is primarily interested in the value of the option from the perspective of buying or trading it, whereas the real option analysis is interested in the value of the options as the benefit compared to available rigid alternatives.

Real option analysis in the narrow sense of the word focuses on the economic characteristics of flexibility and does not consider the other attributes mentioned in the definition. Furthermore, it is debatable if the focus of option analysis on the trading value of flexibility is suitable for the measurement of flexibility. The costs and benefits of flexibility seem more suitable for the measurement of flexibility. In addition, the practical implementation of the real option analysis has several problems. There are doubts if the real options analysis, in the narrow sense of the term, can be transferred to the field of urban drainage system. Nevertheless, the real option analysis is a valuable theoretical approach, which offers basic ideas for the measurement of flexibility.

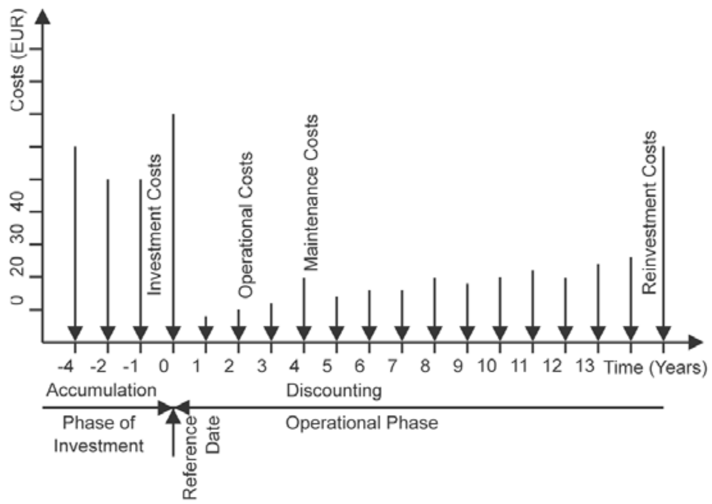


Figure 26: Cost Line 'Life-Cycle Costs'

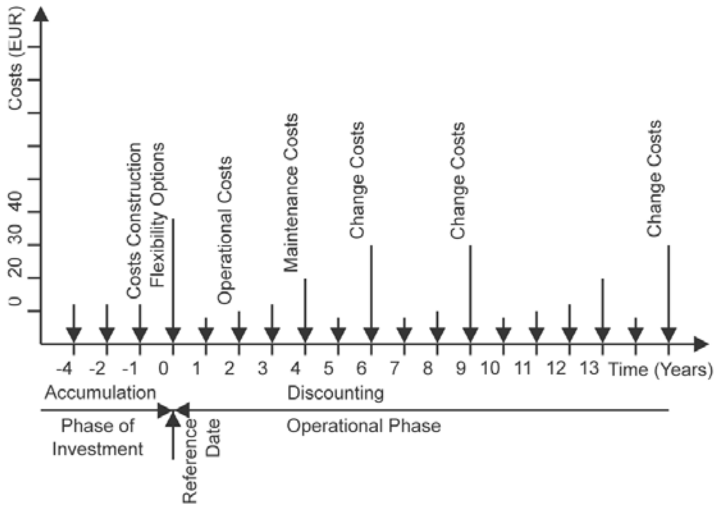


Figure 27: Cost Line 'Costs and Benefits of Flexibility'

3.4.3 Flexibility Measurement Based on Decision Analysis

Several methods for the measurement of flexibility are based on an approach developed in decision analysis to compare the system performance of alternative solutions for different possible future states. The starting point of this approach is the development of several alternative designs of a system, which represent the available flexibility options at the beginning of the planning process. Furthermore, different future states of the system are considered. The future states represent the uncertain future drivers and alternating basic conditions. The performance of the alternative solutions is ascertained for the different future states. The flexibility is assessed by comparing the system performance for different future states of the different alternative designs of the system. This basic approach for the measurement of flexibility is varied for different measurement procedures as well as for different flexibility metrics.

(de Neuville et al. 2008) term these measurement methods as 'Decision-Tree Methods'. It is possible to illustrate the comparison between different future states and alternative solutions by means of a decision tree (Figures 28 – 30). A decision tree is an approach used in decision analysis, which illustrates the available decisions, possible future states, and the probability of these future states (Laux 2005) or (de Neufville et al. 2008). The decision situation is represented by a tree like structure with nodes and connections. There are three types of nodes in decision tree:

- decision nodes

- chance nodes and
- value nodes.

The decision nodes represent the several possible decisions available at a particular point of time. The branches starting from the decision node are the available capacity to act (flexibility options). The capacity to act could be connected with two types of uncertainties. On the one hand, the consequences of an action are deterministic so that the branch leads from a decision node directly to a value node. On the other hand, the consequences of the decision could be uncertain, so that the branch leads from the decision node to a chance node. The branches of the chance node represent the probability that a particular future state occurs. At the end of the ‘chance branches’ there are value nodes. The entirety of the value nodes represents all possible combinations of decision alternatives and possible future states. For the measurement of flexibility, at least a two-staged decision tree is required. The available flexibility options are represented as branches of the decision node. The chance nodes represent the possible future states. The value nodes illustrate the system performance for all possible combinations of flexibility options and future states.

Homogeneity System Performance

Koste et al. (1999) and Upton (1994) use the homogeneity of the system performance for different future states as one characteristic to define flexibility (compare figure 28). The average value as well as the value of the homogeneity of performance for different future states is calculated. Alternative solutions with a high homogeneity for different future states are required. The premise is that alternative solutions with a high homogeneity are not fixed to a particular future state. The homogeneity indicates the appropriateness of the alternative solutions for different future states and uncertainties. When the possibility to change the system during operation is considered, the measured homogeneity represents the characteristic flexibility (Koste et al. 1999), (Upton 1994). When no changes to the system during operation are considered, the metric then represents the robustness of a system. According to (Kühn 1989) a high robustness indicates, that with a high probability an acceptable system performance is achieved without taking changes into regard.

A comparable approach was developed by (Helm 2007) see also (Sieker et al. 2008) for the measurement of the flexibility of urban drainage systems. For the measurement of flexibility a metric called 'external homogeneity' is considered. The 'external homogeneity' is defined as the standard deviation of the performance for the different future states and different alternative solutions. For the measurement of performance, the ability of the system to adapt to

future alterations is considered. As a final calculation, the homogeneity of performance is combined with the mean total performance leading to a multi-dimensional, multi-variant degree of target achievement. This value is interpreted as equating to the flexibility of the alternative solutions.

The approach is a pragmatic method for the measurement of flexibility or robustness. The metric of homogeneity of the system performance is deduced from the definition of flexibility. But this metric only represents one characteristic mentioned in the definition of flexibility (the system performance) and neglects other characteristics like cost of change, duration of change etc. Hence, when the metric is used independently, the definition of flexibility is only partly represented. However, in combination with other characteristics of flexibility the homogeneity of the system performance can serve as a metric for flexibility.

Minimax-Regret-Principle

The minimax-regret-principle (also called Savage-Kneepans-Principle) is, in addition to the minima and the maxima principle, a basic principle of decision theory for decisions made under uncertainty. The system performance under uncertain future states has to be aggregated and assessed based on what is called in decision theory 'the regret of the system performance'. The regret of an alternative is the difference between the actual benefit and the benefit that would have been obtained if a different alternative were chosen. Hence (Loomes et al. 1982) and (Katzenberger 2004) recommend the minimax-regret-principle as a criterion for the valuation of flexibility.

The performance of the systems for different alternative solutions and different future states has to be modelled. The alternatives are not assessed according to their immediate performance but the differences between the performance of the assessed alternative and the maximal possible performance if another alternative is chosen are considered. The regret of an alternative is the difference between the actual benefit for different future states and the benefit that would have been obtained if a different alternative were chosen. The alternative solution is choose, which minimises the disadvantage and with it the regret for all considered possible future states (Eisenführ et al. 2003). If during the measurement of performance, the implementation of change measures are considered, the flexibility of the system is measured. On the contrary, when no change measures (flexibility options) are considered the metric represents the robustness of a system.

The advantage of the regret approach is, that no probability of the uncertain future development is required for calculation. The disadvantage of the approach is, that the uniformity of

the regret for different future states is not considered. Furthermore, the metric only represents one characteristic of the definition of flexibility, which is the performance. In combination with other characteristics of flexibility the regret of the system performance can serve as a metric for flexibility.

The Amount of Alternative Actions

A simple method for the measurement of flexibility is using the amount of alternative actions as metrics. The method is based on the definition of flexibility from (Schlüchtermann 1995) as *'Flexibilität ist die Zahl der Alternativen die verbleiben, wenn eine bestimmte Entscheidung getroffen worden ist' 'Flexibility is the number of alternatives which remain, after a particular decision is chosen'*. To measure flexibility the extent of alternative actions of all alternative solutions are assessed for different future states. To develop a comparable value of flexibility the number of alternative actions for one alternative solution are compared with the total amount of possible alternative actions for all alternatives of the system. A decision tree can illustrate this measurement method (see Figure 29). The amount of alternative actions is the number value nodes. This measurement approach is frequently discussed in the field of business management. Documented implementations for urban drainage systems are not known.

There are two variations to the basic approach. In the simple variation, all alternative actions are counted. (Schlüchtermann 1995) and (Kühn 1989) criticise the fact that all alternative actions are considered even if they do not contribute to the adaptation or relevant changes for the improvement of the system. This criticism leads to the development of a second variation of the measurement approach. In this variation (Schlüchtermann 1995) not all alternative actions but only those, which contribute to the performance of the system, are considered. The number of these target oriented alternative actions for one alternative solution are compared with the amount of target orientated alternative actions for the whole system. Targets for the aspired minimum performance substantiate the characteristic 'target orientation'. Several other characteristics of flexibility like the duration of change, the costs of change etc. could be considered by these pre-requirements. However, (Kühn 1989) expresses methodical reservations, because there is no defined method for the development of the pre-requirements so that the selection is arbitrary.

The advantage of this approach is the catchy definition and the simple evaluation procedure to describe the range of change. However, there are practical problems to determine the number of available alternative actions. In a real world decision situation, a nearly unlimited

number of different action alternatives could be developed. Furthermore, in the measurement approach several characteristics of flexibility like the uniformity of performance or the effort of change are not considered.

Level of Target Achievement

The achievement of the system objectives for different future states is used as a metric for the measurement of flexibility, The system objectives are the performance of the system e.g. measured by a value of benefit, the profit of a system etc. In the procedure for measurement, the flexibility of an alternative solution is assessed in comparison with the hypothetical optimum (perfect flexibility) as well as the poorest solution (total inflexibility). In the technical literature, different versions of this approach are discussed. In the following sections the methodologically sound approach of (Kühn 1989) see also (Schneeweiß et al. 1990) is presented.

The flexibility is measured by comparing realised, optimal and minimal flexibility:

Flexibility = (realised flexibility – minimal flexibility)/(optimal flexibility – minimal flexibility).

The different parameters are defined as follows:

- The realised flexibility is the performance of an alternative solution for different future states. The value of the realised flexibility is not more than the optimal and not less than the minimal flexibility, in practice mostly between the both extremes. In a decision tree, this is the average value of an alternative solution for all possible future states (see Figure 8).
- The minimal flexibility is also termed as a zero alternative. (Kühn 1989) defines the minimal flexibility as the performance of a totally rigid system when after the initial decision no additional changes to the system are possible. In a decision tree this is illustrated as a direct link from a decision to a value node (see Figure 30).
- The optimal flexibility is also termed total flexibility or prophetical planning. (Kühn 1989) defines optimal flexibility as the performance, which can be achieved when a prophetic decision maker is able to adapt decisions to all future developments. Another definition is to choose the best possible decisions out of the occurrence of developments if at the end all decisions can be revised. Illustrated in a decision tree, this is the

situation where for the different future states always the alternative solution with the best performance is chosen (see Figure 30). As a result, for all possible combinations of future states always the best performance is achieved.

A comparison between the different extreme values has two functions. It enables the scaling of the realised flexibility on a value between zero and one. A solution without any flexibility has the value zero whereas one that can be adapted to all possible future states with the best performance is assigned a flexibility of one. Thereby the flexibility of different alternative solutions and different systems can be compared. The comparison also offers a systematic method for the development of different alternative solutions based on flexibility options. Thus, the alternative solution of minimal flexibility is explicitly developed without any flexibility options, whereas the alternative solution of total flexibility includes the best possible combination of flexibility options.

The measurement approach follows the definition of flexibility from (Kühn 1989) as a target-orientated changeability. The measurement approach is focused on the objectives of the system. Also the 'capacity to act', the possibility to respond to relevant alterations is represented by the measurement method. The capacity to act is compared for different alternative solutions and future states. However, the implementation of the approach is associated with several problems. (Hocke 2004) and (Pibernik 2001) mention two problems associated with the definition of optimal as well as minimal flexibility. The details of both definitions are vague and it is not possible to anticipate the determination of the value of the parameters. Only in retrospect can the value of the parameters be specified. In addition, there are problems with the definition of the considered performance parameters. (Schneeweiß et al. 1990) identify two requirements for the parameters. The parameter needs to represent the quality of the system performance but the parameter should also be measurable with a cardinal scale. However, these requirements do not offer guiding principles for the consideration of characteristics of change such as those for the overcoming of alternations or the effort for change. Hence, (Hocke 2004) criticises the method for not considering systematically the essential characteristics of the definition of flexibility. Finally, (Pibernik 2001) criticises the relationship between the performance of the system and the flexibility parameters for not being consistent. Therefore, the flexibility parameters are not defined independently from the other parameters of the system performance. As a consequence, there is the danger that the performance of the system is considered in the decision process twice. Firstly the system performance is considered directly as a value of benefit and secondly the performance is considered indirectly as part of the flexibility of the system. According to (Pibernik 2001) the consequence is that the measurement of flexibility does not offer any new information for the decision analysis.

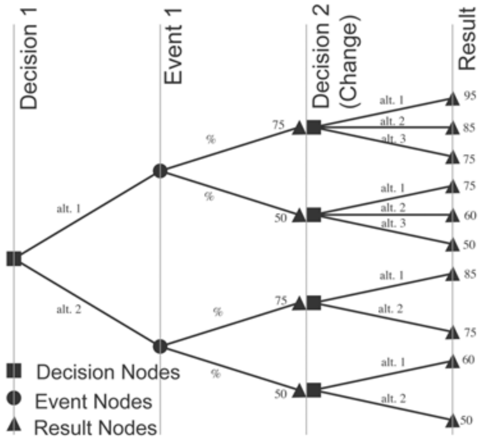


Figure 28: Decision Tree 'Homogeneity or Regret System Performance'

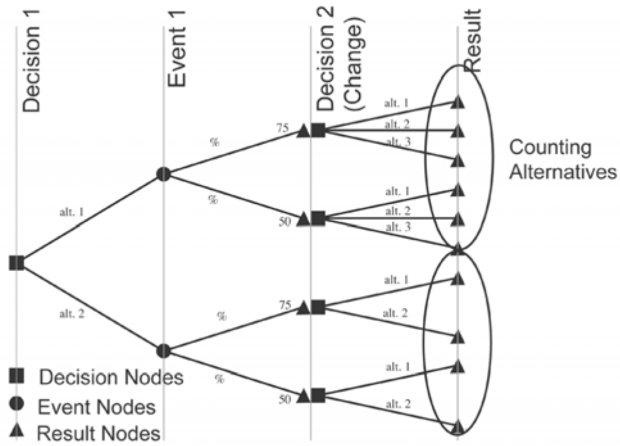


Figure 29: Decision Tree 'Amount of Alternative Actions'

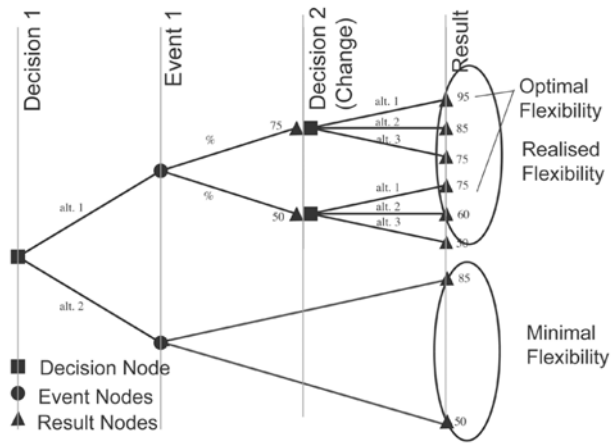


Figure 30: Decision Tree 'Level of Target Achievement'

3.4.4 Flexibility Measurement Based on System Analysis

Several methods for the measurement of flexibility are based on the general theory of systems analysis. In business management several flexibility concepts utilise general systems analysis or special applications such as the concept of 'Complex Adaptative Systems' (Gell-Mann 1995), (Hocke 2004). In engineering science, systems analysis is used to improve the general performance as well as the flexibility of systems (de Neufville 2000), (Nilchiani et al. 2007). A common aspect of the methods is, that the metrics used for the measurement of flexibility are deduced by means of systems analysis. To solve this problem a systematic deduction of the criteria based on systems analysis is proposed. For the implementation of systematic flexibility metrics, different measurement methods are used. The different measurement methods are presented below.

Dimensions of Flexibility

(Hocke 2004) see also (Hocke et al. 2006) developed an approach for the measurement of flexibility, which systematically considers the different characteristics of flexibility. The method is based on the measurement of different characteristics of flexibility (Hocke 2004 uses the term dimensions), which are deduced from a systematic analysis of the definition of flexibility. To comprehend the derivation of the dimensions of flexibility, two essential sources are presented, before the method of (Hocke 2004) is described.

(Upton 1994) deduces the characteristics of flexibility based on his definition as *'the ability to change or react with little penalty in time, effort, cost or performance'*. The first characteristics identify the 'ability to change' part of the definition whereas both the other characteristics emphasise the 'little penalty in time, effort, cost or performance'.

- Range: This characteristic represents the ability to affect a large range on the dimension of change of the flexibility option. This range can be represented as the number of viable positions within the range or as the distance between the extremes of the range.
- Mobility: This characteristic is the ability to provide mobility within the dimension of change. The transition penalties for moving (time or costs of change) are described.
- Uniformity: This characteristic is the uniformity of the system performance, within the range of the dimension of change. The characteristic represents the 'indifference' where within the range the system is operating.

(Koste et al. 1999) developed four characteristics of flexibility based on an analysis of the technical literature. These characteristics serve as basis for the analysis of flexibility.

- Range-number: This characteristic represents the number of different alternative actions, which can be reached by a given flexibility option. The indicator is the number of action alternatives of a system alternative.
- Range-heterogeneity: This characteristic describes the range of the alternative actions, which can be achieved by a flexibility option. The characteristic is focused on the heterogeneity and differences of future alterations, which can be handled by a flexibility option. As an indicator the heterogeneity of the system performance of a flexibility option is considered.
- Mobility: This characteristic indicates the ease of change to move from one state to another. As an indicator the constraints of the change like the costs or duration of change are considered.
- Uniformity: This characteristic describes the uniformity or heterogeneity of the system performance of a flexibility option for different future states. As an indicator the similarity of system performance for different future states is considered.

Based on the sources and on the definition of flexibility as *'the ability of a socio-technical system, to adapt itselveto target-orientated, based on their scope of operation on relevant system external as well as system internal induced changes, which can imply chances as well as risks.'* (Hocke 2004) developed a method for the measurement of flexibility. The following characteristics of flexibility are considered (see Figure 31):

- Range: This characteristic represents the ability to react to relevant alterations of the basic conditions. The indicator is the range of future states, which can be handled by a flexibility option.
- Mobility: The constraints for the change of the systems like the costs and duration of change are considered by this characteristic. The costs of change are expenses, which can be allocated to the change process. The duration of change is the period between the recognition of altering basic conditions and the successful implementation of flexibility options.
- Uniformity: This characteristic represents the performance of a system for different future states. The performance of the whole operational life span of the system is ana-

lysed, considering different future states as well as the implementation of flexibility options.

- Provision Cost: The costs for the construction of the flexibility options (which can be used later) are considered independently because these expenses do not arise directly from the change process. Nevertheless, this characteristic is required for the comparison of different flexibility options.

In the measurement method of (Hocke 2004) these characteristics of flexibility are ascertained, aggregated and assessed step by step. Different approaches for the aggregation of the single characteristics can be used, so that the method could be customized to specific requirements. The measurement method is based on comparing the system performance for different alternative solutions and several future states, an approach already described above.

- The different characteristics of flexibility are ascertained individually. When for a characteristic of flexibility several values exist, they are summarised to one value per future state and alternative solution.

- The different characteristics of flexibility, mobility, cost of providing, and uniformity are summarized into one value per future state and alternative solution. The value represents all characteristics of flexibility. Only the characteristic 'range' is considered separately. If the ability to react to future alterations does not exist, the alternative solution is not flexible and the other characteristics could not be ascertained.

- The value representing all characteristics of flexibility is summarized for the different future states to one value per alternative solution. Therefore, it is required to consider the probability of the different future states. Different approaches can be used to develop the probability of uncertain future states. (Hocke 2004) recommends using the Laplace principle where every future state has the same probability of occurrence. Thereby the decision under uncertainty is transferred to decisions with probalistic risk.

- Finally, a normalized value of flexibility for the different alternative solutions is ascertained. The approach of comparing the realized, optimal and minimal flexibility already described above is used. The realised flexibility of an alternative solution is represented by the value developed in the step before. The optimal and minimal flexibility have to be ascertained independently.

(Hocke 2004) combines in his approach elements from different measurement approaches of flexibility with a systematic derivation of the considered characteristics of flexibility. The

characteristic 'range' represents the amount of alternative actions adopted from the measurement approach already described above. The characteristic 'uniformity' considers the homogeneity of the system performance for different future states presented above. The characteristic 'mobility' considers the effort of change like the costs of change already mentioned in economic measurement methods. Hence, the single characteristics of the method of (Hocke 2004) are based on already existing approaches. The feature of this method for the measurement of flexibility is the reasonable combination of the different characteristics so that the problems with the derivation of suitable criteria for the measurement of flexibility can be solved. The measurement method considers all characteristics of flexibility mentioned in the definition.

Sustainability Criteria

In the field of urban drainage systems, different approaches for the measurement of flexibility based on a systematic derivation of the criteria of flexibility are presented. The approaches are developed within the discussion about the sustainability of urban drainage systems.

(Sundberg et al. 2004) develop an approach for the measurement of flexibility based on the ideas of (Bossel 1999). A comparable approach was developed by (Engel et al. 2006). The approach focuses on the measurement of sustainability of urban drainage systems. Their definition of sustainability is *'sustainable systems are characterized by their potential to survive over time, with their potential to deal with diverse conditions as well as to respond and adapt on short-term and long-term contextual changes'* including the aspect of flexibility. Hence, this approach is of interest for the measurement of flexibility. (Sundberg et al. 2004) substantiate the following characteristics and static indicators for sustainable urban drainage systems.

- Existence: The urban drainage system has to prove itself in the normal conditions of the environment. The Indicator is the renewal and degradation rate.
- Effectivity: The urban drainage system has to protect and conserve the resources from the environment, which are required to ensure their viability. As indicators the investment costs, work hours for operation and energy consumption are used.
- Freedom of action: To facilitate the reaction of different future developments the urban drainage system should have a capacity to act. As indicators, the different sources of separate storm water (not combined sewage) are considered.

- Security: The urban drainage system should have the possibility to respond to normal fluctuations of the basic conditions. The indicator is the number of unplanned reparation measures.

- Adaptability: Urban drainage systems should have the possibility to respond to fundamental and comprehensive changes to the environment. Two indicators are proposed for the ability; the sensitivity to an altering population density and the flexibility of the management structure.

- Coexistence: The urban drainage system has to exist together with other superior systems, sub-systems or parallel systems.

The method facilitates the derivation of indicators for the measurement of sustainability. However, the criterion flexibility is only considered in a simplified form. Firstly, the measurement procedure is based on simple static indicators, which do not consider the future uncertainties sufficiently. Secondly, flexibility is only considered as one criterion besides others. The other categories are not relevant for the measurement of flexibility.

Another measurement approach for the flexibility of urban drainage systems has been developed from the work done by (Sieker et al. 2007a). The method for the assessment of the ecological and economical characteristics of sustainable urban drainage systems is based on the derivation of the costs-benefit-analysis, which considers also non economical values. To guarantee that the indicators are not chosen arbitrarily they are derived based on systems analysis. As one dimension of sustainability, the changeability of the system is considered and is substantiated by the following characteristics:

- Flexibility - variety of elements: For sustainable urban drainage systems a variety of different management elements are available. These varieties of elements facilitate the customisation of urban drainage systems for local requirements. The indicator is the variety of available elements.

- Flexibility - constructional changes: Subsequent changes of existing urban drainage systems are expensive but because of the uncertain and changing basic conditions, it is not possible to avoid such subsequent changes to the system. As an indicator, the duration of change and the possibility to prepare change measurement during the normal operation are considered.

- Flexibility - failures: The failure of the system should be prevented. Because of additional objectives like resource efficiency and the over-dimensioning of the system

should be avoided. As an indicator the extent of performance loss and possible damage are used.

- Flexibility – environmental alterations: The urban drainage systems should be flexible against alterations to the system environment. Therefore, the consequential costs of changes should be minimised. The indicator is the ability of the system to adapt to alterations with low costs and little impairment of performance.

- Fault tolerance: The reaction of urban drainage systems to unforeseeable events is considered. Occurring defects should be remedied without affecting the system performance. The indicator is the degree to which the performance of the system is affected.

- Flexibility - employment of staff: Also, the flexibility for staff employment is considered. The absence of single persons should not affect the performance of the system. The indicator is the ability to replace staff.

In the assessment approach described by (Sieker et al. 2007a) in addition to flexibility other criteria for the sustainability of urban drainage systems are considered such as the efficiency of the energy and resource consumption or the objectives of flood protection and water pollution control. For all sustainability criteria the average as well as the homogeneity of the benefit value is ascertained. Holistic cost-benefit-analysis results in a multidimensional level of goal achievement as well as the achievement of the economic objectives being calculated. However, the assessment does not consider different future states so that future uncertainties are not presented sufficiently. Therefore, the measurement approach does not represent all characteristics of flexibility.

Change Propagation Method

For the measurement of flexibility of systems, the change propagation method of (Eckert et al. 2004) and (Clarkson et al. 2001) can be used. According to (Eckert et al. 2004) the basic assumption of this method is, that in a complex system with close interactions between the different elements, a change to one element (caused by future alterations) is highly likely to result in changes to other elements, which in turn can propagate the change further. The consequence of this kind of change propagation is that a simple change in one element may have consequences elsewhere in the system incurring significant cost. The method developed by (Eckert et al. 2004) to predict the change propagation in systems, can also be used for the measurement of flexibility.

The change propagation method considers two metrics i.e. the probability of occurrence and the impact of change (Clarkson et al. 2001). Probability is defined as the average likelihood that a change of one element will lead to a change in another element by propagation across its interfaces. The impact of change, in particular the costs of change, are considered. The consequences of change are analysed for each single element of the system.

The procedure of the change propagation method proposed by (Clarkson et al. 2001) is presented below. The approach is a combination of design structure matrix analysis and risk management techniques. The interconnectivity of the elements for a particular system structure are illustrated in dependency matrices of the system (Clarkson et al. 2001). Based on the dependency matrices it could be analysed how the change in one element caused by uncertain future drivers results in the change of other elements considering direct as well as the indirect propagated changes. (Eckert et al. 2004) identify four categories of change propagation behaviour (see Figure 32):

- Constant: The constant elements remain totally unaffected by the change in the system. These elements neither absorb other changes nor cause changes themselves.
- Absorbers: The absorber elements absorb more changes than they cause. Some elements are even total absorbers, which can absorb all changes without causing further consequences.
- Carriers: The same number of changes affect the carrier elements as they affect changes of other elements. Therefore, carrier elements absorb a similar number of changes as they cause.
- Multipliers: Multiplier elements are affected by less change than they affect themselves. As a consequence, multiplier elements generate more change than they absorb.

The change propagation behaviour of a system is not a static characteristic. On the contrary, a change absorber can easily transform to a change multiplier if the particular change is too big to be absorbed by the specific tolerance margin. Hence (Eckert et al. 2004) recommend a system design, which is not optimal for the present conditions, but includes tolerance margins to cope with future alterations. Therefore buffer elements should be considered, which can absorb a certain degree of change. The objective of the buffer elements is to prevent the transformation of absorber elements to multiplier elements (Eckert et al. 2004). The aspired performance of the buffer elements can be guaranteed by rigid tolerance margins as well as by flexibility options.

As a result the change propagation method illustrates the risk, that the change of one element propagates in the systems and affects the change of other elements. The risk can be used as a metric for the flexibility or robustness of the system, dependent on whether flexibility options are considered or not. The measurement method considers two characteristics mentioned in the definition of flexibility; the range of change and the costs of change. A detailed measurement of the homogeneity of performance is missing. The feature of this method is the consideration of the system specific characteristics of change propagation.

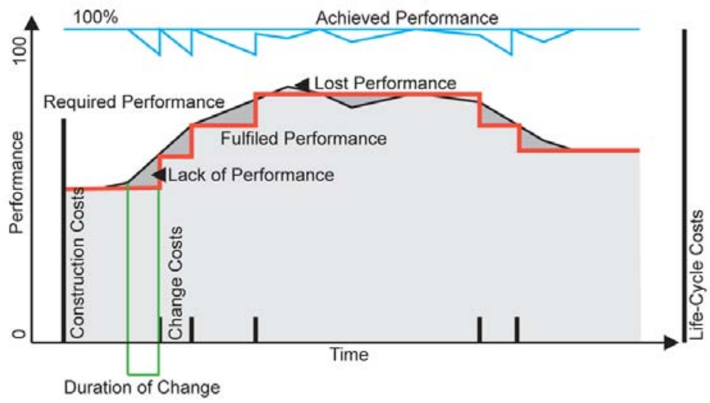


Figure 31: Time / Performance Diagram 'Dimensions of Flexibility'

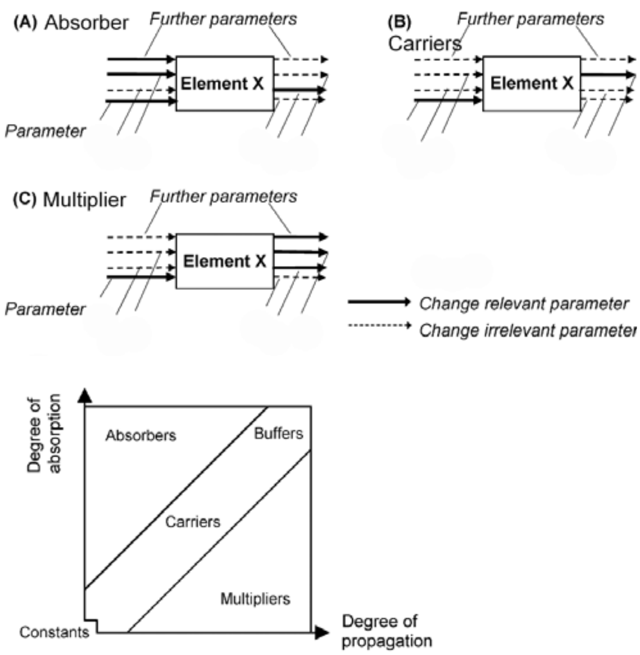


Figure 32: Type of Change Propagation (Eckert et al. 2004)

3.4.5 Flexibility Measurement based on Simulation Methods

In the technical literature several simulation methods for the optimization of flexibility are presented (Silver et al. 2007), (Engel et al. 2006), (de Neufville et al. 2006) and (de Neufville et al. 2008). The methods serve to optimise the flexibility of systems. However, the simulation methods for optimization could also be used as a framework for the measurement of flexibility.

According to (Diwekar 2000) optimization is an approach applied in system structural decision-making especially in situations, which are characterised by several simultaneous events and constraints to various factors. The goal of optimization is to ascertain the value of the decision variable used to optimize the objective function, while ensuring the system operates within established limits described and specified by constraints. According to (de Neufville et al. 2006) the optimization of flexibility of engineering systems requires a three-step framework. Within this generic framework, modules from different optimization approaches are presented.

- In the first step, the key sources of uncertainty have to be identified and a limited number of future states have to be developed. The essential drivers for future uncertainties are identified. Different methods are available. Simplistic approaches used by (de Neufville et al. 2006) consider several future scenarios developed by a manual scenario building process. Other approaches use mathematical algorithms to consider uncertain future developments. These include the Monte Carlo algorithm (de Neufville et al. 2008) or the geometric Brownian Motion algorithm (Silver et al. 2007). These mathematical simulation algorithms enable the consideration of a large number of possible future developments.

- In the second step, the different alternative solutions are analysed for the future states. During the design of a system, numerous combinations of alternative solutions and the different future states are possible. From this set of solution possibilities the optimal solution has to be calculated in respect to the optimization function. Hence, the optimisation method should consider all possible solutions or at least develop a set of possible solutions, which includes the most promising solutions. However, even for simple problems the number of possible solutions can make manual optimisation approaches unfeasible. Hence automatic simulation methods to generate a promising set of possible solutions have been developed. Two approaches are possible. Genetic algorithms, which are a search-optimization procedure that is based on the idea of natural selection and genetics, is one possible approach. It is already applied in different fields of urban

water management (Diogo et al. 2000) and (Maharjan et al. 2009). By different random mutation and combination of alternative solutions and the selection of the best solutions the performance of the system is improved step by step. As a result of the genetic algorithm an optimal solution is developed. According to (de Neufville et al. 2008), in the genetic algorithm approach it is not possible to verify whether the absolute optimum or only a local optimum is achieved. (Silver et al. 2007) have developed an algorithm for the identification of optimal solutions called 'Time-Expanded Decision Networks'. The different future states and solution possibilities are converted step by step in a mathematical network problem, which is solved mathematically. In both approaches, the effect of the different combinations of solution possibilities and future states is modelled. Hence, the existing effect models of urban drainage systems like hydraulic models or pollution models have to be modified.

- In the third step, an optimal initial design of the system is selected according to the optimisation function. The optimisation function consists of criteria, which should be maximised or minimised and associated constraints. For the optimisation of the flexibility metrics such as life-cycle-costs, change costs or performance criteria are used (Silver et al. 2007) and (de Neufville et al. 2006). The criteria correspond with the metrics used in other measurement methods already mentioned above.

As mentioned above the simulation methods serve to enable the optimisation of the flexibility of system. The simulation methods could also be used for the measurement of flexibility. So the simulation algorithms for optimisation are similar to the already presented approach of comparing different future states and alternative solutions. By using mathematical simulation algorithms, more complex decisions could be considered than with the manual approach of decision analysis. For the measurement of flexibility, the simulation methods have to be modified:

- When the flexibility of a particular alternative solution is to be assessed, it is necessary to ascertain both the value for the optimal solution as well as the value for the assessed solution. The use of automatic simulation algorithms facilitates a work saving calculation of the value of flexibility.

- The optimization algorithm supports the determination of a scaled value of flexibility. The flexibility value of the optimal solution can be compared with the value of the realised flexibility of the alternative solution. The already presented approach for the comparison of optimal, minimal and realised flexibility can be used. As a result, flexibility

is scaled on a value between zero and one. But the limitations of the optimization algorithms have to be considered.

The measurement methods for flexibility, which are based on simulation methods, consider all steps of the framework for the planning and management of flexibility. So different future states are considered and the flexibility of different alternative solutions are compared with each other. The different characteristics of flexibility mentioned in the definition can be considered in the optimization function. Because of the mathematical simulation algorithm the measurement method can also be applied to tasks, which are characterised by a large number of possible future states and alternative solutions. Once created the simulation algorithm facilitates an easy and quick measurement of flexibility. However, the creation of simulation algorithms is associated with a high degree of effort. The algorithm has to be customized for the special application case by considering the type of systems as well as the different flexibility options. For the definitive assessment of the flexibility of urban drainage systems such simulation algorithms are not currently available. The implementation of automised algorithms for urban drainage systems is difficult because a huge number of different performance indicators as well as a combination of quantitative and qualitative indicators need to be considered.

3.4.6 Conclusions Measurement of Flexibility

There are a variety of different generic approaches for the measurement of flexibility, but until now no approach is established as a standard. Different metrics for the measurement of flexibility have been discussed. Established and suitable metrics are, in particular, the range of change (the ability to cope with a large range of future alterations), the uniformity (the homogeneity of the system performance, within the range of alterations) and the mobility (the transition penalties for change like duration or costs of change). These metrics have a close association with the characteristics of flexibility mentioned in the definition. The procedures behind most measurement approaches are based on the comparisons of the performance of the metrics for different future states and different alternative solutions. Flexibility is therefore a relative characteristic, which can only be presented by a comparison between different alternative solutions for a system. There are several variants of this basic procedure considering different goals such as the calculation of absolute metrics or a work saving automised measurement of flexibility. The selection of the detailed metrics and the particular measurement procedure depend on the aspired application of the measurement method.

For urban drainage systems, different methods for the measurement of flexibility have been developed, such as static indicators, scenario tree methods or economic analysis. However, the methods to measure the flexibility of urban drainage systems face problems, which have been solved in other disciplines. The most criteria for the measurement of flexibility are derived unsystematically without considering the characteristics of flexibility. These weaknesses of the present methods could be eliminated, if confident approaches for the measurement of flexibility were used. Until now the measurement methods for flexibility in the field of urban drainage do not make use of the well established theoretical background already existing in other disciplines.

3.5 Application of the COFAS Tool

The objective of the COFAS tool is to aid decision support when designing urban drainage systems. Depending on the specific basic conditions of the decision situation, different decision criteria are used. In the following section, brief guidance is offered on decision criteria that are suitable for different basic conditions.

- Efficiency / Effectivity: This decision criteria can be used, when comparing the performance of alternative solutions, where no future uncertainties exist. However, for most decision situations involving urban drainage systems, relevant future uncertainties (e.g. climate change or spatial development) have to be considered. Only in a few situations involving urban drainage systems for very small catchments areas and for facilities with short average life spans can these future uncertainties be neglected. When no future uncertainties exist the COFAS tool can be used for a multidimensional assessment of the performance of alternative solutions.

- Flexibility: When the urban drainage system is affected by future uncertainties, the decision criterion flexibility should be used. This decision criterion is suitable for most urban drainage systems and is considered as a normal case. The COFAS tool supports the measurement of flexibility.

In the following section two approaches for the measurement of flexibility are presented. Which of these approaches is chosen, depends on the requirements of the decision situation and, in particular, the amount of work and the required accuracy of the measurement.

- A pragmatic approach for the measurement of flexibility, which could be performed with a limited amount of effort, is measurement by means of static indicators. For this measurement the indicator 'homogeneity of performance' is recommended, because it is based on a theoretical foundation. This indicator describes a single static characteristic of the system neglecting different future states, so that it could be ascertained with limited effort. The COFAS tool described in chapter 2 supports the determination and assessment of the indicator 'homogeneity of performance'. However, there are also limitations to the use of static indicators. (Jacob 1989) and (Pibernik 2001) have criticised the fact that the static indicators do not offer a direct coherence with flexibility. Because of the static approach an essential characteristic of the framework for planning and management of flexibility, the dynamic future development is not considered. The approach is a simple and pragmatic approach for the measurement of flexibility with limited ef-

fort. A detailed application of the approach is described in chapter 2. It is in particular suitable for project assessment in real world planning situations but in the interpretation of the results the limitations of the approach have to be considered.

- For a comprehensive more detailed measurement of flexibility, a second approach exists which is based on the comparison of the systems performance with respect to different future states and system alternatives. As a metric to describe flexibility, the capability to change the system, the performance of the system, the costs of changing the system and the duration of change are considered. The approach enables a precise description of the different characteristics mentioned in the definition of flexibility. In the following section, a customized framework for the measurement of flexibility for urban drainage systems is presented. The COFAS tool supports parts of the framework. However, the approach of considering different future scenarios requires a significant higher amount of work than the use of static indicators and the required work multiplies with every future scenario considered. Because of the large amount of work required for the measurement of flexibility, this approach is mainly suitable for scientific purposes.

3.5.1 Measurement of Flexibility in COFAS

In COFAS the indicator 'homogeneity of performance' is used for the measurement of flexibility. This indicator is based on the theoretical assumption, that the higher the homogeneity of system performance of different indicators, the higher the flexibility. It represents the variety of performance of a system to react to altering requirements within the existing scope of operation. So unspecialised and multi purpose technical infrastructure systems offer a high flexibility and robustness against future uncertainties.

The flexibility is measured in two steps. Firstly, a regular value of benefit analysis is performed. The objectives, related indicators and utility functions of the urban drainage system are determined and weighting factors are defined in the COFAS tool. The performance of the indicators is ascertained by external modelling of the effects of the urban drainage system. Then the value of benefit for the single objectives as well as the weighted average value of benefit for each alternative solution is calculated by the COFAS tool.

Secondly, besides the average value of benefit, also the homogeneity of the value of benefit for the different objectives is calculated for each alternative. The homogeneity is represented by the relative standard deviation for the different values of benefit. The simple standard

deviation is the average square deviation of the single values from the average value. The relative standard deviation is the standard deviation divided by average value of benefit and is calculated by using the equation below:

$$Hom = \begin{cases} 1 - \dfrac{\sigma}{tUV} & where\ \sigma \le tUV \\ 0 & where\ \sigma > tUV \end{cases}$$

$$\sigma = \sqrt{\sum_{i=1}^{n} w_i \left(pUV_i - tUV\right)^2}$$

Hom	Internal homogeneity
tUV	Total utility value (weighted mean of the partial utility values)
pUV	Partial utility value (utility value of one criterion)
σ	Standard deviation of the partial utility values
n	Number of criteria = number of partial utility values
w_i	Weighting factor for criterion i ($\sum_{i=1}^{n} w_i = 1$)
i	Index for partial utility values

The flexibility of single alternative solutions is evaluated in comparison to other alternatives. The higher the homogeneity of an alternative solution, the higher the flexibility. In the CO-FAS tool, the homogeneity can be visualized in a sector diagram where the radius of a sector represents the benefit value while the aperture angle shows the weighting factor of the indicators (Figure 5). The homogeneity is visible by comparing the radius of the different sectors. A detailed documentation of the measurement approach is presented in chapter 2.

3.5.2 Framework for Detailed Measurement of Flexibility

An approach for the detailed measurement of flexibility of urban drainage systems is presented below. The COFAS tool supports a part of the measurement procedure. The metrics of flexibility as well as the measurement procedure are illustrated.

The criteria for the measurement of flexibility are systematically deduced from the definition of flexibility as '... *the ability of (urban drainage) systems, to use their active capacity to act, to respond on relevant alterations in a performance-efficient, timely and cost-effective way.'*

Based on this definition the metrics 'capability of change', 'costs of change', 'duration of change' and 'performance of system' are substantiated for urban drainage systems.

- Capability to change: The capability for change indicates for which uncertain future developments a change of the system is possible. A high flexibility is given, when a wide range of future states can be managed by a particular flexibility option. To measure the capability of change the range of uncertain future developments, which can be solved by flexibility options, is recorded.

- Performance of system: The metrics represent the performance of the urban drainage system after altering future conditions. The future alterations as well as the implementation of flexibility options can cause a varying performance during the operational life span of the urban drainage system. The performance of the urban drainage system is described by a multi criteria value of benefit and is ascertained by modelling the effects. There are two possibilities to measure the performance. The homogeneity of the system performance for different future states can be analysed. The advantage of this approach is that the uniformity of the system performance represents a characteristic of flexibility. The disadvantage of the approach is that for the calculation of the homogeneity of performance the probability of the different future states is required. Because most future developments are associated with uncertainty, this probability is not known in advance. Hence, the Laplace-Principle has to be used, that all possible future states have the same probability of occurrence. Alternatively, the system performance for uncertain future states can be aggregated based on the regret of the system performance. The advantage of the regret approach is that no probability of the uncertain future developments is required for calculation. The regret is the difference between the value of benefit of the assessed alternative solution and the maximal possible benefits if other alternatives. In the assessment, for every alternative solution the highest regret for different future states is considered. The disadvantage of the approach is that the uniformity of the regret for different future states is not considered. Both approaches have their advantages and disadvantages therefore depending on the requirements both approaches could be used.

- Costs of change: As a metric for the effort of change, the costs are analysed. Because of the long operational life span of urban drainage systems not only the costs of a single change event but the costs for the several changes in the whole life span of systems should be considered. Hence, the costs of change are represented as part of the whole life-cycle-costs. Besides the general construction and operation cost of the urban drainage system, the costs for construction, maintenance and implementation of the flexibil-

ity options as possible damage costs caused by missing adaptation measures are also analysed.

- Duration of change: As an additional metric describing the effort of change, the duration of the change process is considered. The duration of change is the period, which is required to adapt the system to new requirements. The duration of change includes the observation period, decision period, implementation period, effect period and control period.

Based on the general approaches for the measurement of flexibility, the comparison of different future states and alternative solutions, a generic framework for the measurement of flexibility can be customized for urban drainage systems (Figure 33).

- Preparation: The urban drainage system, for which the flexibility options are to be assessed, has to be defined in respect to the spatial, functional and temporal boundaries of the system. An effect model for the qualitative and quantitative performance of the urban drainage system is developed. Furthermore objectives, indicators and utility functions for the value of benefit analysis are developed.

- Future states: The relevant future drivers for the urban drainage system are ascertained and the range of the possible future developments for the period under review is described. To reduce the effort for calculation, the huge number of possible future states are summarised into three or four meaningful future scenarios.

- Alternative solutions: Flexibility is a relative value of systems, which has to be assessed through the comparison of different alternative solutions. Hence, different alternative solutions for the urban drainage system are generated. For the different alternative solutions, flexibility options have to be generated and already embedded options identified.

- Modelling the effects: For all alternative solutions and different future scenarios the system performance is modelled in time steps. Furthermore, the costs that accrue during the time step (construction costs, operational costs, maintenance costs and adaptation costs) as well as the duration of change are ascertained. For the urban drainage system, minimum performance demands are determined which serve to trigger impulse for the implementation of the flexibility options. When the system performance falls below a trigger level, the flexibility options are implemented. Then for this time step

the modelling of the effects will be repeated with realized flexibility options. The results for the different time steps are documented.

- The first aggregation step: The results of the different time steps are summarised in one result per future scenario for different alternative solutions. As a result the life-cycle-costs and the performance for the whole operational life span are presented. Based on a multi criteria analysis the different performance metrics (e.g. number of combined sewer overflows, number of flooding events etc.) are summarized into one value of benefit. Then the performance values for the different time steps are summarised to one result per future scenario. Therefore, the average values as well as the homogeneity of performance are assessed for the different time steps. As a result, one value of benefit for performance per future scenario is presented for the different alternative solutions. The COFAS tool supports this aggregation step. The life-cycle-costs and duration of time for the different alternative solutions per future scenario are aggregated separately to one value for the effort of change.

- The second aggregation step: The results for the different future scenarios are summarised in one result per alternative solution. The aggregation of the uncertain future scenarios can be based on the regret of the different alternative solutions or the homogeneity of performance for different future states. For every alternative solution, the regret or homogeneity of performance is ascertained. The results for the different performance categories and the effort of change are calculated separately.

- Comparison results: The effort of change as well as the value of system performance is compared for the different system alternatives. The regret or homogeneity for the system performance is compared with the regret or homogeneity of the effort of change. The system alternative with the minimal regret or the highest homogeneity is the more flexible one. In other words the system alternative, which minimises the disadvantage for the different future scenarios, has the highest flexibility.

- Normalized value: If required a normalized value of flexibility can be calculated in an additional aggregation step by comparing the realized, optimal and minimal flexibility based on the method of (Kühn 1989).

3.5.3 Conclusions

Flexible urban drainage systems guarantee, that present decisions do not affect the future capability for change to react to future alterations. Flexibility offers the chance to make the

required decisions for urban drainage systems despite future uncertainties. Hence, it is recommended, to use flexibility as a decision criterion for urban drainage systems. COFAS represents a tool for the measurement of flexibility for urban drainage systems and provides a tool to support the implementation of flexible urban drainage systems.

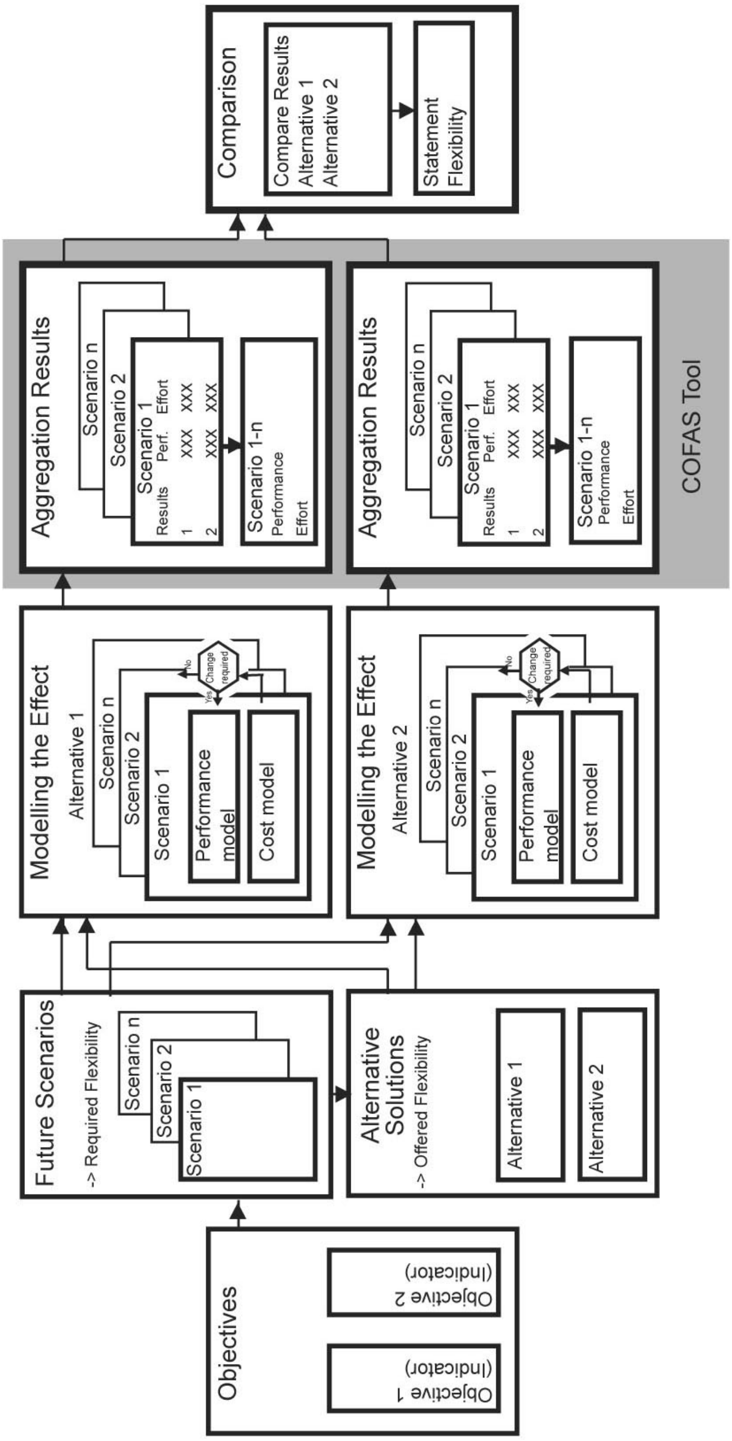


Figure 33: Framework for Detailed Measurement of Flexibility

4 Glossary

Numerous methods are available in the field of multi criteria analysis. Sometimes slight differences between methods are referred to by different names. However, the exact naming of those methods often varies from author to author. This becomes even more confusing when comparing the literature from different languages. In the following glossary, the terms used in this paper are stated and a German translation is given.

English Term	Explanation	German Term
Alternative	Set of measures for an urban drainage system.	(Planungs-) Alternative
Alternatives Alternative solutions	The capacities to act to achieve the system objectives, which can be chosen in the decision situation.	(Planungs-) Alternativen
Adaptability Adaptive flexibility	The ability of a system to be changed in order to deliver the required performance under altering conditions.	Anpassungsfähigkeit
Criterion	Refers to an identified parameter, e.g. COD-load, P-load. Compare objective.	Kriterium
Effectiveness	The proportion between the required performance and the achieved performance of a system (level of goal attainment).	Effektivität

Efficiency	The ability of a system to provide the required performance, relative to the amount of resources used (economy of a system).	Effizienz
External homogeneity (exHom)	Homogeneity of the total utility values of an alternative for different future scenarios	Externe Homogenität
Flexibility	The ability of a system, to use its active capacity to act, to respond to relevant alterations in a performance-efficient, timely and cost-effective way.	Flexibilität
Flexibility option	The ability to modify a system in operation to adapt to future demands by either avoiding detrimental consequences or by exploiting beneficial opportunities.	Flexibilitätsoption
Future Scenario	Set of boundary conditions that are assumed for a point in the future. Description of a realistic spectrum of possible future developments, considering the systematic inter-relationships between the different future drivers.	Zukunftsszenario
Indicator	Synonym for Criterion	Indikator

Internal homogeneity (Hom)	Homogeneity of the partial utility values	Interne Homogenität
Multi-dimensional Degree of Target Achievement (dDTA)		Multidimensionaler Ziel-erreichungsgrad (dZEG)
Multi-dimensional, multi-variant Degree of Target Achievement (dvDTA)		Multidimensionaler multi-varianter Zielerreichungs-grad (dvZEG)
Objective	Refers to superordinate or general objectives, e.g. “water quality”. Compare criterion.	Ziel
Partial utility value (pUV)		Teilnutzwert
Required flexibility	The expected range of per-formance relevant alterations in the system environment.	Flexibilitätsbedarf
Risk	The level of uncertainty when the date of occurrence of an event is not known but the probability as well as impact of occurrence of the event is known (risk = prob-ability*impact).	Risiko
Robustness	The ability of a system to be insensitive towards altering requirements and delivering the aspired performance without being changed.	Robustheit
Scenario	Synonym for alternative	Szenario
Total utility value (tUV)		Gesamtnutzwert

Uncertainty	Incalculable and not predictable future developments.	Unsicherheit
Utility Value (UV)		Nutzwert
Utility analysis		Nutzwertanalyse
Utility function		Nutzenfunktion
Utility value (UV)		Nutzwert
Weighting factor (w)		Gewichtung

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