Measuring the Flexibility of Urban Drainage Systems

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Abstract

Urban drainage systems are influenced by several future drivers, which affect the performance as well as the costs of the systems. To deal with these future uncertainties flexible urban drainage systems are required. Flexible urban drainage systems guarantee, that present decisions do not affect the future capability for change to react on future alterations. A precondition for the implementation of flexible urban drainage systems is a method to measure flexibility. In the present technical literature profound insights about the measurement of flexibility for urban drainage systems are missing. Hence approaches for the measurement of flexibility from other disciplines are presented. The paper illustrates that a transfer of the general approaches to the field of urban drainage systems is possible. Two approaches for the measurement of flexibility developed in the research project SWITCH are presented. First a pragmatic and simple approach for the measurement of flexibility by means of static indicator 'homogeneity of performance' is illustrated. Second an approach for a more detailed measurement of flexibility is presented. The approach based on the comparison of the systems performance with respect to different future scenarios as well as alternative solutions. The criteria for the measurement of flexibility are 'capability of change', 'costs of change', 'duration of change' and 'performance of system'. Depending on the requirements of the decision situation in particular, the amount of work and the required accuracy a suitable approach could be selected. With the presented approaches for the measurement of flexibility a basis for the implementation of flexible urban drainage systems is offered.

Keywords: *Measurement of Flexibility, Flexible Urban Drainage Systems*

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1. The need for methods to measure flexibility

The planning and design of urban drainage systems is confronted with a dilemma. On the one hand it is foreseeable that uncertain future drivers like climate change or spatial development will affect the basic conditions of the urban drainage systems during their long operational life span. On the other hand with the design of urban drainage systems long-lasting decisions have to be taken. To deal with this dilemma several authors propose flexible urban drainage systems (Scholes et al. 2006) or (Ashley et al. 2007). Flexible urban drainage systems guarantee that current decisions do not affect the capability for subsequent adaptation measures adversely. Therefore flexibility facilitates the implementation of required urban drainage systems despite of current uncertainties. For the implementation of flexible urban drainage systems, the measurement of flexibility is required.

Precondition for the measurement of flexibility is a detailed definition of the term. 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). This results in confusion between the term flexibility and other terms related to the ability of systems to handle future alterations such as adaptability, resilience, robustness etc. In this paper flexibility is defined as: *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 (Eckart et al. 2010).* Task of the measurement method is according to (Kühn 1989) to substantiate and operationalize the characteristics mentioned in the definition of flexibility.

In several disciplines, but particularly in engineering science (de Neufville et al. 2008) and (Shah et al. 2006) and business management (Schlüchtermann 1995), (Pibernik 2001), (Patig 2001) and (Kühn 1989), 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. Hence only few and mainly simplified approaches for measurement of flexibility for urban drainage systems exist. In this paper the transferability of generic approaches for the measurement of flexibility to the field of urban drainage systems is analysed. First, the already existing definitions, generation approaches and measurement methods for urban drainage systems are reviewed. Second, the transfer of the general measurement methods is systematically assessed based on the questions if the terms are known in urban drainage, if the requirements for the implementation are fulfilled in urban drainage systems and if benefits for urban drainage systems are expected. Third approaches for the measurement of flexibility for urban drainage systems developed in the SWITCH project are presented. As result a scientific foundation for the measurement of flexibility is presented.

2. Different measurement approaches for flexibility

Because of the larger number of different measurement methods a systematisation of the approaches is required. The methods are grouped according to their theoretical background (see figure 1).

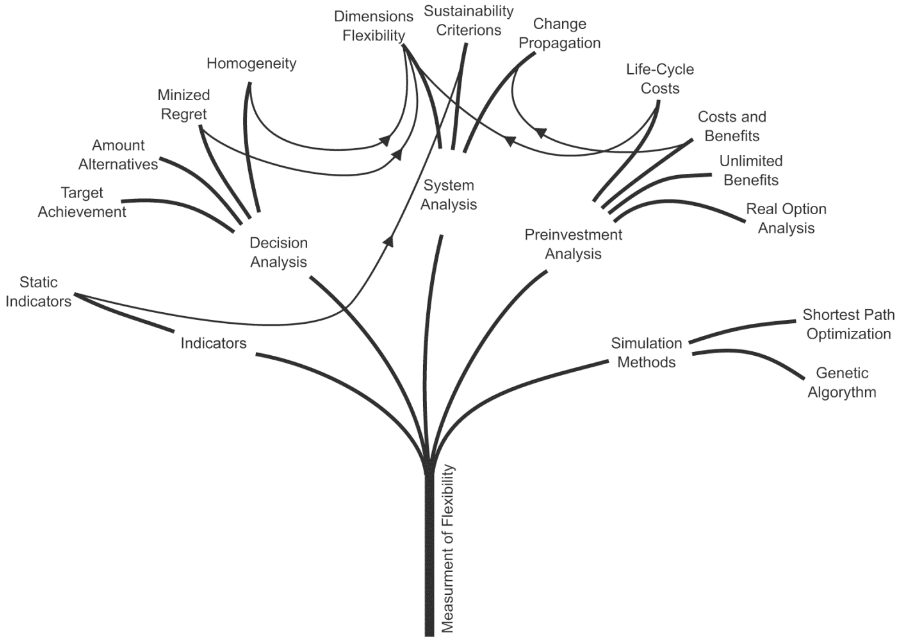

Figure 1: Methods for the Measurement of Flexibility

2.1 Indicator based measurement

Several indicator based measurement methods for flexibility exist. Flexibility is presented by single static characteristics of the system not considering different future states. An example for a static indicator for the flexibility of urban drainage systems is presented by (Helm et al. 2009) and (Sieker et al. 2008). Flexibility is described by the homogeneity of performance for different system objectives of the urban drainage system. The basic idea 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 (Winkler 1989) non-specialised technical infrastructure systems offer a high flexibility. A low degree of specialisation enables a system to perform a higher diversity of functions. Hence, systems with a low degree of specialisation have a high probability that the system will be suitable also for new requirements. (Helm et al. 2009) describes this characteristic by the indicator 'homogeneity of performance for different system objectives'. Another example for static indicators to measure flexibility for urban drainage systems is described by (Revitt et al. 2003). 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 that static indicators neglect the required consideration of uncertain future developments.

2.2 Flexibility measurement based on pre-investment analysis

As one approach for the measurement of flexibility in pre-investment analysis the real option analysis is presented. Other approaches are the consideration of the Switching costs (Shah et al. 2007) or (Silver et al. 2007) or the concept of unlimited benefits (Marschak et al. 1962). 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). 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 assessed 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. However, there are also limitations to real option analysis (de Neufville 2004) and (Schierenbeck et al. 2008). 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 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. Hence 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. 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.

2.3 Flexibility measurement based on decision analysis

Several methods for the measurement of flexibility are based on an approach developed in decision analysis. 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 used in different measurement approaches like the 'Minimax-Regret-Principle' (Loomes et al. 1982), the 'Amount of Alternative Actions Approach' (Schlüchtermann 1995) or the 'Level of Target Achievement Approach' (Kühn 1989). (de Neuville et al. 2008) term these measurement methods as 'Decision-Tree Methods' because it is possible to illustrate the comparison between different future states and alternative solutions by means of a decision tree (see figure 2).

(Koste et al. 1999) and (Upton 1994) base their measurement approach on the characteristic homogeneity of the system performance for different future states. 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 aspired. 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. When the possibility to change the system during operation is considered, the measured homogeneity represents the flexibility of the system (Koste et al. 1999), (Upton 1994). A comparable approach was developed by (Helm et al. 2009) 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, which represents the standard deviation of the performance for the different future states and different alternative solutions.

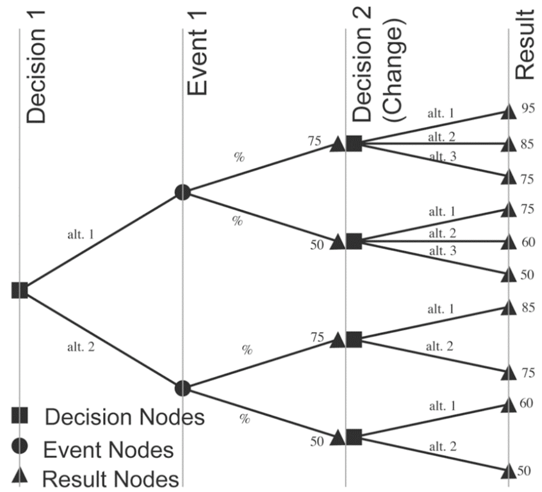

Figure 2: Decision Tree 'Homogeneity System Performance'

3.4 Flexibility measurement based on systems analysis

Several methods for the measurement of flexibility base on deduction of the metrics used for the measurement of flexibility by means of systems analysis like the change propagation method of (Eckert et al. 2004) or the sustainability based measurements methods for urban drainage systems of (Sundberg et al. 2004) and (Sieker et al. 2007a).

(Hocke 2004) developed an approach for the measurement of flexibility, which systematically considers following dimensions (characteristics) of flexibility (see figure 3).

- 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 analysed, considering different future states as well as the implementation of flexibility options.
- Provision Cost: The costs for the construction of the flexibility options are considered independently because these expenses do not arise directly from the change process.

These characteristics of flexibility are ascertained, aggregated and assessed step-by-step based on comparing the system performance for different alternative solutions and several future states, an approach already described above. (Hocke 2004) combines in his approach elements from different measurement approaches of flexibility with a systematic derivation of the considered characteristics of flexibility. The feature of this method for the measurement of flexibility is the reasonable combination of the different characteristics.

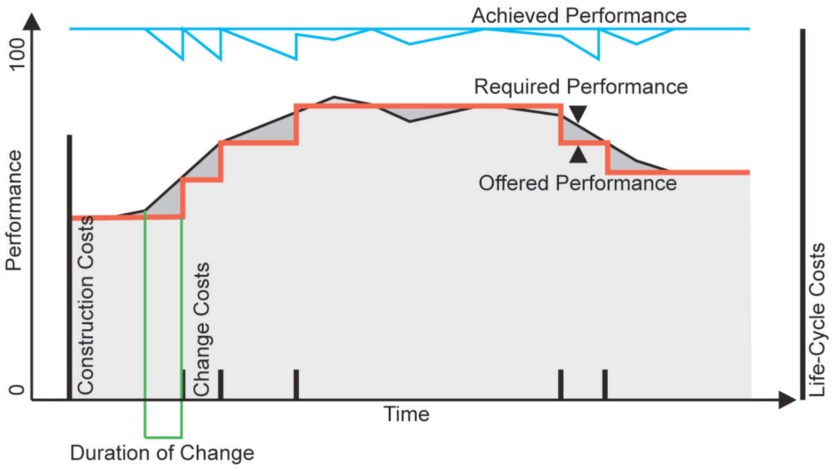

Figure 3: Time / Performance Diagram with different 'Dimensions of Flexibility'

3.5 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. The most measurement methods consist of two components, different types of flexibility metrics as well as different measuring procedures. 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.

For urban drainage systems, different methods for the measurement of flexibility have been developed, such as static indicators, methods based on decision analysis as well as methods based on preinvestment analysis. But until now no approach is established as standard. Hence the transferability of the existing theories is analysed. First, the terms used in the different measurement approaches of flexibility like performance, costs, value of benefit etc. are familiar for urban drainage. The transfer is facilitated by the fact, that in the measurement methods general terms from system analysis or preinvestment analysis are used. In addition the preconditions of the single measurement approaches have to be considered. So a preinvestment method should be used, which is customized to the characteristics of urban drainage systems like long operational life span, high investment costs etc. Furthermore the present measurement methods for flexibility discussed for urban drainage systems are characterised by several problems. So the most methods do not consider the general framework for the generation of flexibly with the steps identification of uncertainties, development of systems alternatives, effect modelling, comparison of results and decision. As consequences the implementation of the measurement methods is aggravated. The most criterions for the measurement of flexibility are derived unsystematically without considering the characteristics of flexibility. These weaknesses of the present methods could be eliminated, if profound approaches for the measurement of flexibility are used.

3. Measurement Method

To support the implementation of flexible urban drainages system in SWITCH two approaches for the measurement of flexibility were developed.

3.1 COFAS method

The COFAS approach based on the static indicator 'homogeneity of performance'. The flexibility is measured in two steps. Firstly, a regular value of benefit analysis is performed. The value of benefit for the single objectives as well as the weighted average value of benefit for each alternative solution is calculated. 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. This indicator 'homogeneity of performance' is used for the measurement of flexibility. The indicator based on the theoretical foundation that unspecialised and multi purpose technical infrastructure systems offer a high flexibility against future uncertainties. The COFAS method was tested in a case study for the municipality Kupferzell in Southwest Germany for urban drainage systems. A detailed description of the approach is presented by (Helm et al. 2009) and (Sieker et al. 2008).

3.2 Framework for detailed measurement of flexibility

The framework for a more detailed measurement of flexibility based on the comparison of the systems performance with respect to different future scenarios as well as alternative solutions. 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. First metric is the capability for change, which indicates the range of future developments for which 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. Second metric is the performance of the system for different future states described as regret. The regret is the difference between the value of benefit of the assessed alternative solution for different future states and the maximal possible benefits if other alternatives are chosen. The lower the regret of the alternative for different future states, the higher the flexibility. Third metric is the effort of change represented by the costs of change as well as the duration of the change process. The lower the effort to change the system during operation the higher the flexibility of the system.

The metrics are integrated in a framework for the measurement of flexibility (see figure 4). The framework was tested in a master thesis (Garcia-Sepulveda 2010) for a real but anonymous case study of an urban drainage system.

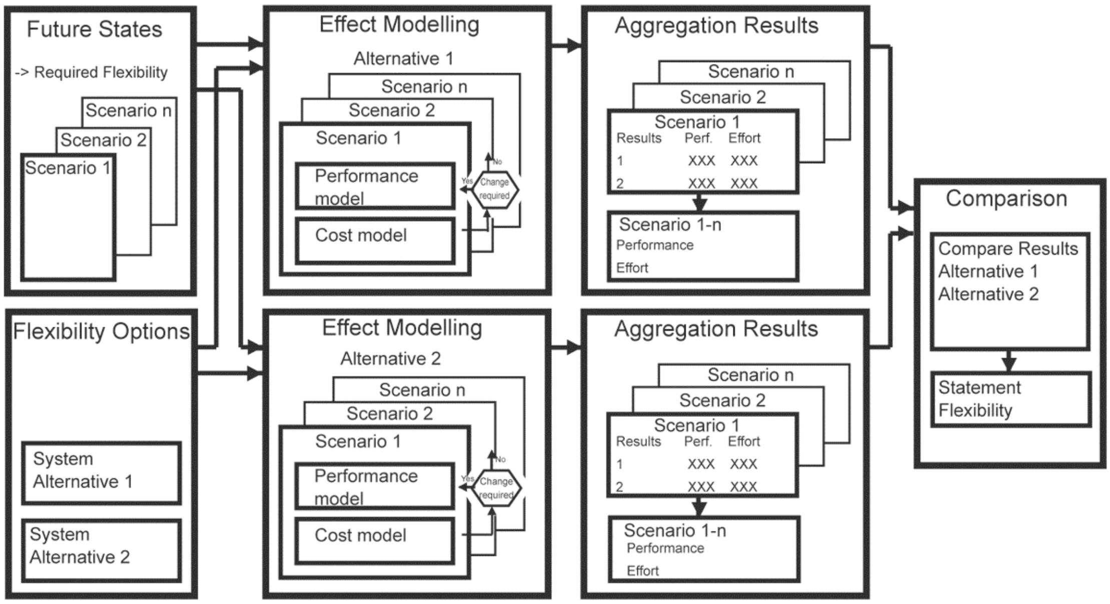

Figure 4: Framework for the measurement of flexibility

- Future states: The relevant future drivers for the urban drainage system are ascertained and the range of possible future development is described. In the case study drivers like climate change, the development of the sealed surface as well as the pollution load are considered. To reduce the effort for calculation, the huge number of possible future states is summarised 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, with different flexibility options. Hence, different alternative solutions for the urban drainage system are generated. In the case study three alternatives with different embedded flexibility options are considered, a conventional separated drainage system, a sustainable urban drainage systems and a sustainable urban drainage system with additional space for flexibility options.
- Modelling the effects: For all alternative solutions and different future scenarios the system performance is modelled. As performance metrics the hydrological risk, the flooding and the pollution load in the receiving water bodies are considered. Furthermore the construction costs, operational costs, maintenance costs and adaptation costs are ascertained. For the urban drainage system minimum performance requirements are determined, which serve as trigger impulse for the implementation of the flexibility options. When the system performance falls during the time of operation below the trigger level, the flexibility options have to be implemented.
- Aggregation results: In several steps the results of the different time steps, different alternative solutions and future scenarios are aggregated to one value per alternative. The performance values as well as the life-cycle costs of the different alternatives are considered. For all alternative solution the regret of performance and the effort of change are ascertained.
- Comparison results: The efforts of change, the range of change as well as the regret of the system performance are compared for different alternative solutions. The alternative, which minimises the disadvantage for the different future scenarios, has the highest flexibility. In the case study both alternatives considering sustainable urban drainage systems offer a significant higher flexibility than the conventional drainage system. The

differences between the different sustainable urban drainage systems (additional space for the implementation of flexibility options) are from minor importance.

4. Conclusions

Flexibility offers the chance to make required decision for urban drainage systems despite of the future uncertainties. Hence the authors recommend, utilising flexibility as a criterion for the design of urban drainage systems. For the implementation of flexible urban drainage systems approaches for the measurement of flexibility are required.

In SWITCH two approaches for the measurement of flexibility for urban drainage systems are developed. The selection of the suitable measurement method depends on the aspired application. On the one hand the static indicator 'homogeneity of performance' of the COFAS method is a pragmatic approach for the measurement of flexibility. 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. But for the interpretation of the results the limitations of the approach like the missing representation of the uncertain basic conditions have to be considered. On the other hand the approach for a more detailed measurement of flexibility enables a precise description of the different characteristics mentioned in the definition of flexibility. 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.

References

Ashley R., Blanksby J., Cashman A., Jack L., Wright G., Packman J., Fewtrell L., Poole T., Maksimovic C. (2007) Adaptable Urban Drainage: Addressing Change in intensity, Occurrence and Uncertainty of Stormwater (AUDACIOUS), in: Built Environment Vol 33/2007 pp. 70 – 84

Eckart J., Sieker H., Vairavamoorthy K. (2010) Flexible Urban Drainage Systems, in: Water Convention at Singapore International Water Week 2010

Eckert C., Clarkson J., Zanker W. (2004) Change and customisation in complex engineering domains, in: Research in Engineering Design (2004) 15 pp. 1-21

Engel A., Browning T. (2006) Designing Systems for Adaptability by Means of Architecture Options in: System Engineering: Shining Light on the Tough Issues INCOSE 2006 – 16th Annual International Symposium Proceedings

Garcia-Sepulveda B.A. (2010) Flexibility of Sustainable Urban Drainage Systems for Water Pollution Control, unpublished Master Thesis University of Birmingham

Helm B., Träckner J., Sieker H., Krebs P., (2009) Flexibilität als Bewertungskriterium bei der Planung von Systemen der Regenentwässerung (Flexibility as decision criterion for the design of urban drainage systems), Korrespondenz Abwasser Abfall 2009 (56) Nr. 4 pp 372 – 381

Hocke S. (2004) Flexibilitätsmanagement in der Logistik – Systemtheoretische Fundierung und Simulation logistischer Gestaltungsparameter, Bayreuth 2004

Jacob H. (1989) Flexibilität und ihre Bedeutung für die Betriebspolitik, Adam Dietrich (Hrsg.) Integration und Flexibilität: eine Herausforderung für die allgemeine Betriebswirtschaftslehre, Münster 1989, S. 15. ff

Koste L., Malhotra M. (1999) A theoretical framework for analyzing the dimensions of manufacturing flexibility; in: Journal of Operations Management 18 / 1999 S. 75-93

Kühn M. (1989) Flexibilität in logistischen Systemen, Heidelberg 1989

Loomes G., Sudgen R. (1982) An Alternative Theory of Rational Choice Under Uncertainty, in: The Economical Journal, 92/368, 1982 pp. 805-824

Marschak T., Nelson R. (1962) Flexibility, Uncertainty and Economic Theory, in: Metroeconomica: international review of economics 14/ 1962. S. 42 ff.

de Neufville R. (2004) Uncertainty Management for Engineering Systems Planning and Design, in Engineering Systems Monograph MITesd March 29-31, 2004

de Neufville R., Cardin M.A. (2008) A Survey of State-of-the-Art Methodologies and a Framework for Identifying and Valuing Flexible Design Opportunities in Engineering Systems, Working Paper Massachusetts Institute of Technology Cambridge 2008

de Neufville R. Hassan R. (2006) Design of Engineering Systems under uncertainty via Real Options and Heurestic Optimization, Massachusetts Institute of Technology

Pating S. (2001) Flexible Produktionsfeinplanung mit Hilfe von Planungsschritten – Ein Planungsansatz zum Umgang mit Störungen bei der Produktion, Frankfurt am Main 2001

Pibernik R. (2001) Flexibilitätsplanung in Wertschöpfungsnetzwerken, Frankfurt Main 2001

Revitt M., Ellis B., Scholes L. (2003) Criteria Relevant to the Assessment of BMP Performance, Project Daywater 2003

Salehn J., Hastings D., Newman D. (2001) Extracting the Essence of Flexibility in System Design, Massachusetts Institute of Technology Engineering Systems Divison Working Paper Series ESD-WP-2001-04

Schierenbeck H., Wöhle C. (2008) Grundzüge der Betriebswirtschaftslehre – Studienausgabe 17. Auflage, München 2008

Schlüchterman J. (1995) Planung in zeitlich offenen Entscheidungsfeldern, Münster 1995

Scholes L., Ellis B., Revitt M., et. al (2006) Review of the adaptability and sensitivity of current stormwater control technologies to extreme environmental and socio-economic drivers, SWITCH Deliverable 2.1.1, London 2006

Shah N., Wilds J., Viscito L., Ross A., Hastings D., n.Y. Quantifying Flexibility for Architecting Changeable Systems, Paper 154 Massachusetts Institute of Technology, Cambridge

Sieker F., Zweynert U., Schlottmann P. (2007a) Ökologische und ökonomische Vergleichsbetrachtung zwischen dem Konzept der konventionellen Regenwasserentsorgung und dem Konzept der dezentralen Regenwasserbewirtschaftung, Umweltbundesamt Texte 19/07, Hannover 2007

Sieker H., Helm B., Krebs P., Schlottmann P., Tränker J. (2008) Flexibility – a planning criterion for stormwater management, 11th International Conference on Urban Drainage, Edingburgh UK 2008

Silver M., de Weck O. (2007) Time-Expanded Decision Networks: A Framework for Designing Evolvable Complexe Systems, in Systems Engineering Vol 10 No 2 2007 S. 167 – 186

Sundberg C., Svensson G., Söderberg H. (2004) Re-framing the assessment of sustainable stormwater systems, in: Clean Technology Environment Policy 6 (2004) S. 120-127

Upton D.M. (1994) The management of manufacturing flexibility in: California Management Review 1994, S. 72-89

Winkler R. (1989) Flexible Infrastruktur – Möglichkeiten und Konsequenzen für die Versorgung mit öffentlicher Infrastruktur, in: RaumPlanung 46/47 1989, S. 158 ff.