Doctoral Thesis

# A Method for Determining Optimal Intervention Programs for Interrelated Infrastructure Networks

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# A METHOD FOR DETERMINING OPTIMAL INTERVENTION PROGRAMS FOR INTERRELATED INFRASTRUCTURE NETWORKS

A thesis submitted to attain the degree of
DOCTOR OF SCIENCES of ETH ZURICH (Dr. sc. ETH Zurich)

presented by

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# Abstract

Cities provide goods and services, such as electric power, gas supply, mobility, water supply and wastewater removal/treatment to the public in order to improve prosperity, quality of living, and opportunities for businesses. These services and goods are distributed via urban infrastructure networks. In order to sustain the provision of service on these networks, interventions have to be executed, that ensure that the state of the objects of the infrastructure network is such that disturbances to the service can be avoided. However, these interventions themselves also cause disturbances to the service. Therefore, the task of urban infrastructure management is to balance these two disturbances to find an optimum that fulfils all necessary requirements, such as minimal service level, budget limitations etc. In this thesis, a methodology to determine optimal intervention programs for urban infrastructure networks is presented, that encompasses a suitable deterioration and level of service model while accounting for interactions between networks, and is able to construct intervention programs for multiple infrastructure networks ensemble, with grouping of interventions for multiple time frames. This methodology is set up in a modular way in order to adapt the accuracy to the data input and computational power available. From the scientific point of view, this thesis provides besides the presented methodology also two additional components that are used to 1) group interventions into intervention clusters by applying a dynamic neighbourhood methodology, and 2) measure loss in level of service in a consistent way in order to facilitate the ensemble calculation. The methodology is based on a genetic-algorithms founded optimisation approach. It is found that the methodology is able to calculate intervention programs for multiple infrastructure networks ensemble, with grouping of interventions for multiple time frames. The advantages, disadvantages, and future research directions are discussed.

# Zusammenfassung

Städte bieten Dienste wie Stromversorgung, Gasversorgung, Mobilität, Wasserversorgung und Abwasserentsorgung / -behandlung, um Wohlstand, Lebensqualität und Chancen für Unternehmen zu verbessern. Diese Dienste werden über städtische Infrastrukturnetze verteilt. Um die Bereitstellung von Diensten in diesen Netzwerken aufrechtzuerhalten, müssen Massnahmen durchgeführt werden, die sicherstellen, dass der Zustand der Objekte des Infrastrukturnetzes so beschaffen ist, dass Störungen der Dienste vermieden werden können. Diese Massnahmen selbst verursachen aber auch Störungen der Dienste. Die Aufgabe des städtischen Infrastrukturmanagements besteht darin, diese beiden Störungen auszugleichen, um ein Optimum zu finden, das alle notwendigen Anforderungen erfüllt, z. B. minimale Servicelevel, Budgetbeschränkungen etc. In dieser Arbeit wird eine Methodik zur Ermittlung optimaler Massnahmenprogramme für städtische Infrastrukturnetze präsentiert, die eine adäquate Modellierung zu Zustandsveränderung und Dienstniveau umfasst, während sie Interaktionen zwischen Netzwerken berücksichtigt und in der Lage ist, Massnahmenprogramme für mehrere Infrastrukturnetzwerke zu erstellen, wobei die Gruppierung von Massnahmen über mehrere Planungsperioden erfolgt. Diese Methodik ist modular aufgebaut, um die Genauigkeit an die Datenverfügbarkeit und die zur Verfügung stehende Rechenleistung anzupassen. Aus wissenschaftlicher Sicht bietet diese Arbeit neben der vorgestellten Methodik auch zwei zusätzliche Komponenten, die verwendet werden, um 1) Massnahmen durch Anwendung einer dynamischen Gruppierungsmethodik in Massnahmencluster zu kombinieren und 2) den Verlust des Dienstniveaus in einer konsistenten Weise zu bestimmen, um die gemeinsame Berechnung zu erleichtern. Die Methodik basiert auf einem Optimierungsansatz, der genetische Algorithmen verwendet. Es wird gezeigt, dass die Methodik in der Lage ist, Massnahmenprogramme für mehrere Infrastrukturnetzwerke gleichzeitig zu berechnen, und dabei Massnahmengruppierungen über mehrere Planungsperioden durchzuführen. Die Vorteile, Nachteile und zukünftige Forschungsrichtungen werden diskutiert.

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Last but not the least, I would like to thank my family, Rhea, and all my friends for supporting me spiritually throughout writing this thesis and my life in general.

# Foreword

Most people in urban areas get angry when a road in their neighbourhood is opened up the year after it was resurfaced. They blame this, and are often right, on a lack of coordination between the managers of multiple infrastructure networks. This lack of coordination is annoying because it results in increased costs and increased interruptions to service than what is necessary. With the increasing availability of data on these networks, the increasing use of geographic information systems and the increasing professionalisation of infrastructure management, this is no longer necessary.

In his thesis, Mr. Kielhauser shows how state-of-the art technologies can be used to optimally coordinate interventions on multiple interrelated infrastructure networks in urban areas. He does this by developing a methodology to determine optimal interventions on multiple interrelated infrastructure networks taking into consideration the objects on all of the networks, their changing state over time, the risk associated with each, the closeness of the objects to others, the interruption to service during preventive interventions, and the synergies of executing multiple interventions simultaneously.

His methodology is a significant advancement on the state-of-the-art methodologies used to construct intervention programs for road networks, sewer networks, water distribution networks, gas networks and electricity distribution networks, as well as methodologies used to construct intervention programs for multiple networks simultaneously. It is particularly innovative through his use of Voronoi cells to mathematically define closeness and his mathematically consistent way to model the service provided by road, sewer, water, gas and electricity distribution networks. Mr. Kielhauser demonstrates how his methodology works, by planning the interventions on the five networks in a fictive but realistic network, modelled after those in Wermatswil, Switzerland.

The developed methodology, once extended to cover all aspects of real networks and implemented in useable software, can be used by infrastructure managers in urban areas to improve the development of intervention programs. Improved intervention programs will result in lower costs for infrastructure managers, and ultimately taxpayers, improved service, or both. In other words, Mr. Kielhauser's methodology will help to ensure that we are intervening in ways on our infrastructure to ensure that we are obtaining the most from our infrastructure.

Although the most beneficial when considering multiple networks, Mr. Kielhauser's methodology would also yield benefits if used to develop intervention programs for single networks where infrastructure managers want to take into consideration quantitatively the synergies of executing interventions on multiple objects simultaneously. As an increasing number of infrastructure managers are concerned about determining optimal intervention programs, and to do so are increasingly relying on computerised decision support systems, the methodology proposed by Mr. Kielhauser, or extensions of it, will be increasingly required.

Through his work, Mr. Kielhauser has demonstrated that he has the ability to conduct work rigorously at a high academic level, and make contributions to the state-of-the-art in a new emerging field of research. On behalf of the Institute for Construction and Infrastructure Management at the Swiss Federal Institute of Technology, Zürich, I thank him for his thorough and constant investment to his thesis, his substantial help over the years with the System Engineering course and the supervision of Master students, and for his personal contributions to team spirit in IBI.

Zürich, 17.04.2018 Professor Dr. Bryan T. Adey

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# Nomenclature

### Definitions

| | |
|---|---|
| Algorithm: | An optimisation technique that finds the exact optimum of an optimisation function (i.e. a function of the value(s) to be optimised) in a finite number of steps |
| Chronological age: | Age measured in calendar time |
| Countermeasure: | An activity that modifies how infrastructure is used, which is usually executed to ensure that an adequate level of service is provided. Countermeasures are executed by the producer. |
| Cumulative service age: | Age measured in operating time |
| Distributor: | Entity responsible for the distribution of the goods, i.e. ensures that the goods produced reach the receiver |
| Expected unserved energy: | Probability of not being able to provide a certain power to a customer, considering the customers' expected demand |
| Heuristic: | An optimisation technique that has a lower bound at the iterative method and an upper bound at an algorithm, i.e. in the worst case, a heuristic behaves like an iterative method, and in the best case a heuristic behaves as algorithm. |

| | |
|---|---|
| Interrelated: | Having a reciprocal relation to one another |
| Clustered intervention program: | A list of the type and time of intervention executed on different objects, also containg information about which interventions are executed jointly (as a cluster) and which interventions are executed individually. See also intervention strategy and intervention program. |
| Intervention program: | A list of interventions to execute over a defined period of time. See also intervention strategy and clustered intervention program. |
| Intervention strategies: | A set of rules to decide when and what kind of intervention is executed on different objects. See also intervention program and clustered intervention program |
| Intervention: | A group of activities that are to be executed at the same time on infrastructure. |
| Iterative method: | An optimisation technique that converges infinitely close to the exact optimum of an optimisation function |
| Level 1 object: | An object that is selected directly for an intervention |
| Level 2 object: | An object that is considered to be combined into a cluster, but not selected as level 1 object |
| Level of service: | Degree of how well a service is delivered to a customer |
| Loss of load probability: | Probability of not being able to provide a certain power to a customer, regardless of the customers actual demand |

Lower flammability limit: Lower end of the concentration range over which a flammable mixture of gas or vapour in air can be ignited at a given temperature and pressure

Object: The smallest entity of the network that is investigated (e.g. a pipe section, a valve, a switch,...) and can be assigned its own condition, deterioration, material etc. in the scope of the investigation.

Potential network: A network, where the flow is caused by potential differences between the nodes

Preventive replacement: Replacement of an object that is still in acceptable condition before the failure of the object.

Process: A set of tasks to be executed in a certain logical order

Producer: Entity responsible for producing goods or services to be distributed by the network

Receiver: Entity receiving goods or services that are distributed by the network

Task: One single entity of a process diagram. If one task is expanded, it becomes a process

**Mathematical Symbols**

$\alpha_g$ The reduction of costs due to grouping of interventions

$\delta^{I}_{n,m}$ Logical level 1 selection vector element

$\vec{\delta}^{I}_{n,m}$ Logical level 1 selection vector

$\delta^{II}_{n,m}$ Logical level 2 selection vector element

| | |
|---|---|
| $\vec{\delta}_{n,m}^{II}$ | Logical level 2 selection vector |
| $\delta_{n,m,\kappa,t}$ | Binary indicator for object $o_{n,m}$, for intervention type $\kappa$ at time point $t$ |
| $\vec{\delta}_{n,m}^{C,D}$ | Close object set indicator |
| $\vec{\delta}_{n,m}^{C,D,II}$ | Close object level 2 set indicator |
| $\eta_m$ | Logical nodes of network $m$ |
| $\gamma_{n,m}$ | Conductivity term for object $o_{n,m}$ |
| $\gamma_{n,rd}$ | Conductivity of network in actual state |
| $\gamma_{opt,rd}$ | Conductivity of network in optimal state |
| $\lambda_{elec}$ | Ageing factor for electricity network object over time |
| $\lambda_{gas}$ | Ageing factor for gas network object over time |
| $\lambda_{road}$ | Ageing factor for road network object over time |
| $\lambda_{sew}$ | Ageing factor for sewer network object over time |
| $\lambda_{water}$ | Ageing factor for water network object over time |
| $\Psi$ | Genome representing the intervention program |
| $\sigma_{n,m}$ | Slimness term for object $o_{n,m}$ |
| $\tau_{n,m}$ | Transmission factor |
| $\Xi$ | Algorithmic chromosome representing $\Psi$ |
| $\vec{\xi}_{n,m,t}$ | Transmission vector |

| | |
|---|---|
| $\zeta$ | Penalty factor |
| $A_m$ | Service on network $m$ |
| $B_{fric}(t)$ | Service power friction loss on network $m$ |
| $B_{in}(t)$ | Service power input on network $m$ |
| $B_{leak}(t)$ | Service power leak on network $m$ |
| $B_{loss}(t)$ | Service power loss on network $m$ |
| $B_m$ | Service power on network $m$ |
| $B_{out}(t)$ | Service power output on network $m$ |
| $B_{rd,opt}$ | Traffic power in an optimal case (i.e. no closed roads) |
| $B_{rd,out}$ | Traffic power in an actual case (i.e. with closed roads) |
| $C_{LOS,el}$ | Costs for loss in level of electricity service |
| $C_{LOS,gas}$ | Costs for loss in level of gas service |
| $C_{LOS,sw}$ | Costs for loss in level of sewer service |
| $C_{LOS,water}$ | Costs for loss in level of water service |
| $c_j$ | Setup costs for intervention cluster $j$ |
| $c_{loss,el}$ | Cost per unit electric energy that is lost during the transmission |
| $c_{loss,gas}$ | Cost per unit gas power (product of flow and pressure) that is lost during the transmission |

| | |
|---|---|
| $c_{loss,rd}$ | Additional costs for impossible trips |
| $c_{loss,water}$ | Cost per unit water power (product of flow and pressure) that is lost during the transmission |
| $\boldsymbol{C}_m$ | Incidence matrix of network $m$ |
| $C_m$ | Service pressure on network $m$ |
| $c_{n,m}$ | Unit costs without setup costs for each intervention on each object |
| $c_{poll,sw}$ | Cost per $m^3$ sewer overflow |
| $CS_{elec,t}$ | Condition state for electricity network object over time |
| $CS_{gas,t}$ | Condition state for gas network object over time |
| $CS_{road,t}$ | Condition state for road network object over time |
| $CS_{sew,t}$ | Condition state for sewer network object over time |
| $CS_{water,t}$ | Condition state for water network object over time |
| $c_{travel,rd}$ | Average travel time cost per hour |
| $d_{lim,m}$ | Distance threshold for network $m$ |
| $\mathbf{D}_m$ | Minimal distance matrix for all objects in network $m$ |
| $D_m$ | Service flow on network $m$ |
| $\mathbf{D}_{m,\eta}$ | All logical node pairs distance matrix for network $m$ |

| | |
|---|---|
| $d_{travel}$ | Distance neighbourhood threshold |
| $E_m$ | Service unit on network $m$ |
| $Eps$ | Distance variable, representing a search area around points |
| $f^I$ | Level 1 selector function |
| $f^{II}$ | Level 2 selector function |
| $F$ | Chromosome fitness function |
| $F'$ | Adjusted chromosome fitness function |
| $G_{int}(\Psi)$ | Intervention costs |
| $G_{LOS,m}$ | Costs occurred by the loss in level of service for network m |
| $G_{LOS,m,fix}$ | Fixed costs for operating the network |
| $g_{prod,m}$ | Costs per service power unit produced |
| $g_{rcv,m}$ | Revenue per service power unit recieved |
| $\mathbf{I}_D$ | Intervention cluster matrix |
| $\mathbf{I}_D^{'}$ | Filtered intervention cluster matrix |
| $\vec{P}$ | Pressure vector |
| $\boldsymbol{K}_m$ | Reachability matrix of network $m$ |
| $k_{m,i,j}$ | Reachability matrix element |
| $\boldsymbol{L}_m$ | Adjacency matrix of network $m$ |

| | |
|---|---|
| $\mathbf{M}$ | Network characteristic matrix |
| $MinPts$ | Minimal number of points, that make up a cluster |
| $\mathbf{N}_C$ | Temporal neighbourhood matrix |
| $nc_{n,m,j,k}$ | Temporal neighbourhood matrix element |
| $\mathbf{N}_D$ | Dynamic neighbourhood matrix |
| $\mathbf{N}_N$ | Distance neighbourhood matrix |
| $\mathbf{N}_T$ | Topological neighbourhood matrix |
| $n_t$ | Temporal neighbourhood time |
| $\mathbf{N}_V$ | Voronoi neighbourhood matrix |
| $P$ | Penalty |
| $R_{lim}$ | Global restriction limit |
| $R_{lim}(t)$ | Temporal restriction limit |
| $\vec{R}_{n,m}$ | Voronoi regions of objects $\vec{o}_{n,m}$ |
| $R(\Psi)$ | Restricted global feature of chromosome $\Psi$ |
| $R(\Psi, t)$ | Restricted global feature of chromosome $\Psi$ |
| $\mathbf{S}$ | Transmission matrix |
| $s_{ij}$ | Transmission matrix elemtent |
| $u_{n,m}$ | Object size |

# 1. Introduction

## 1.1. Situation description

Cities are growing worldwide, and are becoming the new focal points of our society. In order to sustain cities, goods and services such as electric power, gas supply, mobility, water supply and wastewater removal/treatment need to be provided to the public living there (UN-Habitat, 2013). These services and goods are distributed via urban infrastructure networks. Due to the growing size of the cities and the increased standard of living, the urban infrastructure networks are becoming increasingly complex. Furthermore, the networks have to be built closer and closer together to cope with the growing density in the urban areas. As shown in UN-Habitat (2013), the complexity of urban infrastructure networks is linked to the degree of prosperity, and as such suggesting that a stable city life is closely linked to a high demand for well-functioning infrastructure. The degree of "well-functioning" can be measured in terms of level of service that is provided. There are many urban infrastructure networks, but for this thesis, the focus will be put on the electricity, gas, road, sewer and water network.

In order to sustain the provision of service on these networks, interventions have to be executed, that ensure that the state of the objects of the infrastructure network is such that disturbances to the service can be avoided. However, these interventions themselves also might cause disturbances to the service. Therefore, the task of urban infrastructure management is to balance these two disturbances to find an optimum that fulfils all necessary requirements, such as minimal service level, budget limitations etc.

Additionally, due to the density of the urban environment, the electricity, gas, sewer and water network are often buried underneath the road network. This leads to the situation that any intervention on those networks also affect the road network, and possibly also the networks that are buried above the one having an intervention executed. For example, the sewer network has to be buried underneath the water network, as to avoid sewage leakage contaminating the water network through undetected leaks. Therefore, any intervention on the sewer network may disturb the soil above it, and thus also affect the water network by unwanted differential settling of the soil. In any case, when buried underneath a road, the road has to be opened, which introduces breaking points that accelerate the deterioration of the road itself. However, the majority of intervention programs is still calculated separately for each infrastructure network.

In order to account for these interaction circumstances, a methodology to determine optimal intervention programs for urban infrastructure networks should take into account these interactions, and combine (if sensible) interventions on different infrastructure networks in spatial proximity to each other into combined intervention programs. This methodology should ideally address both the practical and the scientific needs.

## 1.2. Practical challenges

At the present situation, each network operator maintains “their” urban infrastructure network in an optimal way from their own perspective. For this, methodologies exist, that are presented in chapter 2. Some of those methodologies require a large amount of data for model calibration, which might not be readily available. Therefore, at present, urban infrastructure managers tend to revert to simpler models that can be applied with the information available. Another issue is the limited budget availability, and therefore the need to justify the budget expenses in order to obtain a sufficient budget for the next intervention period during the budget negotiations.

Due to the density of urban infrastructure networks, interactions between the networks exist, and should be considered when planning interventions on urban infrastructure networks (Bobylev, 2010). For example, on a street, the sewer pipes are replaced in year 1 (as it is the optimal point in time for the sewer network), the gas pipes are replaced in year 2 (the optimal point for the gas network) and the electric conductors (i.e. the cables) are replaced in year 3 (the optimal point for the electricity network). While this is optimal for each network on its own, the traffic disruptions are higher than if all interventions were bundled into an intervention group.

Additionally, the setup costs for the intervention site and costs for excavation will be lower in the bundled interventions. Therefore, synergies exist, that can be taken advantage of. This bundling of interventions however leads to an increased workload that complicates the planning process. For example, in some cities, the responsibility for the urban infrastructure networks is divided into different management units, or the networks are even owned by different private companies. Thus, intervention coordination has to be performed across multiple responsible institutions, and due to the distributed responsibility, the incentive to coordinate the interventions is rather limited. This is even more so as any bundling leads to moving interventions away from the optimum for each single network to a global optimum, which decreases single network efficiency in order to achieve better global efficiency. In the example of the sewer, gas and electricity interventions from the beginning of this paragraph, if the bundled intervention program would be performed in year 2, then it would be optimal for the gas network, as the intervention time does not change. For the sewer network, an intervention later than at the optimal point means that there will be additional deterioration of the sewer pipe due to the longer time in service, and this may be associated with a higher failure probability and associated risk than desired. For the electricity network, an early intervention means losing useful service life (in this case 1 more year would be possible without intervention). Both lead to higher costs for the respective networks, but also to benefits due to synergies from the joint intervention. For the gas network however, there are only benefits, as the pipe is replaced at the optimal point in time, and additional benefits from intervention bundling arise. At the moment, the coordination of this maintenance work is done only to a limited amount, as shown in chapter 3. Some cities perform manual coordination, i.e. urban infrastructure managers sitting together and discussing possible combinations. This is perceived as being effective, but as it involves discussion between the urban infrastructure network managers, and makes use of their experience, it is hard to prove (or disprove) the efficiency as the coordination is subjective, only partially clear and understandable to the outside. Other cities employ a “no touching scheme”, i.e. that once an intervention was performed at a certain location, the same location cannot have an intervention for a certain time span. For example, if an intervention on the sewer network was performed on road X, no intervention can take on road X for the next 5 years. This forces the managers from the other urban infrastructure networks to either coordinate, or let the condition of the other networks’ objects deteriorate further than it might be desirable.

Summarising, the coordination of interventions on urban infrastructure networks is an ongoing problem in practice. Managers of urban infrastructure networks do see the potential of synergies that can be created, but the limited quantifiability makes it difficult to judge the benefits of increased coordination from a financial point of view. Therefore, a methodology is needed that presently does not exist.

## 1.3. Scientific challenges

From a scientific point of view, a methodology to determine optimal intervention programs for urban infrastructure networks should be able to improve the state of practice (section 1.2) in three areas:

1) the development of suitable deterioration and level of service models that balance data availability with accuracy, 2) the development of an interaction model that captures the interactions between the networks and is able to perform an interaction-based grouping of interventions, and 3) the integration of an appropriate optimisation technique, that is able to cope with the dimensional complexity of infrastructure networks.

The development of a suitable deterioration and level of service model is challenging, as the different networks investigated in this thesis have differing properties, and as such the deterioration and level of service models developed for each single network (shown in chapter 2.1) have to be unified in a way that allows a joint calculation, while using the data available. The development of an interaction model is challenging, as there are many different ways of interaction, and grouping can be performed based on various parameters. Both need a balance between accuracy and calculation complexity, as grouping is a combinatorial problem that grows exponentially with the number of objects involved. Therefore, a suitable optimisation technique has to be used that is able to tackle the problem of dimensionality, while also being able to cope with the available models for deterioration, level of service and intervention grouping.

## 1.4. Aims of this thesis

Summarising, a methodology to determine optimal intervention programs for urban infrastructure networks should encompass a suitable deterioration and level of service model while accounting for interactions between networks, and be able to construct intervention programs for multiple infrastructure networks jointly, with grouping of interventions for multiple time frames. Ideally, this methodology should also be set up in a modular way, so that computational models for sub-components can be exchanged in order to be able to adapt the computation to the data availability (i.e. if a certain computational model requires unavailable data, it can be exchanged for another model, that only requires available data). Moreover, the methodology has to be able to demonstrate its viability and applicability in order to convince the decision makers of the advantages of joint intervention planning. Ideally, the methodology should also be able to compare different intervention programs (e.g. a comparison of a joint intervention program, and an intervention program that is calculated for each network separately), in order to visualise the benefits of joint intervention programs.

## 1.5. Relevance of this thesis

In this thesis a methodology is presented that addresses both the practical and scientific challenges. From the practical challenge point of view, this thesis provides a modular concept that is able to construct intervention programs for multiple infrastructure networks simultaneously. Due to the modularised structure, each module can be replaced with methods and functions that are available to the infrastructure managers, depending on the data availability and the available computational power. From the scientific point of view, this thesis provides besides the presented methodology also two additional components that are used to 1) group interventions into intervention clusters[1] by applying a dynamic neighbourhood methodology, and 2) measure loss in level of service in a consistent way in order to facilitate the ensemble calculation.

[1] interventions that are executed jointly

## 1.6. Organisation of this thesis

First, a literature review is presented in chapter 2, that examines the existing literature on optimal intervention planning on infrastructure networks with a special focus on definitions of level of service on these networks. Additionally, the literature review also examines research from other scientific areas that might be helpful in the development of a methodology to determine optimal intervention programs. In chapter 3, an overview is given about the current state of practice, as there is a significant difference between the models used in practice and the scientifically available models. Then, in chapters 4, 5, and 6, the methodology is presented. In chapter 4, the technical concept is presented in process diagrams that help understand the methodology. In chapter 5, the mathematical formulation that translates the concept into a mathematically tractable problem is shown. In chapter 6, the algorithmic implementation of the mathematical formulation is presented, that translates the mathematical problem into a computer program that is able to construct optimal intervention programs for urban infrastructure networks. In chapter 7, the methodology is applied to a real-world example network of a small town, also showing the results of this example application, together with a sensitivity analysis. In chapter 8, the results are thoroughly discussed, together with the advantages and disadvantages of the presented methodology, as well as a conclusion that discusses which parts of the identified gap are filled, and which parts are still open. Finally, in chapter 9, an outlook is given for the real-world implementation of the presented methodology.

# 2. Literature review

This literature review is divided into four research areas. The first area discusses the intervention planning and the loss of service definition on single infrastructure networks, showing the advances, but also the gaps present in the current state of infrastructure intervention planning.

In order to fill the gap demonstrated in the first area, current research in other scientific fields can be of help. These other three fields, that are helpful, are not directly related to infrastructure management, but provide models and algorithms that are used in this thesis. This is important, because 1) to model interactions between networks, a "system of systems" approach is needed, 2) networks are often modelled as graphs, and as such graph theory provides algorithms for various calculations, and 3) optimisation techniques provide models and algorithms to tackle the high complexity of the problem.

- In the first research area, intervention planning, there has been substantial research over the last 40 years in the determination of optimal intervention strategies for single objects and an increasing amount of research in the last 10 years on the determination of optimal intervention strategies for infrastructure networks. In order to evaluate the optimality of the intervention programs, that are created by these intervention strategies, an optimisation goal has to be set, that determines the optimality of the generated intervention program. For urban infrastructure networks, this optimisation goal is tied to the level of service for which different definitions on the different infrastructure networks exist. Both research about optimal intervention strategies/programs, and the definitions of level of service will be presented in chapter 2.1, grouped by each network type. The key findings of this literature are also summarised in section 2.5 in tabular form.

- The second area, research about the interrelations between infrastructure networks, uses a "system of systems" approach, i.e. examines the processes and phenomena that occur from the interrelation of the infrastructure networks. For interrelated infrastructure networks, the main strand of research has been vulnerability and risk analysis, i.e. to identify the elements of a network that are most susceptible to attacks or failures and then calculating the vulnerability for the network, or further adding expected costs for the failure and thus calculating the risk. Selected research and models that are in line with the methodology presented in this thesis is presented in chapter 2.2.

- The third area of research is the mathematical branch of network and graph theory that serves as a mathematical foundation for the presented methodology. Network and graph theory presents different types of graphs (i.e. sets of nodes and edges), different mathematical problems associated with these graph types, and solution algorithms to solve said problems. The developed algorithms aid in an efficient calculation by translating the optimisation problem of the presented methodology into a network and graph theory problem for that a solution algorithm exists. Literature belonging to the sphere of network and graph theory, that contributes to the methodology from this thesis is presented in chapter 2.3.

- The forth area, research about optimisation techniques, serves as a foundation for translating the mathematical formulation into a prototype calculation algorithm that tackles complexity and runtime issues. Chapter 2.4 presents optimisation algorithms that seem promising to tackle network optimisation problems for the presented methodology.

## 2.1. Optimal intervention programs and determination of level of service on single networks

This section presents literature related to the determination of optimal intervention programs on infrastructure networks, together with research on how the level of service can be determined for these networks. The next subsections show both research areas, grouped by each network. However, first some terms have to be defined, in order to facilitate readability:

**Infrastructure management:** The process used to ensure that existing infrastructure items (objects and networks) provide adequate levels of service for specified periods of time (Adey, 2017)[1].

**Intervention:** A group of activities that are to be executed at the same time on infrastructure.

**Intervention strategy:** A set of rules and procedures that generates an intervention program.

**Intervention program:** A list of interventions to execute over a defined period of time.

**Clustered intervention program:** An intervention program also containing information about which interventions are executed jointly (as a cluster) and which interventions are executed individually.

**Unclustered intervention program:** An intervention program not containing information about which interventions are executed jointly (as a cluster) and which interventions are executed individually.

### 2.1.1. Electricity

Electricity networks are characterised by their binary state objects (working / not-working) with very limited inspection possibilities, as the most part of the network is (at least in a European context) inaccessibly buried. Therefore, the research on the determination of intervention programs is mostly based on the probability of failure of the objects. Stillman (2003) proposed to classify interventions on electricity network objects in two classes: 1) Emergency interventions, where upon failure the object is brought back as quickly as possible to a "before failure" state, and 2) preventive interventions, where an object is replaced at a prearranged point in time. In that sense, emergency interventions do not improve the object's condition nor affect the preventive intervention program, as they merely "correct" statistical outliers,

[1] In some parts of infrastructure management, (ISO 55000: 2016) is also referred to for management strategies. However, ISO 55000 refers to any physical assets of any organisation ("An asset is an item, thing or entity that has potential or actual value to an organisation. The value will vary between different organisations and their stakeholders, and can be tangible or intangible, financial or non-financial."), and is therefore deemed too general to be used without further specification.

i.e. objects that fail before the prearranged preventive replacement. The optimal intervention program is based on a minimisation of the sum of three cost categories: 1) costs of emergency interventions (that encompass only the intervention costs themselves), 2) costs of preventive interventions (again, only intervention costs), and 3) costs of service interruptions due to both types of interventions. As a boundary condition, a maximal allowed probability of failure for each object is set as a safety constraint. With that in mind, the optimal replacement interval for each object is calculated analytically. The main focus of this paper is, however, the process of accurately estimating the statistical processes in order to come up with the correct type and parameter values of the probability function. To reach that goal, the following assumptions were made: 1) the time out of service during the intervention was ignored , 2) replacement is perfect (i.e. no defects in material or workmanship), and 3) objects are independent from each other, and their times between failure are identically distributed. Network effects and other infrastructure networks were not considered.

Louit et al. (2009) also use the preventive maintenance approach to determine the optimal intervention program for electricity distribution network conductors. The presented method allows the intervention program to be based on a minimisation of the total costs per time unit (with the same cost categories used as in (Stillman, 2003)), a maximisation of the availability of the network, or a maximisation of the profit for the network operator, under boundary conditions for budget and availability limits. Again, as in (Stillman, 2003), the main focus of this work is on the accurate statistical estimation of the probability parameters with the available data. The result was the optimal time between interventions for each conductor. To do this, the following assumptions were made: 1) Failure modes were disregarded, 2) a fixed policy was assumed for the whole system, and 3) costs were assumed as not time-dependent. The authors recommend to extend the model to incorporate network effects, but in that paper it was omitted as the available data would not allow to estimate the needed parameters. Additionally, other infrastructure networks were not considered.

Dehghanian et al. (2013) presented a methodology to evaluate intervention strategies (not programs) based on reliability-centred measures while maximising the condition improvement to cost ratio. The method is based on a multi-step analysis, that is located more on a general level than on giving specific guidance on how to develop an actual intervention program. For example, one step calls for “outlining maintenance interventions" to treat failure causes, but at the same time provides no more detail about which type of intervention and how an intervention program should be developed. Nevertheless, the paper provides a framework on how to assess the quality of a generated intervention strategy, by giving a structure on the evaluation in the context of a network. In the first step, the critical objects are defined by examining their contribution to network failure, assuming all other objects are in an as-new state. Then, the intervention strategy is evaluated on how much the strategy improves first the condition of the most critical object, then on the second-most critical object and so forth. This is iterated over the whole network until a set reliability level is reached. The intervention strategy with the best improvement-to-cost ratio is deemed the optimal strategy and should then be used to develop intervention programs. While this paper does not give any specific guidance on how to generate intervention strategies or programs, it can serve as a guideline in evaluating existing intervention programs on the basis of reliability. Other infrastructure networks were not considered.

The calculation of losses in level of service on electricity networks is research that is mainly being done at the operational level and conducted by the network operators themselves. However, Rietz and Sen (2006) investigated the used indicators for losses in level of service. They found that the most prominently used indicators are *Loss of Load Probability* and *Expected Unserved Energy*. Loss of load probability is the probability of not being able to provide a certain power to a customer, regardless of the customers' actual demand (i.e. this indicator does not take into account if at the moment of power loss, the consumer is actually demanding power, or not). The expected unserved energy amends this indicator by factoring in the expected energy demand. This however requires information about the expected energy demand, and as such more data for an accurate estimation. Additionally, network operators are, according to the paper, assigning costs to these indicators, but their review showed vast differences in the costs, suggesting that there is a substantial amount of uncertainty in these costs. Therefore, Rietz and Sen (2006) suggest a customer survey in order to obtain reliable results.

Choi et al. (2006) performed a customer survey on industrial customers in order to increase the reliability of the cost data. As a by-product of better estimates for cost data (which was the goal of the study), it was also found that a simplified approach for estimating interruption costs is possible. By building cohorts of the customer type (i.e. by examining the customers processes and the expected energy demand of that processes), an average power use (taking into account the local factors) in combination with a load factor (representing the customer cohort) is sufficient to generate reliable data. However, the authors state that this method is only applicable to industrial customers, but not private customers.

Reichl et al. (2013) tried to fill the research gap from Choi et al. (2006), i.e. estimating the cost data for power outages for private customers. This was done by performing a power outage simulation with different outage times between 1 minute and 48 hours. It was found that the per-unit loss of energy costs for private customers are only 20% of those for the average industrial customer.

Summarising, it can be stated that intervention programs on electricity networks are in general based on the probability of failure of the object, with a significant part of research dedicated to better estimate this failure probability using the available data. Reliability-based approaches are also used, but only from a general, framework-like perspective. This is also due to the fact, that (owing to the mostly private nature of electricity network operators) data to calibrate the approaches is scarce. This general phenomenon also continues in the estimation of level of service. While indicators exist in theory, that measure the loss in level of service, it is (again due to the lack of data) difficult to actually calculate the costs, and so being able to use them in an actual intervention program creation process. This also explains the lack of consideration of interrelations for intervention planning, as for this additional layer of complexity even more information for model calibration is required. Other infrastructure networks are also not considered in the determination of optimal intervention programs.

### 2.1.2. Gas

Gas networks, as electricity networks, are characterised by their binary state objects with very limited inspection possibilities, and, therefore, intervention planning is also centred on the probability of failure of the objects. When this is the case the development of intervention programs is essentially the same as that proposed by Dehghanian et al. (2013) as described in the previous section. To improve upon the limited inspection possibilities, however, Pandey (1998), proposed a probability-based model, that can be used to improve the accuracy in the estimation of failure probability, and subsequently generate a better intervention strategy (as the failure probability can be estimated with higher accuracy, and thus the safety margin attributed to the known uncertainties can be reduced accordingly. The model takes into account the overall defect population as a baseline (i.e. all recorded failure events of all objects), an event-tree based estimation of the probability of defect detection during an inspection (if an inspection is possible), and a probabilistic repair efficiency calculation. Using Monte-Carlo simulation, the failure probability curve is obtained. Based on this failure probability curve (that is characteristic for each inspection method), the optimal time between inspections is calculated, that gives the lowest failure probability, taking into account the detection probability of defects. The intervention strategy is then constructed as follows: When an inspection is performed, and a defect above a certain threshold is found, it is repaired. If the defect is below this threshold, it is used to update the probability functions, and a new inspection interval is calculated. However, the model does not take into account network effects and was calculated with a fixed pipe diameter, a fixed operating pressure, and a linear defect growth (i.e. linear deterioration). Other infrastructure networks were also not considered.

In general, as noted in Bjerketvedt et al. (1997), the implications of a failure and subsequent gas explosion are extremely severe. Jo and Ahn (2005) calculated fatality distances (i.e. distances from different gas explosions with 99%, 50% and 1% fatality rate) in order to estimate the risk associated with gas pipeline failures. For example, the 99% fatality radius for a standard 4 bar distribution pipe can reach up to $100\,m$, depending on the surrounding conditions. Therefore, the main focus is on the safety and reliability side rather than on fine-tuning the intervention program, i.e. the costs attributed to failures and service interruptions are in comparison exceedingly larger than costs for unused service life due to preponed interventions.

This also reflects in the level of service, which is measured by comparison to *Guaranteed Standards of Performance* (e.g. OFGEM (2009)). These standards ensure safety and reliability, while also providing minima for service interruptions, pressure, flow, and gas quality. Penalties for network operators can be imposed if these standards are not met. Therefore, while the fulfilment of these standards is being monitored, actual calculations of losses in level of service are difficult to find, as this research is mostly ongoing in the network operators' spheres and as such not publicly available.

Summarising, it can be stated, that intervention planning on gas networks is very much based on safety and reliability, as the consequences of failure are very high. Therefore, the main focus is put on the accurate estimation of failure probability, while using standard models such as age replacement to create the actual intervention program. Interrelations are considered only unidirectional due to the large contribution to the failures (according to Vianello and Maschio (2014), 50% of all failures are due to foreign damage, i.e. gas pipelines damaged during interventions on other networks).

### 2.1.3. Roads

Road networks are to some extent different from other infrastructure networks, as road objects are much more unique, in a sense that every bridge, underpass or tunnel is adapted to its surroundings, using different construction techniques and materials according to the local properties etc., thus being far less standardised than objects on other networks. Due to this uniqueness, intervention strategies and intervention programs are often made for single objects in road networks first and this information is then aggregated to a higher level (Sathaye and Madanat, 2012; Lee and Madanat, 2015). In other words, for roads there is a distinct tendency for a bottom-up approach in the creation of intervention programs.

On object level, Miyamoto et al. (2000) presented a model for rating concrete bridges using a multi-step model that maximises the condition improvement to cost ratio. The first step consisted of performing bridge inspections. The second step consisted of the evaluation of the inspection results taking into consideration the technical specifications. The third step consisted of ranking the results using a scale of 0 to 100. Based on the rating, the deterioration observations from the inspection could be characterised and the remaining life of the bridge estimated. Combining the cost and effects of both repair interventions and strengthening interventions with the prediction curve of the object deterioration it was possible to determine both the quality and costs related to the candidate intervention programs. Miyamoto et al. (2000) then used genetic algorithms to determine the best intervention program by applying a multi-objective optimisation in two steps. In the first step, the minimal cost solution (i.e. the intervention program with the lowest costs that fulfils all boundary conditions) is found, which gives information about the quality achieved at minimal costs. This is then evaluated incrementally in the sense of an incremental cost-benefit analysis, giving the intervention program that yields the highest quality increase per additionally spent monetary unit compared to the minimal cost solution. However, the created intervention program is only optimal for one single object, and does neither consider other objects, other networks, nor disturbances to the traffic caused by the interventions. Also, the deterioration curve was assumed as a bi-quadratic curve, with the remark, that the actual deterioration curves should be acquired from monitoring and experimental data.

Frangopol et al. (2001) proposed a way to determine intervention programs for bridges based on how the reliability of the bridges deteriorates over time, instead of the how the physical condition was changing over time. This approach is similar to the approaches used for electricity and gas networks, though, with the advantage of better inspection possibilities and as such a better baseline for the estimation of the associated probability functions. Monte-Carlo simulation was used to determine the optimal intervention program with the highest cost-benefit ratio, taking into account the intervention costs but also user costs due to re-routing over the whole object lifetime. Nevertheless, network effects were not accounted for, as the methodology only calculates the optimal intervention program for one single object (a bridge). Additionally, the re-routing assumes a fixed cost for a detour, which implies that network effects (e.g. an intervention on the detour route) cannot be accounted for. Other infrastructure networks were also not considered.

Deshpande et al. (2010) presented a reliability-based approach on pavement replacement, that uses fragility and demand curves to estimate failure probability curves for a single pavement section system consisting of multiple pavement layers with different properties. First, the fragility curves are calculated from pavement demand and pavement capacity (both coming from construction type choices) data. Then, this fragility curve is combined with a traffic demand curve to give a reliability function for each pavement layer. In combination with a set of intervention cost functions, three different optimal intervention programs were calculated with a genetic algorithm approach: 1) The intervention program with minimal costs, given a target reliability, 2) the intervention program with maximal reliability, given a maximum budget and 3) the Pareto-surface for the trade-off between minimal costs and maximal reliability. However, only one intervention type was considered, and only for one single object, thus not taking into account any network-related effects. Other infrastructure networks were also not considered.

On a network level, Hajdin and Adey (2006) and Hajdin and Lindenmann (2007) proposed a model to be used to group interventions on multiple objects into work zones, using the simplex algorithm. The goal of the presented methodology is to combine single interventions to an intervention cluster, in order to optimise the impact on road users. The problem is modelled as a directed graph, with the nodes being the possible places where work zones can start and end, and the arcs are used to represent the costs. This translates the optimisation problem into a shortest-path problem with multiple sources and multiple sinks. The cost values for the arcs include direct intervention costs as well as long-term costs to the road agency and user costs due to the intervention (time delay costs) and long-term costs. Solving this shortest-path problem gives the intervention program clusters (i.e. groups of interventions that are executed together), that are called workzones in that model. The model allows for consideration of network travel effects, workzone constraints (e.g. maximum workzone size), and budget constraints. The problem is then solved using a binary linear program. However, the model is only capable of calculating the clustered intervention program for one time period. Additionally, it is assumed that the work zones are independent, which is only justified, if the distance between these zones is sufficiently large, and it was assumed that no economies of scale in combining the interventions exist. In the context of this thesis, that focuses on urban road networks, both assumption do not hold. Furthermore, a linear program requires (at least approximate) linear relationships for all equations, which might also not be the case for urban infrastructure networks. Other infrastructure networks were also not considered.

Lethanh et al. (2018) extended the model from Hajdin and Adey (2006); Hajdin and Lindenmann (2007), by using a mixed integer linear model and thus relaxing the binary constraint, taking into consideration the spatial distribution of objects in the network and the reductions in costs that were possible by combining interventions. Still, the limitation of linearity and one time period remain. Also, other infrastructure networks were not considered.

Mathew and Isaac (2013) presented a genetic algorithm based model to determine an optimal intervention program over multiple years for a rural road network. The multi-objective model calculates the Pareto-front for a joint pavement condition maximisation and maintenance cost minimisation. The fitness function is based on a road condition index that is improved by performing different intervention types depending on the previous condition index, as well as the costs for the execution of each intervention type. However, the methodology does not consider user costs or network effects. Effectively, the road stretches are regarded as independent, and thus no grouping benefits can be accounted for. Other infrastructure networks were also not considered.

For road networks, the level of service can be seen from two different perspectives: 1) the traffic planning perspective and 2) the road management perspective. For the first, level of service is defined by parameters tied to the traffic flow (Yang and H. Bell, 1998), with the exact parameter depending on the investigated problem. This might be vehicles per hour, passengers per hour, or tons of goods per hour. For the second, the level of service definition is mostly based on an object-by-object approach.

From a traffic planning perspective, Kita (2000) presents a level of service indicator that is based on the instantaneous driver utility, by aggregating the drivers' perception of the traffic, using the drivers' utility functions rather than actual road condition. While this approach is able to account for many phenomena that influence the drivers' perception of service, it is hard to obtain the drivers' utility functions, and is seen as not feasible in the scope of this thesis. A more simplified approach that is able to be calculated for most of all networks is the approach by Yang et al. (2000), who describe level of service as a function of the maximum capacity, with the maximum level of service achieved at a capacity below the maximum, and decreasing values above and below that value. However, exact formulations for the level of service are not given. Bhargrab et al. (1999) fill this gap by providing a function for the level of service that is dependent on the nominal capacity, the speed limit and the free-flow speed, as well as the road condition.

From the infrastructure point of view, Frangopol et al. (2014) defined a set of performance indicators, that measure the level of service for a bridge by looking at fragility curves and deriving risk, redundancy- or robustness-based indicators. This risk- or reliability-centred view is also the main difference to the traffic planning perspective. While traffic planning takes into account the road user directly, the infrastructure management approach uses a network-centric approach instead. For example, Adey et al. (2012) defined financial indicators incurred by the road users that can be interpreted as level of service: 1) reduction of travel time cost, 2) reduction of vehicle operating costs, 3) reduction of discomfort costs and 4) reduction of accident costs, and as well an impact hierarchy for the evaluation of intervention programs in (Adey et al., 2012), and another way to determine financial needs in (Adey and Hajdin, 2011). However, these indicators are not able to work independently from a baseline, i.e. a value the actual state can be compared to in order calculate the reduction. Other publications follow the same "reduction of..." approach, such as ASTRA (2003); NZ Transport Agency (2016). While this approach is useful in evaluating new projects, it lacks applicability in the determination of the actual level of service, as no comparison value exists.

Summarising, it can be said that for road network intervention planning, the existing literature is divided into two groups that either focus on single objects while going into a very detailed level about the interactions between the structural components of the single objects, or network-based approaches that model the network as a graph and then solve the intervention planning problem, although due to calculation complexity either multiple time steps or network interactions are omitted. In the level of service literature, also two approaches exist: 1) the traffic-centred approach from traffic planning literature, that is user-centred and calculates the level of service from traffic-flow related parameters, and 2) the infrastructure management approach that evaluates the improvement an intervention program can generate by executing these interventions. However, for that a comparison baseline is needed to compare the improvements to.

### 2.1.4. Sewer

In contrast to electricity and gas networks, sewer networks share the property with roads that object condition is monitored over time albeit to a lesser extent than roads, due to the increased difficulty of access (i.e. in some areas of the sewer network, it is only possible to monitor condition with video camera robots, and not via direct access). This affects the generation of intervention programs in such way, as the general ability to inspect leads to the development of condition-based intervention planning methodologies, but the partly difficulty of access requires the incorporation of statistical approaches, as the uncertainties are at a non-negligible level. For example, Fenner et al. (2000) proposed a GIS-based meta-model to calculate "critical grid squares" where several algorithms (neural networks, fuzzy logic, survival analysis, logistic regression, Bayesian statistics as well as algorithms from electricity and gas network literature (Sections 2.1.1 and 2.1.2)) were used depending on the data availability to predict the likelihood of sewer failure in each grid square. The failure probability of the grid squares was then combined with a consequence factor that estimates the consequence costs of a sewer failure in that grid square. This allowed the determination of geographical "hotspots" as well as finding grids that have the best cost-benefit ratio if the sewers requiring intervention in this grid square were repaired or replaced. From that, the intervention program is constructed by adding grid squares, starting at the highest cost-benefit ratio, until the budget limit is reached. However, as the used grid squares are relatively large ($500\,m$ by $500\,m$), and as network effects are not considered, the authors of this paper consider it only a "screening method", rather than a full intervention planning methodology. Other infrastructure networks were not considered.

Gérard and Chocat (1999) proposed a model that (assuming the main failure mode of sewer systems is overflowing inlets) predicts sewage sections that are vulnerable to sediment build-up (and subsequent overflow) based on a physical model. From there, hazard rankings for each section are calculated, by assigning hazard factors (i.e. numbers that represent the relative risk) depending on surrounding conditions and the location of the pipe section in the network. Finally, vulnerability and hazard ranking are combined to divide the section in five classes by maintenance importance (i.e. combination of vulnerability and hazard ranking). From there, an intervention program can be constructed iteratively by adding pipe sections, starting at the highest maintenance importance class, until the budget limit is reached. Although this paper only focuses on one failure mode, the methodology is able to account for network effects and surrounding factors. Nevertheless, as the presented methodology only uses if-then statements (e.g. "(*IF flooding liability class = 1 AND IF need for repair class ≥4 AND internal hazard factor class < 5) ELSE IF surface property class = 1...*"), an optimisation is very difficult due to the non-smooth properties of the if-then statements. Other infrastructure networks were not considered.

Arthur et al. (2009) proposed a methodology to calculate both intervention programs and adapted monitoring programs for sewer networks, using only limited information. The methodology consists of four modules: 1) A screening module, where any elements with a low probability of failure are removed in order to improve computational efficiency, 2) a consequence scoring module, where the consequences of a failure to the system are calculated, 3) a likelihood scoring module, that estimates the failure probability of the objects, and 4) a combination module that combines the previous information and calculates the intervention program and the adapted monitoring program. Scores were used, as with limited data availability exact calculation of neither consequences nor failure probability were possible. The methodology acts as a framework that can (and according to the authors also should) be filled with more accurate modules that better estimate the failure probability and consequences than a scoring system, if enough data is available. Other infrastructure networks were not considered.

To overcome the problem of data availability, Egger et al. (2013) presented a methodology that estimates sewer deterioration from limited condition data, especially data with a lack of historical records. The methodology is based on a three-condition-states model with interventions being triggered by condition state alone. To obtain the model parameters, Bayesian inference is used in order to incorporate prior knowledge (either from experts or from existing information). Monte Carlo Markov Chain techniques are then used to calculate the posterior distributions. Another approach to increase the data availability is the use of automated inspections, such as robotic CCTV inspection (Kirstein et al., 2012).

Assuming that this information is available, the framework methodology of Halfawy et al. (2008) can be used to determine intervention programs over multiple time steps. In this framework methodology, in a first step, the risk is estimated for each object. Then, the objects are prioritised based on the risk, but also based on other interventions from different infrastructure networks, although this is done only in a unidirectional way, i.e. interventions from other networks are considered, but interventions on sewer networks are not announced to other infrastructure network operators. From the object prioritisation, the intervention program is then calculated using a genetic algorithm based multi-objective optimisation that incorporates object condition, risk, and total costs while taking into account budget, risk and condition state limits. The result of the methodology is a Pareto surface that can be used to calculate an intervention program by choosing appropriate weights for the three objectives. However, the methodology does not consider network effects, and the interaction with other networks is only considered unidirectionally.

For sewer networks, the level of service is tied to a maximum allowable leakage or contamination, with the exact definition depending on local regulations and laws. For example, Gérard and Chocat (1999) describe sewer sediment build-up as a level of service indicator (which leads to overflow and thus potential contamination). Ashley and Hopkinson (2002) define the level of service as the risk of pollution events caused by overflowing and leakage. Le Gauffre et al. (2007) links defects (such as leaks and failures) and dysfunctions (i.e. overflows) to impacts (i.e. the effects of defects and dysfunctions in terms of contamination) in the level of service calculations. In that sense, the level of service can be seen as the environmental impacts caused by non-optimal condition. However, numerical estimates were not given. This gap was filled by Caradot et al. (2011), who used sewer flooding databases in order to give numerical estimates to the defect-dysfunction-impact chain.

Summarising, it can be said that for sewer networks a lack of information exists that influences the methodologies for intervention planning. Either, the methodologies are set up in a way in order to function with a limited data availability (which restricts their accuracy due to the inaccuracies in the input), or methodologies and frameworks are presented that could be used to calculate efficient intervention programs, if enough data was available, which is not the case presently. Therefore, one area of sewer intervention planning is solely focused on improving data availability, either by applying statistical methods or by using automation to gather more data. Interactions between networks are rarely considered, and if, only in a unidirectional way. The level of service definition for sewers is very concurrent in literature, in a sense that it is defined via contamination (either from leakage or overflows). The exact definition however is dependent on local regulations, and as such varies in the numeric values and in what is defined as acceptable.

### 2.1.5. Water

Water distribution networks are, like gas and electricity networks, characterised by their very limited inspection possibilities. Therefore, water distribution networks are also characterised by their binary state (working/non-working). This leads to the same direction in a sense of development of intervention programs: Intervention programs are based on failure probabilities, with the main focus of research put on the exact estimation of the failure probability functions. Shamir and Howard (1979) presented an approach for intervention planning, that uses a statistical evaluation (linear regression) of failure occurrences per year to estimate the failure probability per year. The intervention program is then calculated by calculating the optimal intervention time span for periodic replacement, minimising the sum of replacement costs and expected repair costs due to breaks. However, neither network effects nor other infrastructure networks were considered.

Savic et al. (1995) presented a mathematical framework based on genetic algorithms that can be used to generate intervention programs for water networks for one year, but with inclusion of grouping benefits that arise from combining interventions. The methodology is, however, theoretical in nature and based on the mathematical complexity rather than a real-world problem. No interactions, other networks or multiple years are considered.

Halhal et al. (1997) presented a methodology that is able to calculate intervention programs for water networks for one single year, using a combined cost-benefit approach. The methodology is based on four types of benefits (namely hydraulic benefit, physical integrity benefit, flexibility benefit and quality benefit) that can be generated by replacing pipes in the water network, that are counterbalanced with the costs for the intervention. The intervention program is calculated by applying a genetic algorithm to the optimisation problem (i.e. choosing on which objects an intervention will be executed), that results in a pareto-curve for optimal solutions. This is due to the fact that costs and benefits are measured in different units, and therefore a direct calculation of the optimum is not possible. However, the methodology does not consider other networks or multiple time steps.

Kleiner et al. (2001) presented a methodology that is able to calculate intervention programs for water networks over multiple time steps. The methodology is based on an enhanced age-replacement methodology. First, for each object the cost-minimal intervention age (i.e. the age at which the intervention on the object leads to the minimal overall costs) as well as latest point of intervention (i.e. the latest point in time where the condition of the object does not affect the hydraulic integrity of the network) is calculated. If the "earliest latest point" (i.e. the minimum of the latest points of intervention of all objects) is beyond the planning horizon, no intervention has to be executed. If not, an intervention is executed on the object with the earliest latest point. Additionally, the second earliest latest point is determined. From there, all objects whose cost minimal age of intervention is closer to the first earliest latest intervention point than to the second are combined with the first earliest latest point to an intervention program cluster. This is then iteratively repeated until the next earliest latest intervention time point is beyond the planning horizon. As the methodology allows for different intervention types, this gives multiple possible intervention program clusters. In the last step, these clusters are then evaluated according to their total costs. As this creation and evaluation is a highly dimensional problem, a "dynamic programming combined with partial and (sometimes) implicit enumeration scheme" is employed, without giving more detail. However, this methodology does only consider hydraulic integrity, but no level of service. Additionally, no interactions with other networks are taken into account.

Zayed and Mohamed (2013) presented a method to determine intervention programs using a simulation-based priority index derived from an integrated hierarchy process / multi-attribute utility theory model. Based on this priority obtained from network simulations and the available budget, an intervention program was constructed using the priority index in descending order. By varying the available budget, the optimal clustered intervention program that balances intervention budget and expected failure costs is determined using proprietary optimisation software. However, this methodology neither considers interactions between objects nor interactions with other networks.

Tscheikner-Gratl et al. (2016) presented a methodology that combines water, sewer and road networks into an integrated intervention program. The methodology uses street sections as the smallest unit in which interventions are assumed to be executed jointly. These street sections are then ranked by using priority index that is derived from the condition of the street section objects in each network. Using this combined priority index, as well as boundary conditions for each single network, a prioritisation ranking is calculated that can be used to construct an intervention program by adding the street sections in order of priority until the budget limit is reached. However, this methodology does not account for interactions between the networks, and the level of service changes due to the interventions.

Kerwin and Adey (2017) presented a methodology that combines pipes and facility objects into an integrated intervention program, taking into account length constraints, financial constraints and also expert opinion (i.e. the ability of experts to add or remove objects from the intervention program during the optimisation process). Furthermore, as the methodology is GIS-based, infrastructure managers are able to include freely available geographic information such as road types, road surfaces, soil types as well as geographic information in the form of intervention areas of other utilities in the decision making process, which results in better intervention programs. The methodology accounts for spatial network properties, coordination opportunities with other utilities and priority interventions. Both facility and pipe objects are considered and a common metric (net intervention benefit) is used to optimise interventions. However, interactions between networks are not considered.

There is also a part of literature in water networks, that is focused on network planning (i.e. the determination of an optimal network layout), such as Savic and Walters (1997); Babayan et al. (2005); Matos et al. (2014), but as this thesis is focused on maintenance interventions, this research area is not looked into further.

For water networks, the level of service, as defined by Germanopoulos et al. (1986), consists of three components: 1) hygiene, which refers to microbacteriological and chemical qualities of the water, 2) pressure/flow and 3) temperature. Given that 1) and 3) can be obtained through choice of procurement methods (water sanitation), quality of labour (tight pipe fittings) and burying depth (temperature), only 2) is depending on the state of the network, and therefore within the scope of this thesis. Todini (2000) defines the level of service in terms of an energy balance that compares the demanded hydraulic power (i.e. the product of flow and pressure) to the worst-case hydraulic power need for a network that marginally fulfils the demand without any redundancies. The level of service is better, the greater the difference between actual needed power and worst-case power is. Todini (2000) also presents a level of service estimation in terms of network redundancy that takes into account the different possibilities the demand can be fulfilled (i.e. the more pipe/flow combinations exist that are able to fulfil a demand, the more redundancy is available, and thus the level of service is better).

In summary, it can be said that for water networks the intervention planning literature is based on statistical processes, and is able to calculate intervention programs over multiple time steps. It is also possible to account for other networks, but only to a limited amount, and not with network interactions. The level of service definition, if constrained to pressure/flow components is mainly based on redundancies in providing a sufficient pressure/flow combination.

## 2.2. Suitable models from risk estimation of interdependent networks

In contrast to intervention planning for infrastructure networks, the consideration of interdependence between the networks is one of the key research areas of network vulnerability. Therefore, selected models that were developed for vulnerability analysis are presented that can be used in the context of this thesis.

Johansson and Hassel (2010) presented a model for the vulnerability analysis of interdependent infrastructure networks. Based on a part of the Swedish railway system (17 nodes), a 5-layer interdependent network model (railway network, traction power network, telecommunication network, auxiliary power network and electrical in-feed network) was created. Then, the consequences of removing nodes in a certain location were analysed by evaluating interaction equations between the network. In the context of this thesis, the interaction equations are taken into consideration for setting up the interaction equations between the network. Trucco et al. (2012) extended the model formulation by including the possibility to make the vulnerability analysis time-dependent. This extension (although formulated for vulnerability analysis) can serve as a starting point to develop multiple-year intervention programs for this thesis.

Guidotti et al. (2016) presented a modelling approach to mathematically express the dependencies for urban infrastructure networks, although the focus was on the resilience of critical infrastructure subject to hazard events (i.e. the amount of service that can be provided despite the event-caused failures). The results show the importance of capturing the dependency between networks in modelling the resilience of critical infrastructure, with a remark that these interactions could also be investigated from an infrastructure intervention planning perspective. Additionally, the methodology shows how to find a good balance between calculation time and accuracy, which is taken into consideration when developing the program code for the methodology presented in this thesis.

## 2.3. Suitable models and algorithms from network and graph theory

The research area of network and graph theory presents less a scientific gap, but instead provides algorithms and mathematical models that aid in an efficient calculation by translating the optimisation problem of the presented methodology into a network and graph theory problem for which a solution algorithm exists. If parts of the mathematical challenges in this thesis can thus be translated into an existing graph theory problem, the available solution algorithms can be used (e.g. different flow calculation algorithms on networks).

The following research investigates the applicability of various graph theory algorithms and measures on real infrastructure networks, and as such demonstrate which theoretical models do have practical applicability to infrastructure networks.

In terms of modelling, Eusgeld et al. (2009) investigated the role of network theory and object-oriented modelling for the vulnerability analysis of critical infrastructure.

It was the goal to test the suitability of two network modelling and network analysis methods in order to identify critical links in the Swiss high-voltage power grid. The first method only considered the global topological efficiency of the power grid to calculate the vulnerable line sections, whereas the second method considered both the global topological efficiency and the reliability of the individual lines themselves. The general suitability of both methods has been demonstrated, although the authors state that refinement of these techniques is still needed. In terms of relevance for the methodology in this thesis, the measure of "reliability efficiency" (a network theory measure that accounts for the reliability of the edges in the network) can be reformulated by replacing the "failing edges" from the vulnerability analysis with edges that have an intervention executed on them. Additionally, Eusgeld et al.'s object-oriented modelling (i.e. using a physical resistance model for each object, as is also done in this thesis) goes in line with the research by Van den Berg et al. (2014) presented in section 2.1.1, and thus supports the chosen approach, both from Eusgeld et al. and from this thesis' methodology. In summary, although the area of research done by Eusgeld et al. is not directly related to the determination of intervention programs for urban infrastructure networks, the modelling approach and the network object representation, as well as the network theory measures can be used, as the underlying graph theory problems are of the same nature, albeit with deliberate deactivation of objects (i.e. by executing an intervention) than accidental (i.e. due to vulnerability-caused failures). Additionally, research papers on the topic of intervention planning have been written specifically on risk assessment of network objects (Burkhalter et al., 2018), and the planning of optimal intervention programs on railway infrastructure networks (Mizutani et al., 2017).

Garland et al. (2009) presented a framework to incorporate network topology into asset management decision making. This framework is rather general as it lists the steps ( *"Step 1: Define the systems of interest", "Step 2: Identify the intrinsic components of each network", [...], "Step 7: Asset management analysis"*), but does not go into more detail about how the asset management analysis (in the context of this thesis: the determination of intervention programs for urban infrastructure networks) should be performed. Nevertheless, the modelling approach aids in setting up a network theory based approach that helps in accurately assessing the service on infrastructure networks.

Jiang and Claramunt (2004) conducted a network-theoretical analysis of urban road networks in order to determine their topological type. Using three standard graph measures (mean connectivity, average path length and clustering coefficient) as well as a new proposed measure of k-connectivity, the authors proved that these networks show small-world-network properties[2]. Small-world-networks are very robust against random attacks, but vulnerable against targeted attacks. In the context of this thesis, small-world-network properties signify that the perturbations caused by interventions are strongly dependent on the actual object on which the intervention is executed (with in this thesis the intervention being the counterpart to an attack, as both lead to the object being out of service for a certain time). In the context of this research, this information helps in setting up the level of service model for roads.

In addition to the work that has been specifically done in the context of infrastructure networks, there has also been work done recently to better define graph relations and data mining. This is based on the concept of storing information as graphs (Sowa, 2014) and thus being able to use graph-theory based algorithms to evaluate this information. If information objects are reinterpreted as infrastructure objects, the act of grouping interventions on objects can be reinterpreted as grouping of information. In the context of information, this grouping is referred to as “clustering”, and the grouped (information) objects together are then called clusters. According to Witten and Frank (2005) *”... these clusters should reflect some mechanism at work in the domain from which instances or data points are drawn, a mechanism that causes some instances to bear a stronger resemblance to one another than they do to the remaining instances.”* When thinking of constructing intervention programs, the spatial location of the interventions can be thought of as the domain, the interventions can be thought of as the instances and the resemblance can be thought of as the location. This means that the construction of clustered intervention programs, which involves the grouping of interventions, can be seen as a spatial clustering problem. Fung (2001) presents an overview about different families of clustering algorithms that serve as a valuable contribution to the grouping of interventions, as this paper lists the requirements as well as the expected accuracy of the clustering algorithms.

[2] in the sense that the number of steps required to connect from any street to any other street of a city is in general very small

## 2.4. Supporting optimisation techniques for large problems

As mentioned in chapter 1, part of the challenge to find optimal intervention programs is the combinatorial complexity of the mathematical problem. The scientific field of mathematical optimisation theory provides possible solutions to these problems. However, it is important to note that this field uses different terms and definitions in contrast to the common language when referring to optimisation. The umbrella term used is *optimisation techniques*, that can be divided into three groups, with the following definitions used:

Algorithm: An optimisation technique that finds the exact optimum of an optimisation function (i.e. a function of the value(s) to be optimised) in a finite number of steps (in a mathematical sense, i.e. *countable* steps)

Iterative method: An optimisation technique that converges infinitely close to the exact optimum of an optimisation function.

Heuristic: An optimisation technique that has a lower bound at the iterative method and an upper bound at an algorithm, i.e. in the worst case, a heuristic behaves like an iterative method, and in the best case a heuristic behaves as algorithm.

In common language the terms would perhaps be "exact method", "close method", and "approximate method", but as the presented optimisation techniques in Figure 2.1 bear names according to the shown definitions, the (rather uncommon) definitions have been given in order to improve understandability.

In optimisation theory, one very important theorem is the *"No-free-lunch theorem"* (Ho and Pepyne, 2002). This theorem states, that there is no optimal optimisation technique (i.e. a "free lunch") that works on any problem type, but that any optimisation technique can outperform all the others if this technique is specialised to the specific problem. For example, as shown in section 2.1.3, Hajdin and Lindenmann (2007) employed the simplex algorithm to determine optimal highway worksite zones, by formulating the problem as a shortest-path problem that could be solved by the simplex algorithm. This algorithm relies on the optimisation function to be linear in order to find the optimum. Although few optimisation functions are truly linear, this algorithm is employed successfully in many cases, as for a number of optimisation problems a linearised function is an appropriate approximation. For interrelations between different infrastructure networks however, Szimba and Rothengatter (2012) investigated the use of different optimisation techniques, and recommended the use of heuristics. Heuristics are employed, if an algorithm is computationally unfeasible (commonly found in NP-hard problems) or if an exact solution cannot be found due to mathematical properties of the optimisation functions. So far, many different heuristics have been developed. Since 1986 the term *metaheuristics* started to appear in literature, with metaheuristics being defined as higher-level heuristics designed to find a sufficiently good solution to an optimisation problem, especially with incomplete or imperfect information or limited computation capacity (Bianchi et al., 2009). Figure 2.1 gives a brief overview over the common metaheuristics.

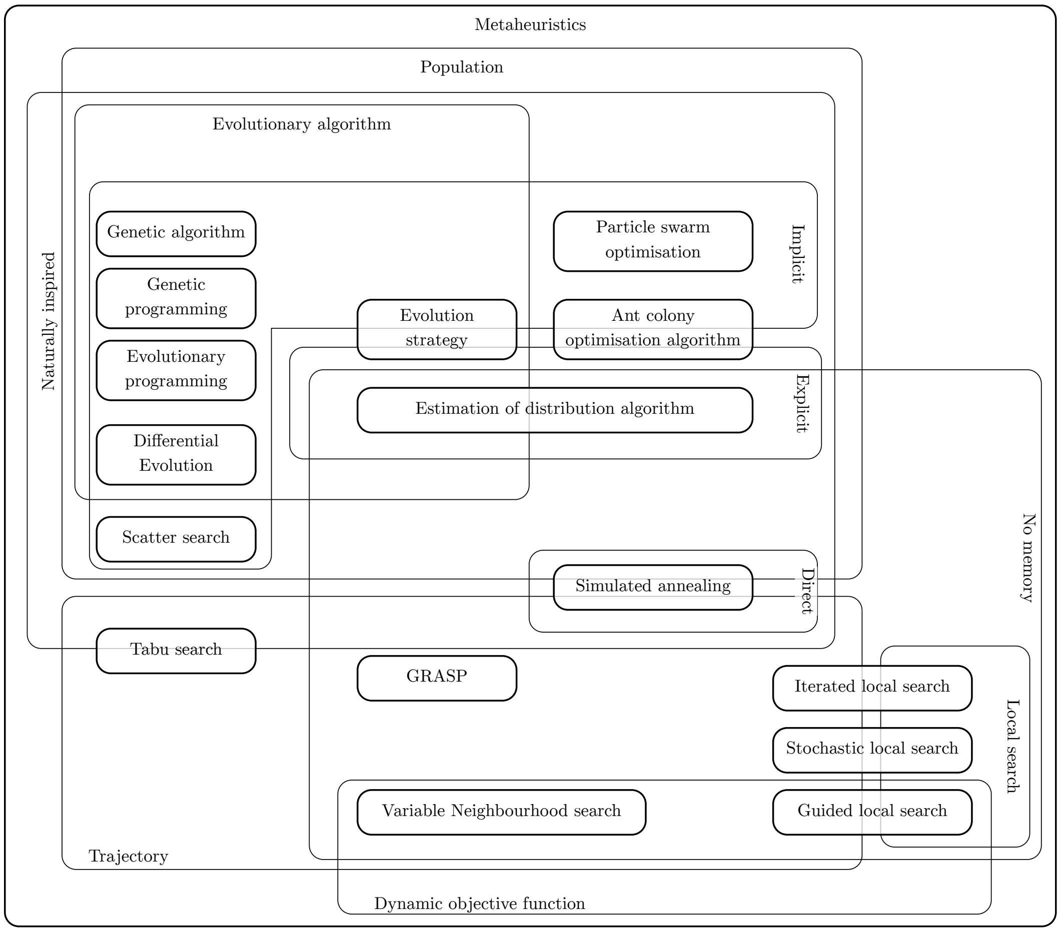



Figure 2.1.: Metaheuristics overview, graphics adapted from Johann "nojhan" Dréo and Caner Candan, licensed under CC-BY-SA 3.0

Note that in Figure 2.1, the term "algorithm" appears in some of the presented metaheuristics. These heuristics are algorithms in the strict sense of the definition, i.e. they return the exact optimum in a finite (although possibly lengthy) amount of time. When going through the respective networks, one very prominent metaheuristic algorithm is the Genetic Algorithm. Note that the designation is true in a sense that a genetic algorithm finds the exact optimum, however in some cases, the number of steps required can be very large, i.e. as it approaches exhaustive enumeration. Genetic algorithms are beneficial for the particular problem of this research project due to their robustness, practicability, and general-purpose stochastic search-based optimisation technique that can provide a comparable level of accuracy while being more efficient than conventional optimisation techniques. Additionally, genetic algorithms only require information about the objective function itself, but not about the gradient, which is a great simplification to the mathematical model. Goldberg and Holland (1988) favour genetic algorithms because it is possible to start with multiple existing solutions to the problem (i.e. initial population; from experience or prior calculations) and use probabilistic rules to generate new and better populations, which is more efficient and increases the likelihood of finding optimal solutions in a timely fashion. Due to that, genetic algorithms are seen as a promising optimisation algorithm for the networks in this research. However, the challenge of using genetic algorithms is to find the right balance between population size (breadth search) and number of generations (depth search).

## 2.5. Summary and identification of scientific knowledge gap

Summarising the literature review, it can be said that the available literature on single infrastructure networks can be divided into two parts: 1) Literature about intervention planning, and 2) literature about level of service. The intervention planning literature is summarised in Tables 2.1 and 2.2, the level of service literature is summarised in Table 2.3. The presented literature in sections 2.2, 2.3, and 2.4 is a selection of models and algorithms that are considered during various modelling and calculating stages in the methodology presented in this thesis.

Table 2.1.: Intervention planning literature summary, part 1

| Author | Network | Object types | Optimisation goals | Considered characteristics | Optimisation technique | Result | Simplifications | Unconsidered characteristics |
|---|---|---|---|---|---|---|---|---|
| Shamir and Howard (1979) | water | pipes | minimise sum of intervention costs and emergency repair costs | failure occurrences per year | linear regression | optimal time interval between interventions | independent objects | network effects, other infrastructure networks |
| Savic et al. (1995) | water | pipes | minimise costs | grouping vs. single intervention | genetic algorithm | optimal intervention program | theoretical model | multiple years, other infrastructure networks |
| Halhal et al. (1997) | water | pipes | multi-objective | network effects, cost | genetic algorithm | optimal intervention program pareto set | linear costs | multiple years, other infrastructure networks |
| Pandey (1998) | gas | pipes | minimise object failure probability | failure probability function, inspection data | Monte-Carlo simulation | optimal time interval between interventions | linear deterioration, only one pipe diameter | network effects, other infrastructure networks |
| Gérard and Chocat (1999) | sewer | pipes | minimise overflow events | pipe properties, location, network effects | iterative method | optimal intervention program | scores instead of real values | user costs, other networks |
| Fenner et al. (2000) | sewer | pipes | maximise benefit-cost ratio | pipe properties, location, | several methods from literature | hot-spot areas | uses grid squares | network configuration, network effects, other networks |
| Miyamoto et al. (2000) | road | bridges | maximise condition improvement to cost ratio | inspection data, failure probability function | genetic algorithm | optimal intervention program for one object | bi-quadratic deterioration | network effects, other objects, other infrastructure networks |
| Frangopol et al. (2001) | road | bridges | maximise benefit-cost ratio | inspection data, fragility curves | Monte-Carlo simulation | optimal intervention program for one object | fixed-route detour | network effects, other objects, other infrastructure networks |
| Kleiner et al. (2001) | water | pipes | minimise intervention costs | deterioration models, network configuration | unnamed dynamic approach | optimal clustered intervention program | only hydraulic integrity | level of service, other infrastructure networks |
| Stillman (2003) | electricity | all | minimise sum of intervention costs, emergency repair costs, service interruption costs | maximal failure probability | analytic | optimal time interval between interventions | independent objects, perfect replacement, no time out of service | network effects, other infrastructure networks |
| Hajdin and Linden-mann (2007) | road | all | minimise short and long-term costs for users and road operators | network structure, traffic configuration | linear program | optimal clustered intervention program for one year | linearisation, independence of work zones | multiple years, other networks |
| Halfawy et al. (2008) | sewer | pipes | Pareto front for cost minimisation, condition maximisation, and risk minimisation | object condition, budget, condition state limits | genetic algorithm | optimal intervention program over multiple time steps | | network effects, interactions between networks only unidirectional |

Table 2.2.: Intervention planning literature summary, part 2

| Author | Network | Object types | Optimisation goals | Considered characteristics | Optimisation technique | Result | Simplifications | Unconsidered characteristics |
|---|---|---|---|---|---|---|---|---|
| Arthur et al. (2009) | sewer | pipes | framework only | failure probability function, inspection data, network effects | framework only | optimal intervention program | scores instead of real values | other networks |
| Louit et al. (2009) | electricity | conductors | minimise cost as in (Stillman, 2003), maximise availability, or maximise profit for the network operator | budget limit, availability limit | statistical estimation | optimal time interval between interventions | failure modes disregarded, fixed intervention policy, costs time-independent | network effects, other infrastructure networks |
| Deshpande et al. (2010) | road | pavement layers | minimise cost, maximise reliability and Pareto surface from both | pavement design demand, traffic demand, actual pavement load | genetic algorithm | optimal intervention program for one object | only one intervention type | network effects, other infrastructure networks |
| Egger et al. (2013) | sewer | pipes | determine deterioration function | failure probability function, inspection data, expert knowledge | Monte Carlo Markov chain | deterioration function posterior distributions | | intervention programs |
| Dehghanian et al. (2013) | electricity or gas | all | maximise condition improvement to cost ratio | failure probability, network reliability | iterative method | optimal strategy to construct an intervention program | general level, no detailed methodologies given | other infrastructure networks |
| Mathew and Isaac (2013) | road | all | Pareto front for cost minimisation and condition maximisation | road condition index, intervention types, condition index history | genetic algorithm | Pareto front to calculate intervention programs | independent objects | network effects, other infrastructure networks, grouping benefits |
| Zayed and Mohamed (2013) | water | pipes | minimise sum of intervention costs and expected failure costs | network simulation | proprietary optimisation | optimal clustered intervention program | objects independent | network effects, other infrastructure networks |
| Lethanh et al. (2014) | road | all | minimise short and long-term costs for users and road operators | network structure, traffic configuration, spatial distribution | linear program | optimal clustered intervention program for one year | linearisation, independence of work zones | multiple years, other networks |
| Tscheikner-Gratl et al. (2016) | water, sewer, road | pipes / road section | minimise criticality | object condition, deterioration models, network configuration | iterative method | optimal clustered intervention program | | interactions between networks, level of service |

Table 2.3.: Level of service literature summary

| Author | Network | Level of service definition | Remarks |
|---|---|---|---|
| Rietz and Sen (2006) | electricity | loss of load probability, expected unserved energy | assigned costs are unreliable |
| Choi et al. (2006) | electricity | expected unserved energy | industry costs can be approximated |
| Reichl et al. (2013) | electricity | expected unserved energy | approximation lacks data |
| (OFGEM 2009) | gas | pressure, flow, reliability and safety | minimal standards, but no real level of service |
| Yang and H. Bell (1998) | road | traffic flow (vehicles per hour, passenger per hour,...) | exact parameter depending on investigated problem |
| Bhargrab et al. (1999) | road | function of nominal capacity, speed, road condition | takes into account road condition directly |
| Kita (2000) | road | instantaneous driver utility | drivers' utility functions are hard to obtain |
| Yang et al. (2000) | road | function of maximum capacity | maximum level of service is below maximum capacity |
| Adey et al. (2012) | road | financial benefit due to reduction in user costs | baseline for comparison is difficult to define |
| ASTRA (2003); NZ Transport Agency (2016) | road | reduction in....(multiple parameters) | baseline for comparison is difficult to define |
| Gérard and Chocat (1999) | sewer | sediment build-up | physical model |
| Ashley and Hopkinson (2002) | sewer | risk of pollution events | pollution costs are hard to define |
| Le Gauffre et al. (2007) | sewer | defect-dysfunction-impact chain | environmental impacts due to sewer condition |
| Caradot et al. (2011) | sewer | defect-dysfunction-impact chain | number estimates for Le Gauffre et al. (2007) |
| Germanopoulos et al. (1986) | water | hygiene, pressure/flow, temperature | |
| Todini (2000) | water | hydraulic power | energy balance approach |
| Todini (2000) | water | network redundancy | flow/pressure combinations that can fulfil the demand |

As can be seen in Table 2.1, most methodologies for infrastructure intervention planning lack consideration for other infrastructure networks, or even other objects in the same network. The few methodologies that consider other infrastructure networks do it either unidirectional or, as a trade-off, do not account for network effects. The methodologies that account for network effects however do not account for multiple time steps, i.e. the intervention program is only developed for one planning period.

So far, a methodology that combines intervention planning over multiple networks with multiple time steps and with consideration of level of service is still lacking.

However, in other scientific fields, several models and algorithms have been presented that can aid in developing such a methodology. Therefore, it can be assumed that it is possible to present a methodology that fills the gap of combining intervention planning over multiple networks with multiple time steps and with consideration of level of service.

# 3. Current situation

In this chapter, the current situation on the investigated networks (electricity, gas, road, sewer, water) is described, in order to lay the foundation for the technical concept (see Chapter 4) of the methodology presented in this thesis. First, an overview about the infrastructure management process (building on the definitions in Adey (2017)) is given from a general perspective, to be able to be applicable to all five infrastructure networks investigated in this thesis. This serves as a background in order to show the practical scope of this work. It also shows how the contribution of this work is embedded in the whole infrastructure management process, as defined in Adey (2017). Then, an introductory section about stakeholders is given, to serve as a basis to define a common language and to show, where the methodology of this thesis contributes to an improvement for the practical problems. Finally, for each network, the general properties of the objects and the provided service, the loss thereof due to deterioration, as well as inspections and the different types of interventions are described from a practical point of view, in order to point out the similarities but also the discrepancies to the academic state-of-the art.

## 3.1. Infrastructure management process

Urban infrastructure networks, such as electricity, gas, road, sewer and water distribution networks, are built to provide services to the public. In order to be able to provide these services, infrastructure networks have to be managed in a way that ensures service provision over the assets' whole lifetime. Figure 3.1 shows a lifetime process of a generic infrastructure network asset, as defined in (Adey, 2017). The process is drawn using *BPMN 2.0*, a standard for drawing process models (for an introduction to *BPMN 2.0*, see Allweyer (2010)).

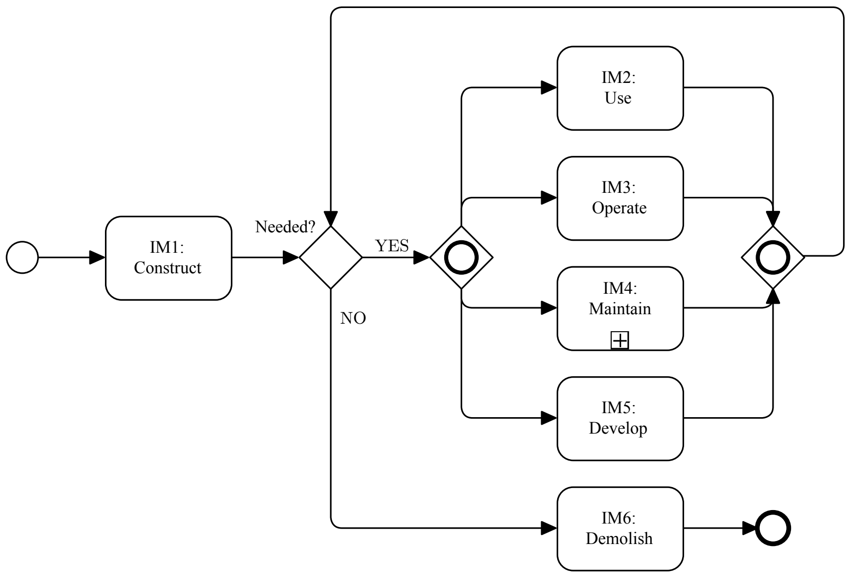



Figure 3.1.: Infrastructure lifetime diagram (Adey, 2017)

First, the asset is constructed at some point in time (Task IM1). Then, a decision loop starts where it is asked, if the asset is still needed. If yes, four concurrent tasks may run at the same time: 1) Task IM2: the asset is used by the customers to receive the service, 2) Task IM3: the asset is operated by the network operator to ensure service provision on a momentary time scale, 3) Task IM4: the asset is maintained by the network operator to ensure service provision on a long-term timescale, and 4) Task IM5: the asset is developed to accommodate for network and demand changes. It is not necessary that all four tasks run at the same time. For example, if a city does neither grow in size nor in population, the network does not have to be extended, and as such the development process might not be active in certain time steps. The decision loop is then iterated over time until the asset is no longer necessary. Then, the asset is demolished (Task IM6) to free the space for other uses.

Infrastructure intervention planning is part of the maintenance task (IM4), therefore this task is shown in an expanded version in Figure 3.2 (expanded tasks are marked with a ⊞ symbol). Figure 3.2 also shows the focus of this thesis, and how it is embedded in the maintenance task.

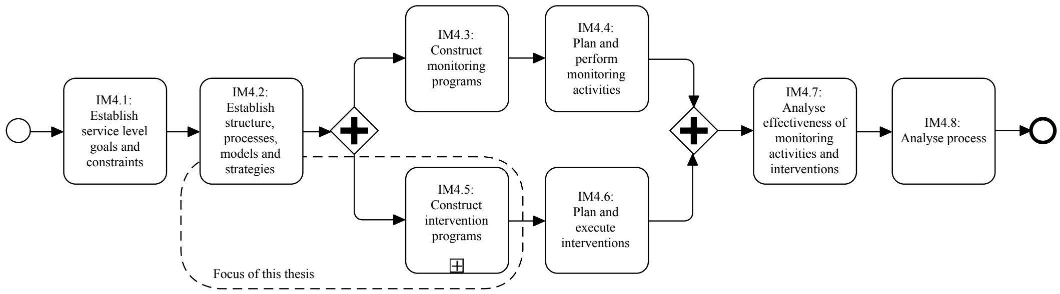



Figure 3.2.: Infrastructure maintenance task, adapted from Adey (2017)

The first task within infrastructure management (IM4.1) is to establish service level goals and constraints, that define what is an optimal service, and what can prevent optimal service provision (e.g. available financial resources). It is an iterative task that brings together the requirements and wishes from multiple sources and coalesces them into a common set of goals and constraints, and eliminates conflicts or makes clear how trade-offs are to be made between them.

The next task (IM4.2) is to establish structure, processes, models and strategies. Structures and processes define the "view of the world" of infrastructure management, i.e. how different actors, models, indicators and evaluations relate to each other, as well as data and algorithmic models and processes. Models are used to help make predictions of what will happen in the future, e.g. the future required service level, the future ability of the infrastructure to provide the service level, and the costs associated with states of the items, and to determine optimal strategies and programs, e.g. optimal monitoring strategies, optimal intervention strategies, optimal monitoring programs, and optimal intervention programs. This is the reason that a small part of this thesis' focus is also put on this task, as the construction of an optimal intervention program is dependent on the models available, which have to be compatible with the optimisation technique used in the construction of optimal intervention programs. Strategies include all activities to be performed on infrastructure taking into consideration many possible states of the infrastructure. These are established independently of the actual state of the infrastructure. When they are developed, consideration is to be given to the range of possible activities in each possible state and the associated costs.

From this task on, two task groups are being executed in parallel: 1) monitoring tasks, i.e. construction of monitoring programs, and planning as well as performing of the monitoring activities, and 2) intervention tasks, i.e. construction of intervention programs, and planning as well as executing the interventions. Both construction tasks build upon the processes, models and strategies that were defined earlier.

The construction of monitoring programs (which can be done bottom-up or top-down) is an iterative process that selects the specific monitoring activities to perform, taking into consideration the actual state of the infrastructure and the strategy to be followed. The constructed monitoring program is then planned and executed, which includes to schedule and perform the monitoring activity, and to verify that the monitoring activity was performed satisfactorily.

The task of construction of intervention programs, which is the main part of this thesis, follows the general process shown in Figure 3.3

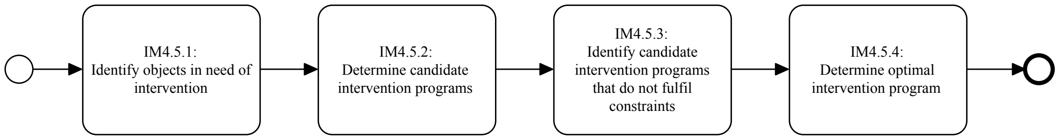



Figure 3.3.: General process for construction of optimal intervention programs, adapted from Adey (2017)

In this process, first, objects are identified that are in need of an intervention. This is done using the models and strategies defined earlier. From these objects, candidate intervention programs are calculated by means of combination, grouping and temporal shift of interventions (i.e. single interventions are combined with other interventions to groups and/or are shifted in time to capture grouping benefits.) These candidate intervention programs are then screened for compliance with the constraints, and only those that fulfil the constraints are passed to the optimisation technique, that in the end determines the optimal intervention program, with the optimum being defined by the goals set in the first task of the infrastructure maintenance process.

After determination of the optimal intervention program, the planning and execution of interventions includes all activities from completion of the intervention programs to supervision of the execution of the interventions.

The analyse of the effectiveness of monitoring activities is then performed to compare the actual completed monitoring activities with the expected monitoring activities, and the actual completed interventions with the expected interventions, with respect to their costs and their effect on the infrastructure. The results of this task can be used to modify existing monitoring programs, but can also be used to update the information used in the processes to establish service level goals and constraints, processes, models and strategies.

The final task of the infrastructure maintenance process is then to analyse the process as a whole to ensure that it is working as expected and to see if possible improvements can be made.

By repeatedly performing this infrastructure maintenance process in the context of the infrastructure lifetime (Figure 3.1), an adequate service can be provided. To be more precise, a service above predefined levels, i.e. levels of service, is provided. For example, $x$ persons should be able to draw $y$ $m^3$ of drinking water at a pressure of $z$. These services, however, cannot always be provided at the desired level of service. A deviation from this level of service happens due to various reasons, such as a leak in water pipes, or potholes in a road that limit its capacity. Interventions, such as replacing a leaking pipe or resurfacing a road are possibilities to counteract this, but they themselves cause a loss in level of service, as the service has to be temporarily reduced or interrupted to be able to execute these interventions. In some cases, other ways to compensate for this loss in level of service are also possible, for example increasing the flow and pressure level in a water distribution network.

The interventions performed on the basis of an infrastructure maintenance process cause effects on the investigated networks (either positive, by improving the condition, or negative due to service interruptions or failures). These effects on stakeholders due to losses in level of service both between and during the execution of interventions can be quantified using monetary units and can be referred to as "costs". In order to determine the optimal intervention programs, it is necessary to estimate these costs. In order to determine the optimal intervention programs for multiple networks of different types, it is useful to have a similar way to estimate the costs related to each. This becomes even more important, if this estimation is used in an iterative optimisation procedure, where the same calculation has to be executed many times in order for the algorithm to function efficiently.

If multiple real world networks are to be considered, it is even more likely than on single networks that the objects are in different phases of their lifecycle (as shown in Figure 3.1), i.e. the networks consist of objects with different age and condition.

In order to calculate optimal intervention programs, this also has to be taken into account. With a general overview of the infrastructure management process given (using the definition of Adey (2017)), the next section explains how this thesis is situated in the infrastructure management process.

## 3.2. General overview of stakeholders and interventions on infrastructure networks

Infrastructure networks are built to provide services to people, and are operated, maintained, and developed by either the government or private entities. The services itself are also produced by certain entities, again either governmental or private. All these entities are stakeholders in those infrastructure networks, however the stakeholders differ from network to network. Therefore, in this section, the general definition of stakeholder used in this thesis is given, together with the different actions the stakeholders perform on the network. The grouping of the stakeholders was chosen in order to best explain the methodology. Certainly it is possible to use a different subdivision of stakeholders. (e.g. the "customers" of a network can for example be subdivided into "private customers" and "public customers" (which can further be divided into e.g "hospital", "police", etc.). However, for ease of understanding, the subdivision presented in the next sections is used. Then, in sections 3.3 to 3.7, the general definition of stakeholders and actions is detailed for each investigated network. In this thesis, a stakeholder is defined as someone who uses the infrastructure to provide a level of service or uses the infrastructure to receive a level of service. Figure 3.4 shows a general overview of the stakeholders:


Figure 3.4.: Stakeholders of a network-distributed service

The producer is responsible for producing the "goods" (e.g. freshwater, gas, electricity) demanded by the receiver. It is also possible that more than one producer exists. The distributor (i.e. the network operator) is responsible for the distribution of the goods, i.e. ensures that the goods produced reach the receiver. It is also possible that two stakeholders are one entity (i.e. company). All three stakeholders influence the transport (i.e. flow) of the goods on the network, but also benefit from the network in one way or the other. The producer can distribute his service on the network and sell it to the receiver. The receiver benefits from the service and pays for it to the producer. The distributor keeps the network in such a state that the distribution from producer to receiver is functioning (i.e. the network is functioning) and charges producer, receiver, or both for providing an adequate level of service on the network.

Over time, the level of service on the network will decrease due to natural deterioration processes. To counteract this, two different actions can be performed, that are defined in the following:

**Intervention:** An activity that modifies the infrastructure, which is usually executed to improve the ability of the network to provide an adequate level of service. Interventions are only executed by the distributor. For example, if the failure probability of a certain object exceeds a defined threshold, it will be replaced.

**Countermeasure:** An activity that modifies how infrastructure is used, which is usually executed to ensure that an adequate level of service is provided. Countermeasures are executed by the producer. For example, if a leak occurs in a water distribution network, the producer may increase pressure and flow to compensate for the losses caused by the leak. This would be the countermeasure[1] to the leak occurring.

Both interventions and countermeasures are conducted to remedy the decreasing level of service that is caused by the deterioration of the infrastructure network objects over time. This deterioration can be caused by many different processes, that are specific to each network and its object types and object properties. They will be explained in the subsequent chapters.

In order to develop intervention programs, intervention strategies (i.e. when and what kind of intervention is executed on different objects) have to be defined. These strategies can be solely based on the age of the object (which can to some extent proxy deterioration), but also be based on actual deterioration. On some objects, depending on object type and network, deterioration can be monitored directly. If part of the intervention strategy (which is depending on the network, and the

[1] The network operator will, in many cases, schedule an (immediate) intervention as well.

monitoring effort), the deterioration can be monitored, and with ample monitoring data, the deterioration functions can be estimated. For other objects, that are not directly monitored (either due to possibility or due to strategy), the estimation of the deterioration function has to be based on failure data, or if available, data from preventive replacement (i.e. if an object is replaced preventively, its condition should be assessed after removal in order to provide more data points for better accuracy in deterioration function estimation).

After obtaining the state of the object (depending on intervention strategy either by age, by deterioration (function), or by other means), an intervention program has to be determined. This process starts with first setting the goal and the constraints of the intervention program. These goals can for example be to maximise reliability, to maximise the service provided, to minimise the total costs, or other goals set by the infrastructure managers. Together with these goals, constraints have to be taken into account. These constraints can originate from laws and regulations, or can be one of the not selected goals. For example, an optimisation goal can be to generate an intervention program that maximises the availability of the service with a given budget limit. In this case, the availability is the optimisation goal, and the budget limit is the constraint. One can also minimise the cost for an intervention program, while assuring a certain minimal level of reliability. In that case, optimisation goal and constraint have been switched.

After setting an optimisation goal, the decision variables have to be determined. These variables are the properties of a specific intervention that can be changed in order to optimise the intervention program, for example time and type of intervention, or if an intervention is executed with total closure of the object or just a capacity reduction. Depending on the network and object type, a capacity reduction may not be possible in all cases (e.g. if a valve has to be replaced, the flow has to be shut off before and after the valve). Interventions also might have an impact on other networks and therefore a decision variable, that determines whether the interventions are grouped or not, can be included in the set-up to be used to determine the optimal intervention program. However, this is rarely done. Instead, when the intervention program is found, some network managers try to benefit from synergies by coordinating the intervention program with other infrastructure networks.

The next sections now describe the investigated networks, starting from the properties and the definition of service on the network. Then, the deterioration is described, together with the way how intervention programs are determined for each network. Finally, remarks about coordination with other networks are given. Section 3.8 summarises the current situation on the networks.

## 3.3. Electricity network

### 3.3.1. Network properties

The urban electricity network (in some literature also called "*power delivery infrastructure*" or "*power distribution grid*") is a potential network (i.e. a network, where the flow is caused by potential differences between the nodes), that consists primarily of two object types: 1) conductors (longitudinal objects), and 2) point-like objects (such as substations, transformers, switches, voltage regulators, monitoring systems etc.). These components have to function as a whole system to provide the service of electric power to the customers. In the process of providing the service, there are three stakeholders involved, that are shown in Figure 3.5.

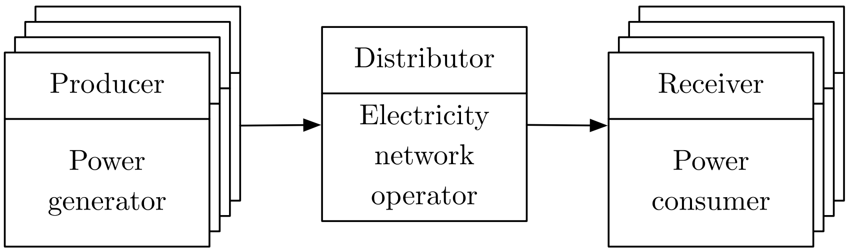



Figure 3.5.: Electricity stakeholders

The first stakeholder is the producer group, that consists of power generation companies, that run power plants. These plants can be located in the vicinity but also at greater distances, and are connected via a wide area grid. Both are connected to local substations, that provide the infeed point to the urban electricity network. This stakeholder group can (and has to) permanently adapt the generated power to the demand to keep the network in balance (i.e. prevent exceedance of the operating limits).

The second stakeholder is the distributor, i.e. the entity that operates the distribution network. It is this stakeholder's responsibility to keep the network in a state that allows to distribute the generated power to the consumers with an acceptable level of losses, both due to the state of the network (e.g. resistive losses on the conductors, transformation losses, power factor, etc.) and the performed maintenance (i.e. service interruptions due to interventions or fault-caused interruptions due to inadequate/insufficient maintenance).

The third stakeholder is the consumer group, that consists of both private and industrial (i.e. large volume) customers. The consumers use the generated and distributed power, and pay for the received service. The payment is then split up into a network fee and a generation fee. There are different types of contracts, that specify exactly the service that should be provided to the customer. The main component of these services is a guaranteed maximum current, as well as certain voltage limits that have to be kept. For example, a customer can order a connection of $125A$ at $230V \pm 5\%$. This gives a power of $125 \cdot 230 = 28.75\, kW$. For industrial customers, there can be additional terms in the contract, which for example allow load-shedding (i.e. allow a disconnection of the industrial customer under certain circumstances in exchange for lower fees). As a general summary, it can be said that contracts (and with that the definition of service) for private customers are more or less standardised, with only the connection current being the adjustable value, but for industrial customers, the contracts are much more specified and tailored to the actual industrial application of electricity (i.e. if the production process allows for temporary power outages, or if a high availability level is needed, and so forth). However, for both customers, the core part is a specified current at a specified level of voltage, i.e. a certain level of power[2].

### 3.3.2. Service definition

The level of service for an electricity network can be defined as:

> "the ability to provide the consumer with a specified level of power at a specified level of voltage"

An adequate level of service is thus the ability to provide this specified level of power at the specified level of voltage to all consumers, and an inadequate level of service is the inability to do so. A loss in level of service is the difference between the desired level of service and the provided level of service.

[2] as power is the product of voltage and current

There are multiple reasons that a loss in level of service can occur. They can be attributed to either the producer or the network operator (in many cases, this is also the same organisation, so that one organisation is responsible for both power generation and distribution). On the production side, a loss in level of service can be caused due to insufficient power generation (in terms of voltage and/or current, as power is the product of both) to provide the desired level of service. On the distribution side, the loss in level of service can be caused by the state of the network, i.e. the condition of the conductors and switches or whether a conductor is out of service due to failure or due to an intervention. A conductor being out of service changes the network configuration and causes the current flow to either being redirected, changing the voltage and current levels in the network, or, if consumers are only connected by out-of-service conductors, the consumer being totally disconnected from the network. The losses due to non-optimal conductor condition can mainly be attributed to stray currents, which are dependent, among other things, on the insulation around the conductors. A good overview about these can be found in Willis and Schrieber (2013). As a countermeasure, the producer has to increase the produced power to sustain the desired level of service, if there is enough power production capacity. Alternatively, the network operator can execute an intervention on the conductors (i.e. repair or replacement) to limit the amount of stray currents and thus the loss in level of service over the network, in which case the cost of taking this conductor out of service is the loss in level of service during the intervention.

### 3.3.3. Deterioration

The deterioration of the electricity network objects is strongly dependent on the type of objects, and can be divided into four main deterioration groups labelled based on their predominant modelling parameter as suggested by Willis and Schrieber (2013): 1) chronological age, i.e. deterioration that only depends on the time since construction: The most important example for this is corrosion, that mainly affects the conductors, but also the point-like components. 2) cumulative service age, i.e. the total amount of operational hours of an object: This is one of the main deterioration cause groups for all mechanical components. An example cause for this would be the number of switching operations of a mechanical switch. 3) abnormal events, i.e. rapid deterioration caused by severe events that are not considered as normal service: The design of electricity components often includes a certain margin of allowable exceedance of normal operation limits in order to prevent total failure of the network. This, however, comes at the price of faster than expected ageing. For example, overcurrent can lead to excessive heat that can affect the chemical composition of the coolant in transformers, rendering the cooling process less effective. 4) technical obsolescence, i.e. objects becoming incompatible with new regulations and system components: Although this type is not a traditional ageing process, it is one of the main contributors for a need to replace objects in electricity networks. For example, the insulation gases (most prominently sulphur hexafluoride $SF_6$) is one of the most potent greenhouse gases with a global warming potential of 23'900 times that of $CO_2$, and as such the use is only permitted until better alternatives are found. As shown in chapter 2.1.1, the deterioration is modelled mainly using failure probability functions. Due to the limited amount of data, however, there is a significant uncertainty connected with these functions.

### 3.3.4. Interventions

In order to keep a certain level of service despite the different deterioration types, interventions are executed on the objects. These can be divided into two groups: 1) emergency interventions, where upon failure the object is brought back as quickly as possible to a "before failure" state, and 2) preventive interventions, where an object is replaced at a prearranged point in time (Stillman, 2003). Referring to the main deterioration causes, the emergency interventions are mostly linked to abnormal events, whereas chronological and service age as well as technical obsolescence can be monitored (for the technical obsolescence, there is a legislative process that gives a certain timeframe to react, and thus to plan the interventions). Therefore, the main focus of intervention planning is put on the accurate estimation of the prearranged point in time to perform the preventive interventions, as demonstrated in chapter 2.1.1

From this basis (i.e. the optimal intervention point in time to execute an intervention for each object), the optimal intervention programs are then calculated by shifting the points in time in order to minimise/maximise certain indicator values (e.g. *Loss of Load Probability*, *Expected Unserved Energy* or marginal cost), that act as an optimisation goal respectively as boundary conditions. The choice of indicator values differ from electricity distributor to distributor, as the choice of the indicator depends on 1) the data availability and 2) whether the distributor is private or public-owned. In the public sector, the optimisation goals are mainly reliability or service based, with the financial indicators being boundary conditions (for example “achieve the maximum reliability for a given budget”), whereas in the private sector boundary conditions and optimisation goals tend to be reversed (for example: “find the cheapest intervention program that fulfils a certain reliability limit”).

There is, however, little consideration for other infrastructure networks and the benefits that can be created from forming joint interventions. Nevertheless there is a great potential, as 1) several objects of other infrastructure networks are depending on a power supply, and thus if such an object has an intervention and therefore does not need power supply, then the connected electricity network object can also have an intervention without loss in level of service, and 2) in an urban environment (especially in Europe), electricity infrastructure tends to be buried and as such benefits in terms of shared excavation / traffic rerouting costs are possible if interventions are combined with other networks.

## 3.4. Gas network

### 3.4.1. Network properties

The urban gas distribution network is, like the electricity network, a potential network with two object types: 1) longitudinal objects (pipe sections) and 2) point-like objects (such as valves, compressors, meters, etc.) These objects have to function as a whole system to provide the service of energy to the customers. In the process of providing the service, there are three stakeholders involved, that are shown in Figure 3.6.

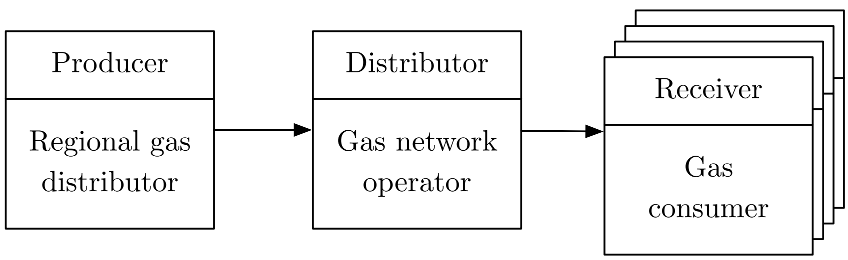



Figure 3.6.: Gas network stakeholders

The first stakeholder is the regional gas distributor, that acts as a “producer” by feeding in gas from the pressure reduction stations of the regional gas network into the urban gas network. The regional gas network receives the gas from international transmission lines, gas storages, or local production. This stakeholder can (and has to) adapt the pressure and volume flows coming from the regional network in order to keep the pressure within an acceptable range, preventing both excessive pressure (which can lead to pipes bursting) and insufficient pressure, causing undersupply. However, as this thesis is focused on urban infrastructure networks, the regional gas distribution network is not considered.

The second stakeholder is the distributor, i.e. the gas network operator. It is this stakeholder's responsibility to keep the network in a state that allows to distribute the gas to the consumers with minimal leakage and an acceptable level of pressure losses, both due to the state of the network (e.g. pipe fittings, wall corrosion) and the performed maintenance (i.e. service interruptions due to interventions, or fault-caused interruptions due to inadequate/insufficient maintenance).

The third stakeholder is the gas consumer group, that consists of both private and industrial (i.e. large volume) customers. The consumers use the supplied gas to generate heat and pay for the received service. The payment is then split up into a network fee and a mass fee (i.e. a fee per supplied mass of gas, calculated via a volume proxy). There are differences in types of contracts that specify exactly the service that should be provided to the customer. The main component of these services is a guaranteed minimum amount of mass flow, as well as a certain minimal pressure. For example, a customer can order a connection of $7\,{}^{kg}\!/_{h}$ at $23\,mbar$.

### 3.4.2. Service definition

The level of service for a gas network can be defined as:

> "the ability to provide the consumer with a specified mass flow at a specified pressure level"

An adequate level of service is when the ability to provide a specified level of mass flow at a specified level of pressure is greater than required. An inadequate level of service is when the ability to provide a specified level of mass flow at a specified level of pressure is lower than required. A loss in level of service is the difference between the desired level of service and the provided level of service. There are multiple reasons that a loss in level of service can occur. They can be attributed to either the producer (i.e. the regional gas distributor, or their supplier) or the network operator (in some cases, this is also the same company, so that one utility company is responsible for both gas procurement and distribution). On the production side, a loss in level of service can be caused due to insufficient gas production or gas import (which can be also influenced by the international trade situation) to provide the desired amount of gas, or by problems in pressure regulation. On the distribution side, the loss in level of service can be caused by the state of the network, i.e. the condition of the pipes, valves and pressure stations, or whether a pipe is out of service due to failure or due to an intervention. A pipe being out of service changes the network configuration and causes the gas flow to either being redirected, changing the pressure and flow levels in the network, or, if consumers are only connected by out-of-service pipes, the consumer being totally disconnected from the network. The losses due to non-optimal pipe condition can mainly be attributed to corrosion-caused leaking and internal friction of the transported gas. As a countermeasure, if a leak is detected, the network distributor has to close off the affected pipe section and re-route the gas flow. The producer has in turn to increase the infeed pressure to account for the re-routing losses, if able. Alternatively, the network operator can execute an intervention on the pipes preventively (i.e. replacement) to limit the probability of leaks and thus the loss in level of service over the network, in which case the cost of taking this pipe out of service is the loss in level of service during the intervention.

### 3.4.3. Deterioration

The deterioration of the gas network object depends on the type of the object, i.e. whether it is a pipe section or a point-like object. Pipe sections deteriorate mainly over time due to material ageing and corrosion processes, whereas point-like objects deteriorate over service time, e.g. the number of actuations of a valve or operating hours of a compressor station. As gas networks are buried, and the condition of pipes can only be monitored with specialised equipment-material combinations (e.g. for metal pipes, a magnetic flux sensor (Pandey, 1998) can be used to locate irregularities in the pipe wall structure), mostly leakage detection is performed with trace gas sensors in order to find small leakages before they develop into significant leaks with the danger of a gas explosion[3]. As shown in chapter 2.1.2, the deterioration is modelled mainly using failure probability functions. However due to the limited amount of data, there is a significant uncertainty connected with these functions.

### 3.4.4. Interventions

In order to keep a certain level of service despite the different deterioration types, interventions are executed on the objects. These can be divided into two groups: 1) emergency interventions, where upon leak detection the local objects are replaced, and 2) preventive interventions, where objects are mostly replaced on a preventive base in order to avoid failure. This is due to the fact, that failures in gas networks are often very violent, with huge flames or explosions, and therefore cause significant collateral damage, which should be avoided. This leads to intervention planning, that is very on the conservative side (i.e. rather early replacement of pipes) as the consequences of a failure are enormous in an urban area. In literature, the main focus is put on the accurate estimation of the prearranged point in time to perform the preventive interventions, as can be seen in chapter 2.1.2. The difference to the practical strategies employed is caused by the lack of data availability in order to estimate the probabilistic parameters presented in the literature.

Therefore, optimal intervention programs are then calculated by shifting the points in time in order to group interventions, while adhering to the boundary condition of safety and ensuring adequate transportation capabilities as given in the network code.

To some extent there is consideration for other infrastructure networks, but only in a sense that the planned interventions are communicated to other infrastructure network operators. This partly collaboration can be extended, and the possible synergies can be increased by not only inform the other infrastructure network operators on planned interventions, but by developing joint intervention programs.

[3] i.e. detecting gas concentrations before they reach the lower flammability limit

## 3.5. Road network

### 3.5.1. Network properties

The urban road network is, unlike the other networks not a potential network in a physical sense, as the flow on the road network depends on individual decisions made by the vehicle drivers. The urban road network consists mainly of road sections (i.e. longitudinal objects). However, there are also objects like tunnels, bridges, or underpasses that add to the plurality of the objects in a road network. These objects have to work together as a whole system to provide the service of mobility to the road user. In the process of providing the service however, there are only 2 stakeholders involved, if the logic of chapter 3.1 is followed, which are shown in Figure 3.7.

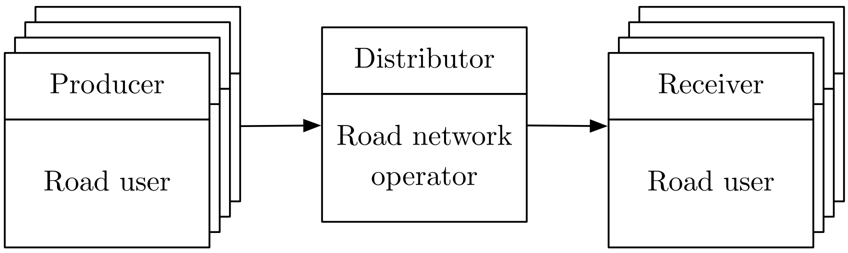



Figure 3.7.: Road network stakeholders

The first stakeholder is the road user, that acts as both a producer and receiver of the service of mobility. The road user has the desire to perform a trip from point A to point B in the road network, and as soon as the road user reaches the destination, the mobility is “received”.

The second stakeholder is the road network operator. It is this stakeholder’s responsibility to keep the network in a state that allows the road users to perform a trip in an acceptable amount of time, both due to the state of the network and the performed maintenance. However, as most of the infrastructure networks are buried underneath the road network, a significant source of network delays is caused by the interventions executed on other infrastructure networks, which impedes the mobility of the road users.

### 3.5.2. Service definition

In that sense, the level of service can be defined as:

> "the ability of a road user to reach any point in the road network from any other point in the road network in a reasonable amount of time"

e.g. with an average speed of $20\,{}^{km}\!/_{h}$.

An adequate level of service is when road users have the ability to travel from all origin to all destination nodes within specified amount of times. An inadequate level of service is when this is not the case. A loss in level of service is the difference between the desired level of service and the provided level of service. There are multiple reasons that a loss in level of service can occur. These can be an inability to reach certain points on the road network, or an excess travel time to reach the destination, i.e. a reduced average speed. The inability to reach certain points is due to closed roads, which lies only in the sphere of the network operator. The excessive travel time is due to congestion, which is dependent on both the road users and the network operator. A poor road condition can lead to a decrease in possible speed on that road, and road closures, when they do not cut off certain nodes in the network, can lead to changes in traffic flow in the network, which can also cause congestion. Additionally, the road user also contributes to traffic congestion through his route choice.

In contrast to the electricity and the gas network, there are no realistic countermeasures to alter how people travel across a road network (such as increasing the pressure in the gas network), although one could imagine using information technologies to inform people of when they should or should not travel. The network operator can, however, execute interventions on the road to improve condition and reduce the amount of time of traffic disturbances due to the execution of interventions, which reduces the loss in level of service over the network, in which case, the cost of executing the intervention is the loss in level of service during the intervention.

### 3.5.3. Deterioration

The deterioration of roads is a research area that has been vastly investigated, partly due to the easy observability of roads. Deterioration can be attributed to two factors,

1) use-dependent deterioration that is caused by mechanical stress to the road, and 2) age-dependent deterioration, that can be attributed to time, and with that mostly climate variations. Due to the observability, the condition of the road network is often monitored by manual inspection, that grades the road with the use of discrete condition states. Automated inspection equipment is also available, with an increasing percentage of use in the monitoring process. For automated equipment, it is easier to produce a continuous scale of condition state than for manual inspection. Therefore, due to the still significant part of manual inspection, most deterioration models for roads are based on discrete states and the progression through these states over time. The most prominent family of discrete state models is the Markov chain model family, with several adaptations and extensions. For objects like bridges, tunnels etc., that consist of a multitude of sub-components whose joint condition defines the overall condition of the object in a sense whether it is an impedance to mobility or not. For those objects, several methodologies exist to combine the condition state of the sub-components to an overall condition for the object, for example, fragility curves or joint failure probability approaches.

### 3.5.4. Interventions

In order to keep a certain level of service despite the different deterioration types, interventions are executed on the objects. For road objects, network operators usually divide those into two groups: 1) operational maintenance interventions and 2) constructive maintenance interventions. However, the distinction between those interventions is not perfectly clear, especially at the border between large operational maintenance and small constructive maintenance. For some infrastructure operators the difference lies in the financial booking rules, while other infrastructure operators have detailed lists of intervention types that are either of one or the other category. In the context of this thesis however, the distinction is of little importance, as both groups of interventions are executed in order to improve the road network condition. Due to the range of different intervention sizes, the result of the intervention is also within a range, going from a mere slowing of the deterioration process without any condition state improvement to medium interventions with a condition state improvement of few discrete states to total renewal, yielding an as-new condition state. These different extents of interventions allow a traffic-centred determination of intervention programs, by providing network managers with possibilities to shift the time point for an object's large intervention by performing interim interventions in order to achieve an intervention program that causes less traffic disturbances. To some extent there is consideration for other infrastructure networks, but only in a sense that the planned interventions are communicated to other infrastructure network operators. This partial collaboration can be extended, and the possible synergies can be increased by not only inform the other infrastructure network operators on planned interventions, but by developing joint intervention programs.

## 3.6. Sewer network

### 3.6.1. Network properties

The urban sewer network is, like the electricity network, a potential network, but with the difference that it is in most cases gravity-controlled. In sewer networks, there are mainly longitudinal objects (pipe sections), but also in some cases point-like objects such as pumps or weirs. These objects have to function as a whole system to provide the service of wastewater collection to the customers. In the process of providing the service, there are two stakeholders involved, which are shown in Figure 3.8.

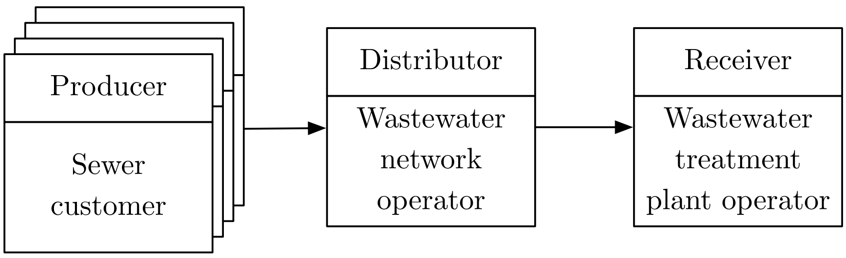



Figure 3.8.: Sewer network stakeholders

The first stakeholder is the “producer” of wastewater, who is the customer of the wastewater disposal service. The customer produces wastewater and pays the wastewater disposal company to dispose of the occurring wastewater. Contracts with customers are however rare, as a connection to the wastewater system is normally prescribed by municipality laws, and the fee is part of the municipality taxes.

The second stakeholder is the wastewater disposal company that acts both as a network operator and receiver of the occurring wastewater. The disposal company has to keep the network in a state that allows to collect the wastewater from the customers with acceptable leakage and an acceptable level of flow capacity in order to transport the occurring wastewater safely to the wastewater treatment plant, both due to the state of the network (e.g. leakage, wall corrosion, sediment buildup) and the performed maintenance. The wastewater treatment plant, as the receiving end of the network has to be able to accept all incoming wastewater and treat it according to local regulations.

### 3.6.2. Service definition

In that sense, the level of service can be defined as:

> "the ability to securely transport (i.e. not exceeding the allowable leakage) a specified amount of wastewater mass of the connected customers to the wastewater treatment plant"

and treat it accordingly.

An adequate level of service is when the ability to securely transport and treat a specified amount of wastewater is above a specified threshold. An inadequate level of service is when this is not the case. A loss in level of service is the difference between the desired level of service and the provided level of service.

There are multiple reasons that a loss in level of service can occur. These include leaks in the pipes, stoppages in the pipes and exceeding the capacity of the water treatment plants. However, although leaks can be detected, it is hard to determine an actual leakage rate (in terms of a specific number) that can be used as a threshold. Nevertheless, for this methodology, a leakage rate has to be determined or derived from qualitative approximations like "medium" leakage rate, in order for the algorithm presented in this thesis to objectively determine an intervention program.

As with the road network, there are no realistic countermeasures to alter how people use the network, and in contrast to the electricity and gas network, there is no immediate possibility to increase the flow in the network, as it is in most cases only gravity-controlled. The network operator, however, can execute interventions on the network to improve condition and to reduce the amount of time of disturbances due to the execution of interventions, in which case the cost of executing the intervention is the loss in level of service during the intervention.

### 3.6.3. Deterioration

Deterioration in sewers networks can mostly be attributed to sediment build-up and corrosion due to the chemical properties of the water, or leakages, as stated in chapter 2.1.4. For leakages, plant roots can detect tiny amounts of flowing water and can grow into water pipes, thus enlarging the leak size due to root pressure and subsequent fracturing of the pipe material. Sewer pipes are monitorable to a certain extent, and thus are in many cases also ranked in certain distinct condition states, based on manual inspections.

### 3.6.4. Interventions

In order to keep a certain level of service despite the different deterioration types, interventions are executed on the objects. For sewer objects, these interventions can be removing sediment built-ups, a restoration of the waterproofing layer inside the pipe (relining, pipe-in-pipe, etc.) or replacement (trenchless or open trench). As it is hard to "re-route" water in a sewer system, most interventions are planned in times where the expected flow is significantly reduced, in order to not being forced to implement solutions to deal with the wastewater, such as wastewater pumping stations or truck disposal. On the other hand, due to the significantly longer expected lifetime, the timeframe to move interventions is larger, and as such it is easier to optimise the intervention program. To some extent there is consideration for other infrastructure networks, but only in a sense that the planned interventions are communicated to other infrastructure network operators. This partial collaboration can be extended, and the possible synergies can be increased by not only inform the other infrastructure network operators on planned interventions, but by developing joint intervention programs.

## 3.7. Water network

### 3.7.1. Network properties

The urban water distribution network is, like the electricity network, a potential network with two object types: 1) pipe sections and 2) point-like objects, for example valves. These objects have to function as a whole system to provide the service of water to the customers. In the process of providing the service, there are three stakeholders involved that are shown in Figure 3.9, but only two entities.

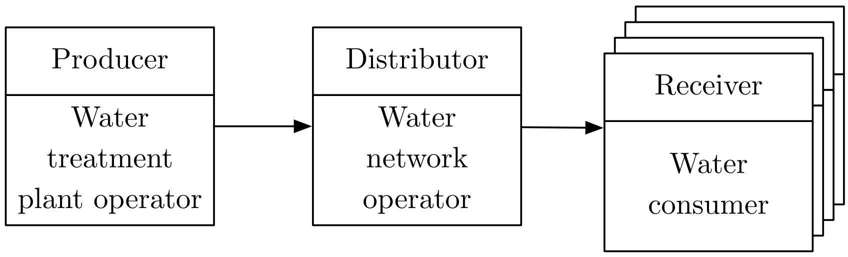



Figure 3.9.: Water network stakeholders

The first entity is the water supplier, that acts both as a producer by treating freshwater from different sources, and then in the stakeholder role of the distributor, distributes the treated water to the customers in the city. On the production side, the water supplier can increase the produced volume or the pressure in order to compensate for losses in the distribution network. The distribution network has to be kept in a state that allows to distribute the water to the consumers with acceptable leakage and an acceptable level of pressure losses, both due to the state of the network (e.g. pipe fittings, wall corrosion, lime buildup) and the performed maintenance (i.e. service interruptions due to interventions, or fault-caused interruptions due to inadequate/insufficient maintenance). However, the water supplier has more freedom to move the focus between countermeasures and interventions, as both are executed by the same company.

The second stakeholder is the consumer group that consists of both private and industrial (i.e. large volume) customers. The consumers use the supplied water for drinking purposes, but mainly for rinsing and cleaning purposes, as the major amount of the used water serves hygienic purposes. Therefore, the water has to conform to chemical, physical and microbacteriological standards to fulfil the consumers' needs.

### 3.7.2. Service definition

An adequate level of service is when

> "the ability to provide the consumer with a specified water flow at a specified pressure level"

is above a specified threshold.

An inadequate level of service is when this is not the case. A loss in level of service is the difference between the desired level of service and the provided level of service.

There are multiple reasons that a loss in level of service can occur. On the production side, a loss in level of service can be caused by the producer not being able to fulfil the demand, e.g. if there is a water shortage. On the distribution side, the loss in level of service can be caused by the state of the network, i.e. the condition of the pipes and valves or whether a pipe is out of service due to failure or due to an intervention. A pipe being out of service changes the network configuration and causes the water flow to either being redirected, changing the pressure and volume flow levels in the network, or, if consumers are only connected by out-of-service pipes, the consumer being totally disconnected from the network. The losses due to non-optimal pipe condition can mainly be attributed to leaks and internal friction. One thing that has to be noted about leaks though, is that a certain amount of leakage is common and also accepted for water networks. If the acceptable amount of leakage is exceeded, an intervention is executed. In that sense, this can also be seen as a binary decision, however with a certain amount of leakage as an inacceptability threshold.

As a countermeasure to leaks, the producer has to increase the flow of water into the network, and as a countermeasure to internal friction (which causes a pressure loss but no volume loss), the producer has to increase pressure. The network operator can execute interventions on the pipes (i.e. repair or replacement) to reduce the amount of leakage and friction, and thus the loss in level of service, in which case the cost of executing the intervention is the loss in level of service during the intervention.

The scope of this thesis is the distribution network. However, as shown in Chapter 2.1.5, there are more aspects of service quality, namely 1) hygiene, 2) pressure/flow and 3) temperature (Germanopoulos et al., 1986). ). In the scope of maintenance of a distribution network, the focus is only put on pressure/flow, as hygiene is mainly in the sphere of the producer (by adequate water sanitation) or network designer (by ensuring adequate hydraulic residence time due to network layout), and temperature can be easily influenced by burying depth, which is also in the sphere of the network designer. Only pressure/flow depends on the state of the network, and therefore within the scope of this thesis.

### 3.7.3. Deterioration

Deterioration in water networks can mostly be attributed to 1) corrosion (either internal, or external, e.g. due to stray currents), or 2) deterioration due to the chemical properties of the water, or 3) leakages. As for many regions it is necessary to mix water from different sources, the process of mixing can lead to a change in chemical properties, such as pH value, which can induce deterioration in different pipe materials. For leakages, plant roots can detect tiny amounts of flowing water, and can grow into water pipes, thus enlarging the leak size due to root pressure and subsequent fracturing of the pipe material. As water pipes are difficult to monitor, mainly statistics-based methodologies are used to determine the likelihood of being in an unwanted state. This also leads to the fact that if a leak remains undetected for a prolonged amount of time, the damages caused by washing out of fine grain can be significant.

### 3.7.4. Interventions

In order to keep a certain level of service despite the deterioration, interventions are executed on the objects. These can be divided into two groups: 1) emergency interventions, where upon failure the object is brought back as quickly as possible to a "before failure" state, and 2) preventive interventions, where an object is replaced at a predefined point in time. Therefore, the main focus of intervention planning is put on the accurate estimation of the predefined point in time to perform the preventive interventions, as shown in chapter 2.1.5. Depending on the layout of the distribution network, the ability to supply water to the customers can be also of importance. In ring-like networks, the redundancy allows for almost permanent supply (i.e. a disruption mainly occurs during the actual breakage, not during the repair period), though sometimes with reduced pressure and volume flow. In tree-like networks however, if a branch is shut off, all customers connected to this branch are disconnected. The closer the branch to the production site, the more the number of affected customers. To some extent there is consideration for other infrastructure networks, but only in a sense that the planned interventions are communicated to other infrastructure network operators. This partial collaboration can be extended, and the possible synergies can be increased by not only inform the other infrastructure network operators on planned interventions, but by developing joint intervention programs.

## 3.8. Summary of current situation

In this section, the current situation on the five investigated infrastructure networks shown in chapters 3.3 to 3.7 is summarised in a concise, tabular way. The network properties of the five investigated networks are shown in Tbl. 3.1, the definition of service on the networks is shown in Tbl. 3.2, and the deterioration types and their observability are summarised in Tbl. 3.3.

Table 3.1.: Summary of network properties

| Network | Network type | Object types | Producer | Distributor | Consumer |
|---|---|---|---|---|---|
| Electricity | potential field (voltage) | longitudinal (conductors), point-like (switches, transformers,...) | power generation | distribution grid | customer |
| Gas | potential field (pressure) | longitudinal (pipes), point-like (valves, compressors,...) | regional grid | urban grid | customer |
| Road | decision-driven (vehicle driver), but may be approximated by potential field | longitudinal (roads) | road user | road network | road user |
| Sewer | potential field (gravity) | longitudinal (pipes), point-like (weirs,...) | customer | water treatment | |
| Water | potential field (pressure) | longitudinal (pipes), point-like (valves,...) | water supply | | customer |

Table 3.2.: Summary of network service definitions

| Network | Service definition | Example |
|---|---|---|
| Electricity | ability to provide the consumer with a **specified level of power** at a **specified level of voltage** | $125\,A$ at $230\,V \pm 5\%$. |
| Gas | ability to provide the consumer with a **specified mass flow** at a **specified pressure level** | $7\,{}^{kg}/_{h}$ at $23\,mbar$ |
| Road | ability of a road user to reach **any point in the road network from any other point** in the road network in a r**easonable amount of time** | average speed of $20\,{}^{km}/_{h}$ |
| Sewer | ability to **securely transport** a specified **amount of wastewater** of the connected customers to the wastewater treatment plant | leakage rate $< 5\%$ |
| Water | ability to provide the consumer with a **specified water flow** at a **specified pressure level** | $7\,{}^{l}/_{s}$ at $3\,bar$ |

Table 3.3.: Summary of network deterioration type groups

| Network | Deterioration group (+example) | Observability |
|---|---|---|
| Electricity | chronological age (corrosion) | no |
| | service age (mechanical wear) | yes |
| | rapid abnormal deterioration (overcurrent/excess voltage effects) | no |
| | technical obsolescence (legal regulations) | yes |
| Gas | chronological age (corrosion) | partly |
| | service age (mechanical wear) | yes |
| Road | chronological age (load-independent deterioration) | partly |
| | service age (equivalent axle load cycles) | yes |
| Sewer | chronological age (sediment build-up, corrosion, tree roots) | mostly |
| Water | chronological age (limestone build-up, corrosion, tree roots) | no |

# 4. Technical concept

In this chapter, the technical concept of a methodology is presented that addresses the gaps shown in introduction and literature, and enables the infrastructure managers to improve upon their current situation, by creating combined intervention programs that take into account not only one infrastructure network, but also the interactions between the networks and the possible benefits that can be created from intervention grouping. The goal of this chapter is to clarify the processes of the methodology by the means of process charts. The mathematical formulation corresponding to the process charts is shown in chapter 5, and the computer algorithm that translates this mathematical formulation into executable code is shown in chapter 6.

The global methodology is a detailed implementation of the conceptual process for constructing intervention programs (see Figure 3.3). The process will be explained in detail in the next sections, by expanding all tasks from Figure 4.1 into subtasks, sub-sub tasks etc. The numbering of the following sections corresponds to the task and subtask numbering in the global methodology. For example, TC1 can be found in chapter 4.1, TC2.2 in chapter 4.2.2. The numbering of this chapter, but also in the following chapters is such, that the section indices correspond to each other, i.e. the technical concept of Task TC2.2 is explained in chapter 4.2.2, the corresponding mathematical formulation in chapter 5.2.2, and the algorithmic implementation in chapter 6.2.2. In some cases, the technical concept may be simple, but the mathematical formulation or the algorithm may be not (or vice versa). Therefore, the situation arises that some parts of the following sections are very short in the technical concept, but more extensive in the algorithm implementation or the mathematical formulation for the benefit of a consistent numbering. Additionally, in order to improve understandability, the following definitions are made:

**Set of intervention program(s) (candidates):** multiple intervention program(s) (candidates)

**Object:** the smallest entity of the network that is investigated (e.g. a pipe section, a valve, a switch,...) and can be assigned its own condition, deterioration, material etc. in the scope of the investigation.

**Level 1 object:** an object that is selected directly for an intervention, because it is deemed optimal to do so from an object level optimal intervention strategy, assuming no other interventions are executed.

**Level 2 object:** an object that is considered to be combined into a cluster, but not selected as level 1 object, because it has reached a certain threshold in the optimal intervention strategy that is high enough for the object to be combined with a level 1 object, but not enough to justify an intervention without combination.

**Process:** a set of tasks to be executed in a certain logical order

**Task:** one single entity of a process diagram. If one task is expanded (expandable tasks are marked with a ⊞ symbol), it becomes a process

The solutions to overcome the challenges and gaps presented in chapter 2 are located in various levels of the methodology, i.e. they form tasks or subprocesses of the global methodology, and thus will be presented at the appropriate position in the next sections.

One of the challenges is the computational complexity of the problem. To overcome this, the methodology is based on an iterative optimisation loop, that can be finished if an appropriately close solution is found. Figure 4.1 shows the general overview of the methodology.

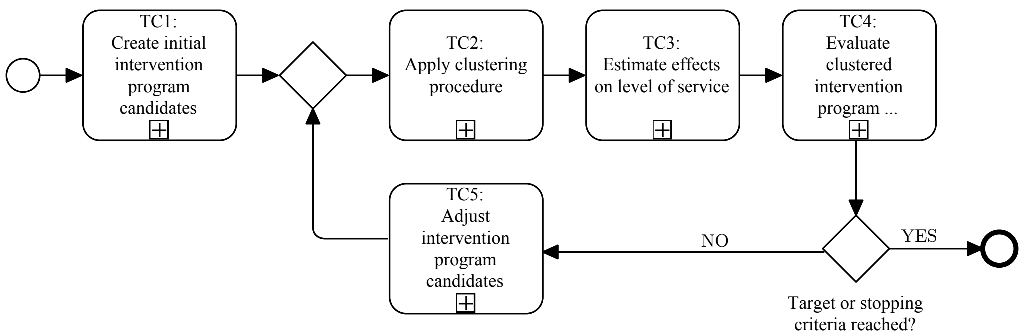



Figure 4.1.: Global methodology overview

The methodology has five main tasks. In TC1, an initial set of intervention program candidates is created. This task is owed to the iterative loop structure of the methodology. In TC2, the initial intervention program candidate set is re-grouped and clustered. This task addresses the challenge of grouping interventions into intervention clusters, taking into account all infrastructure networks instead of only a single one. Additionally, this task contains an interaction subtask, that addresses the challenge of capturing interactions between the networks due to executed interventions. In TC3 the effects on the level of service are estimated that arise from each intervention program candidate. In this task, the challenge of combining the different level of service definitions is addressed, in order to be able to evaluate combined intervention clusters that include objects from different infrastructure networks. In TC4 the clustered intervention program candidate sets are evaluated. This task serves the purpose of 1) finding an optimal intervention program, and 2) taking into account the various restrictions and boundary conditions, that are imposed by the different network properties, standards, budgets, etc. In TC5 the intervention program candidates are adjusted, according to the iteration loop rules in order to find an optimal intervention program.

## 4.1. Create initial intervention program candidates

This task is owed to the iterative setup of this problem, as an iteration requires a first generation of intervention program candidates being generated, that are refined and optimised during the iterations. The process to generate these initial intervention program candidates is shown in Figure 4.2.

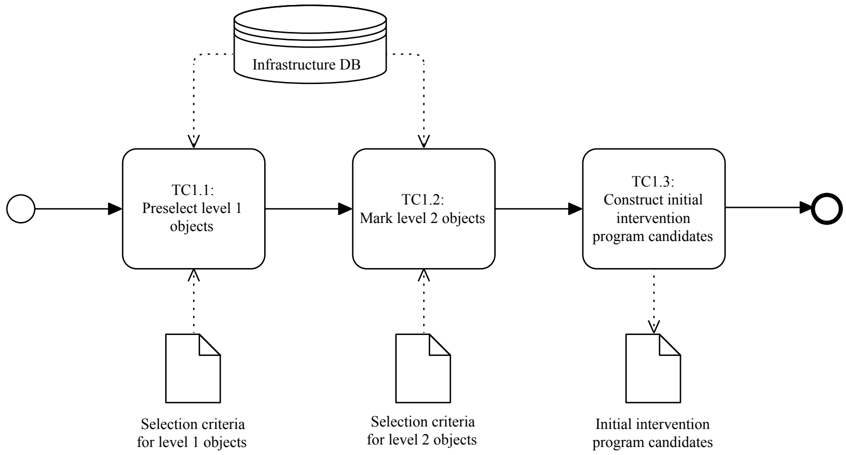



Figure 4.2.: Creation of initial intervention program candidates

The tasks consists of three subtasks. In task TC1.1, single objects from all networks are selected as level 1 objects, according to the selection criteria for those objects. These selection criteria are dependent on the infrastructure network, the defined strategies, and available information about the objects. In task TC1.2, single objects from each network are marked as potential level 2 objects; again according to network-, strategy- and information-based criteria. From that, an initial, un-clustered set of intervention program candidates is generated that serves as the calculation basis for the optimisation process.

## 4.2. Apply clustering procedure

This task (TC2 from Figure 4.1) is the beginning of the actual calculation and optimisation procedure, where the pre-selected level 1 objects are combined, re-grouped and adjusted to form clustered intervention program candidates. An overview of this task is shown in Figure 4.3.

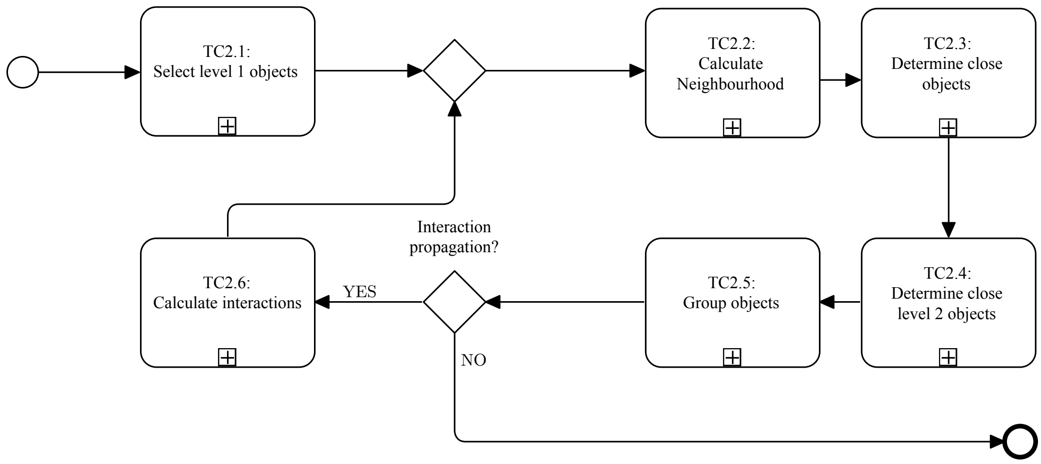



Figure 4.3.: Clustering procedure

It is divided into six subtasks and a logic gate. In TC2.1 the level 1 objects are definitely selected (building on the pre-selection TC1.1). In TC2.2, the dynamic neighbourhood is calculated. This neighbourhood marks a temporal, spatial and logical “area” around the objects. In TC2.3, the close objects, i.e. the objects that are within this neighbourhood, are determined. In TC 2.4, these close objects are then filtered for level 2 objects. In TC2.5, both level 1 and level 2 objects are then grouped into intervention clusters. If there is an interaction propagation over the network, then the interactions are calculated in TC2.6, otherwise the clustering procedure is finished.

### 4.2.1. Select level 1 objects

In this process, the level 1 objects are definitely selected. The process diagram is shown in Figure 4.4.

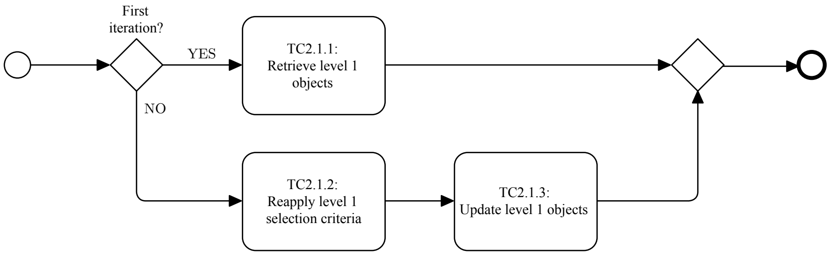



Figure 4.4.: Selection of level 1 objects

If the iteration is the first iteration, then the level 1 objects are simply retrieved from the result of task TC1.3, otherwise the level 1 selection criteria are reapplied, and the level 1 objects are updated. This needs to be done due to the interaction calculation from task TC2.6, that may render objects into level 1 objects due to interactions caused by network effect propagation. The result of this process is the definitive list of level 1 objects, that serves as an input to the next task (TC2.2).

### 4.2.2. Calculate neighbourhood

In this task, the neighbourhood is calculated. The neighbourhood marks a temporal, logical and spatial area around level 1 objects, that is considered close to these objects, and thus being considered for forming intervention clusters. The process of this task is shown in Figure 4.5. A shortened version can also be found in Kielhauser et al. (2014, 2016).

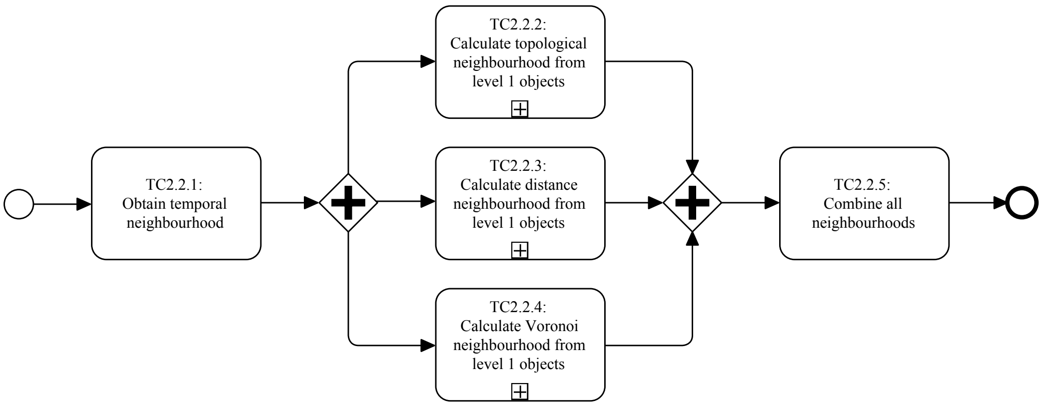



Figure 4.5.: Calculation of neighbourhood

The neighbourhood of object X out of the objects $\{X, Y \in o_{n,m}\}$ is defined as the region around object X, where object Y would be considered close if it lies within that region. The process starts with the calculation of the temporal neighbourhood TC2.2.1. After calculation of the temporal neighbourhood, the output is split into three parts: 1) the topological neighbourhood calculation TC2.2.2, 2) the distance neighbourhood calculation TC2.2.3, and 3) the Voronoi neighbourhood calculation TC2.2.4. Finally, the neighbourhoods are combined (TC2.2.5).

The temporal neighbourhood defines the temporal area, i.e. which level 1 objects are in terms of intervention time-point close. The topological and distance neighbourhoods consist of all objects that are in the neighbourhood of the level 1 object and are in the same network, but are based on a different way of determining the neighbourhood. The Voronoi neighbourhood consists of all objects that are in the neighbourhood of the level 1 objects but are in different networks than the level 1 object. To better explain the different neighbourhoods, a small sample network with 7 objects is shown in Figure 4.6.

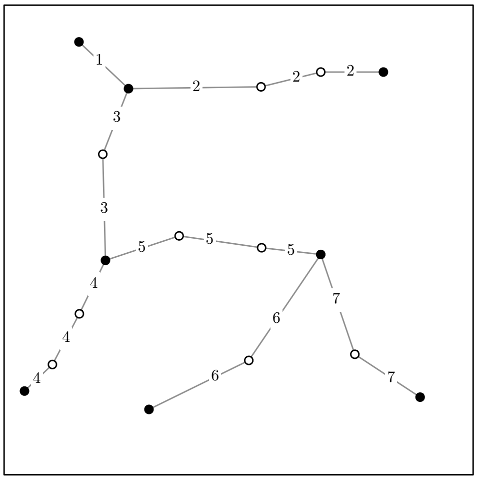



Figure 4.6.: Sample network

Logical nodes are denoted with • and geometric nodes are denoted with ◦. Logical nodes are nodes that signify a join between two or more objects, geometric nodes are nodes that are used to model the shape of an object. Lines with the same number are used to denote one object, while the geometric nodes are used to detail the object shape in between the endpoints (logical nodes). This is used in the Voronoi neighbourhood calculation.

#### 4.2.2.1. Obtain temporal neighbourhood

The first subtask of this process (TC2.2.1) produces the temporal neighbourhood. This is done by defining a timespan around the time-point, when a level 1 intervention is to be done. In Figure 4.7, a schematic drawing of a temporal neighbourhood is shown.

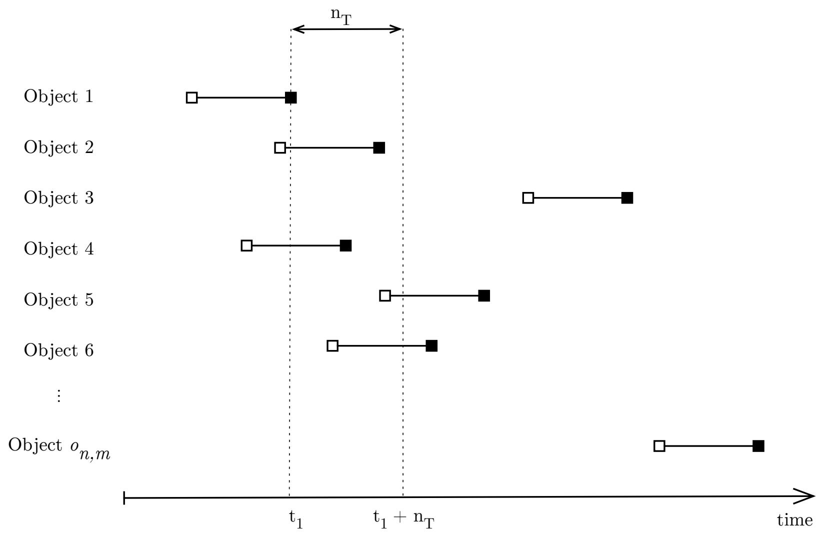



Figure 4.7.: Temporal neighbourhood

In the figure, objects and their intervention time are depicted. The □ symbol denotes the earliest time for an intervention, and the ■ symbol denotes the latest time for an intervention in order to comply with the minimal condition state. For example, object 1 is selected as level 1 object (thus acts as a “seed” for the neighbourhood calculation) with the time-point $t_1$ determined for the intervention, then the temporal neighbourhood would encompass the objects 2 and 4 for a level 1 temporal neighbourhood, as their **latest** time-point for an intervention lies within the temporal neighbourhood time $n_T$, as well as the objects 5 and 6, as their earliest time-point of intervention is also within the temporal neighbourhood. This is done for all level 1 objects in order to define a temporal neighbourhood around them.

The next three tasks (TC2.2.2, TC2.2.3, TC2.2.4) address the challenge of network effects, i.e. the ramifications of infrastructure objects being connected to other objects in a network instead of being “stand-alone”. Therefore, these tasks are subsequently explained in more detail in the next subsections.

The last task of this process (TC2.2.5) then simply combines the neighbourhoods to have a definitive search space to search for close objects (i.e. objects that are within this combined neighbourhood).

#### 4.2.2.2. Calculate topological neighbourhood from level 1 objects

The topological neighbourhood of an object is based on the topological distance along the network. This distance is defined by the number of objects between two logical nodes. In that sense, two objects are neighbours if the network distance between their closest logical nodes is below a certain threshold. For example, in Figure 4.6, the distance between object 1 and 6 is 2, because objects 3 and 5 have to be crossed to get from object 1 to object 6. In that sense, objects which share one logical node (for example objects 3 and 4), have a network distance of 0. If the focus is on object 6 and the distance threshold is 1, then objects 3, 4, 5, and 7 can be considered to be in the same neighbourhood, as at most one object (namely 5) has to be crossed to reach it. The process of the calculation of the topological neighbourhood is shown in Figure 4.8.

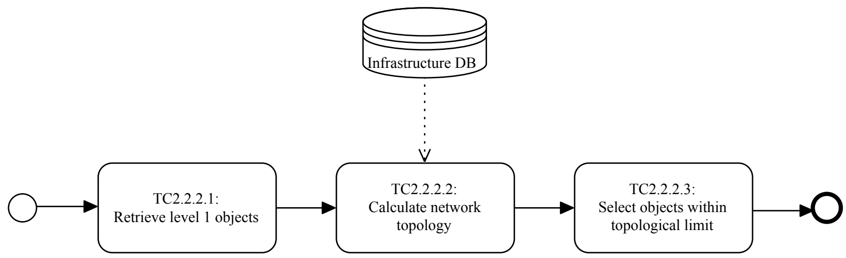



Figure 4.8.: Calculation of topological neighbourhood

In the first task TC2.2.2.1, the level 1 objects are retrieved. Then, the network topology is calculated (TC2.2.2.2) with information from the infrastructure database, on how the different objects are connected to each other. Then, in task TC2.2.2.3, all objects are selected that are within a pre-defined topological limit, with the limit being a management decision. This gives the topological neighbourhood.

#### 4.2.2.3. Calculate distance neighbourhood from level 1 objects

As the sizes of objects can differ by orders of magnitudes (e.g. compare one valve with a $300\,m$ stretch of straight pipe), neighbourhoods can also be defined by distance along the network. This is an alternative neighbourhood definition which takes into account only the physical distance from each other along the network. For this, an object is defined as a neighbour, if it can be reached within a certain distance along the network.

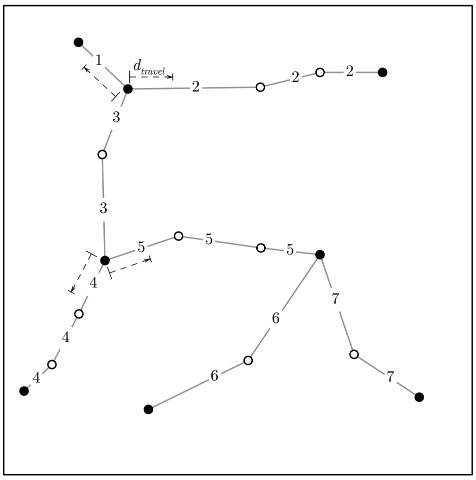



Figure 4.9.: Distance neighbourhood

For example, objects 3 and 5 are within a distance $d_{travel}$ of each other, as shown in Figure 4.9, as their closest nodes are within a distance of $d_{travel}$. The process of the calculation of the distance neighbourhood is shown in Figure 4.10.

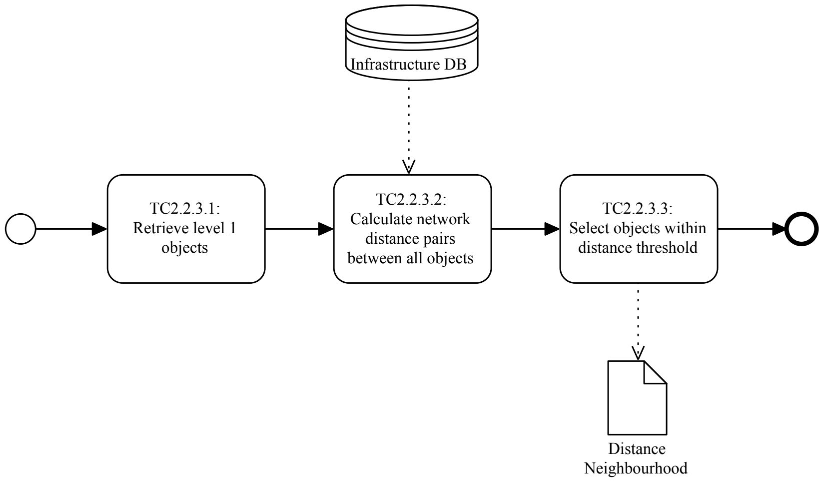



Figure 4.10.: Calculation of distance neighbourhood

In the first task TC2.2.3.1, the level 1 objects are retrieved. Then, the network distance between all object pairs is calculated (TC2.2.3.2) with information from the infrastructure database, on how the different objects are connected to each other, and information about the object dimensions. Then, in task TC2.2.3.3, all objects are selected, that are within a pre-defined distance limit, with the limit being a management decision. This gives the distance neighbourhood.

#### 4.2.2.4. Calculate Voronoi neighbourhood from level 1 objects

Both, topological and distance neighbourhood definitions have the prerequisite that all objects have to belong to the same network. To overcome this limitation, the neighbourhood can also be defined by Voronoi cells. Figure 4.11 shows a Voronoi tessellation of that example network.

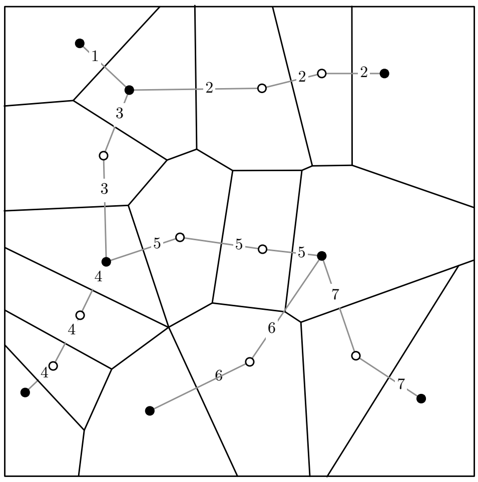
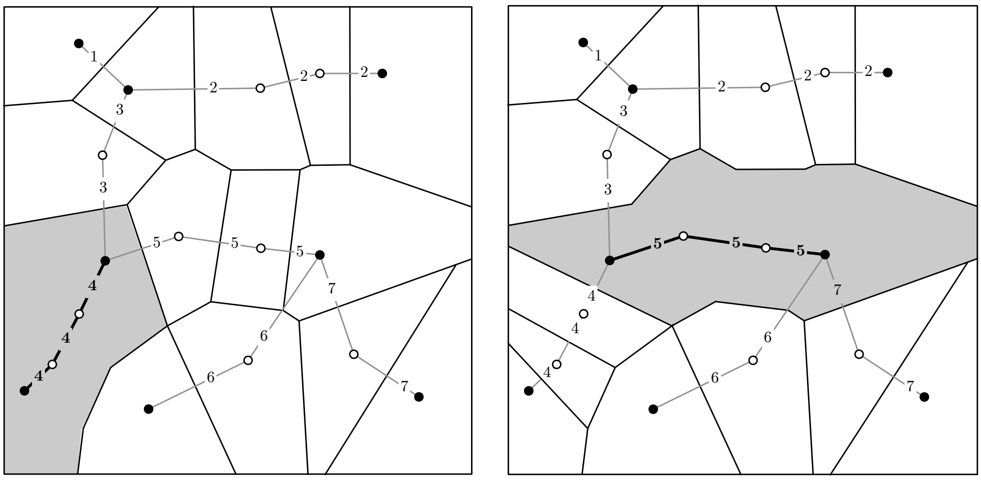



Figure 4.11.: Voronoi Cells

Starting from a given set of points (in this case: all network nodes, both logical and geometric), Voronoi cells consist of every point whose distance to this set of points is less or equal to any other point. A Voronoi region for one object is then the set of all Voronoi cells emanating from the nodes of that object. (see Figure 4.12a or 4.12b)



(a) Voronoi region for object 4

(b) Voronoi region for object 5

Figure 4.12.: Voronoi regions

Combining those regions gives the set of all Voronoi regions for all objects. This can be used to define the neighbourhood as follows: objects X and Y with $\{\mathrm{X}, \mathrm{Y} \in o_{n,m}\}$

are neighbouring, if object Y touches object X's Voronoi region. In Figure 4.13, the process diagram for task 2.2.4 is shown.

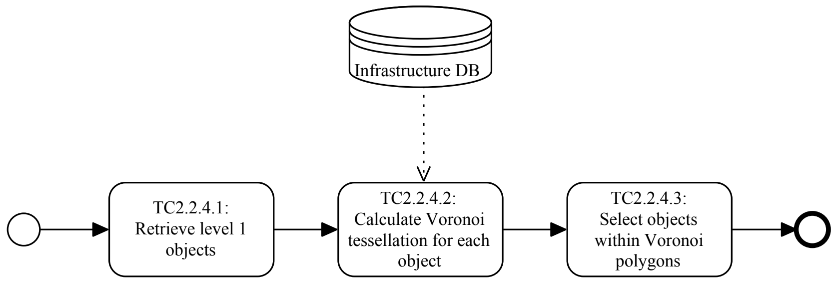



Figure 4.13.: Calculation of Voronoi neighbourhood

In TC2.2.4.1, the level 1 objects are retrieved. Then, for those level 1 objects, the Voronoi tessellations and regions are calculated in task TC2.2.4.2 with information from the infrastructure database, on how the different objects and both their logical and geometric nodes are spatially located. Then, in task TC2.2.4.3, all objects are selected, that touch the voronoi regions. This gives the Voronoi neighbourhood.

### 4.2.3. Determine close objects

In this task (TC2.3), the close objects are finally determined. The process of this task is shown in Figure 4.14.

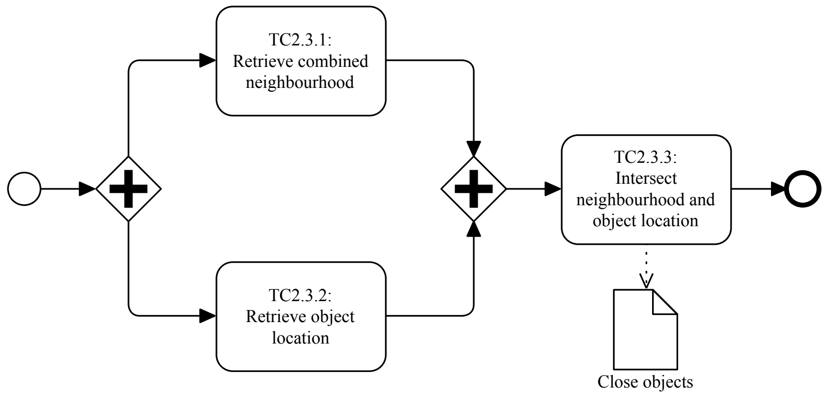



Figure 4.14.: Determination of close objects

First, both combined neighbourhood (TC2.3.1, from TC2.2.5) and object location

(TC2.3.2) are retrieved. Then, in task TC2.3.3, both are intersected, giving the close objects. Although the objects were already selected in the previous tasks TC2.2.2.3, TC2.2.3.3., and TC2.2.4.3, this intersection is needed in order to remove double-selections. Performing this gives the close objects.

### 4.2.4. Determine close level 2 objects

In this task, the close level 2 objects are determined. The process of this task is shown in Figure 4.15.

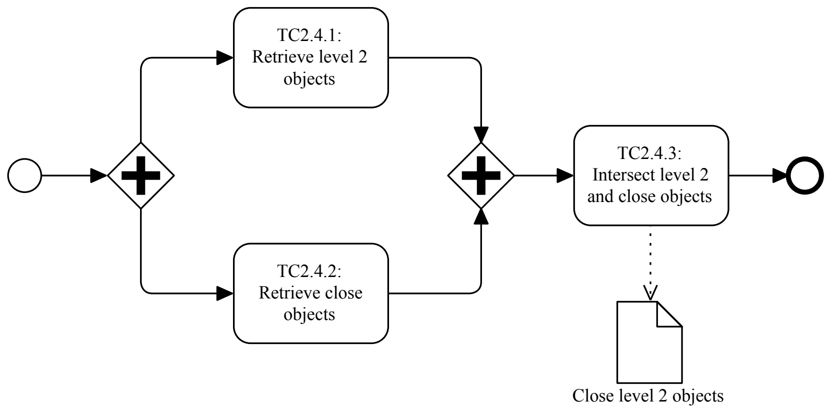



Figure 4.15.: Determination of close level 2 objects

First, both level 2 objects (TC2.4.1) and close objects (TC2.4.2) are retrieved. Then, in task TC2.4.3, both are intersected, giving the close level 2 set, which is the final set of objects, that is considered for adding to the clusters, that will be constructed in the next task (TC2.5).

### 4.2.5. Group objects

In this task TC2.5, the objects are then re-grouped and formed into intervention clusters, building the final clustered intervention program candidate set. The process for this task is shown in Figure 4.16.

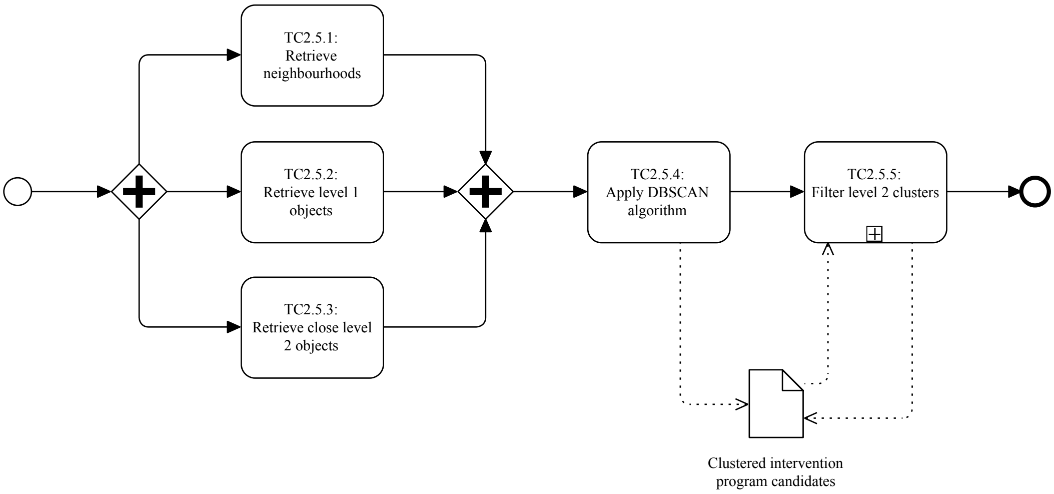



Figure 4.16.: Grouping of objects

The process consists of the tasks TC2.5.1, TC2.5.2, and TC2.5.3 that retrieve the object information, as well as the neighbourhood information from the previous tasks. Then, the main grouping is done by the DBSCAN (Density-Based Spatial Clustering of Applications with Noise) algorithm (Ester et al., 1996). This is the core part of the methodology that performs the actual grouping of the interventions. Here, the level 1 and level 2 objects, which have been identified in the previous steps, are combined into intervention clusters. This is needed because tasks TC2.2 to TC2.3 calculate the neighbourhood from the level 1 objects, i.e. define a subset of all objects from all networks, that is close to the level 1 objects. This, however produces objects that could either be level 2 or objects that do not need an intervention. Therefore, these objects not in need of an intervention are separated in task TC2.3 and thus removed from the subset. With a change in the subset elements, there is a certain possibility that the grouping is not valid any more. Therefore, the intervention objects (both level 1 and 2) need to be regrouped. This is done using the DBSCAN algorithm as described in Ester et al. (1996). This algorithm takes the centroid point coordinates of the objects requiring intervention and two values as inputs:

**Eps:** the distance, that defines a neighbourhood, in this case, the maximum distance in which two interventions should be grouped into one intervention cluster

**MinPts:** the number of interventions, that form the smallest group size. For most practical contexts, this will be '2'

Then, the points are classified as either belonging to a cluster or being single objects. If they belong to a cluster, then the interventions are included in the intervention program as a cluster, otherwise it has to be discerned between level 1 and level 2 objects, which is done in task TC2.5.5.

#### 4.2.5.1. Filter level 2 clusters

In this task, the clusters are filtered for level 2 objects. This is done, because level 1 single objects are also included in the intervention program as intervention, although they could not be grouped, because per definition level 1 signifies that an intervention is justified even without grouping. Level 2 objects belonging to no group however, or groups only consisting of level 2 objects, will be discarded. The process is shown in Figure 4.17.

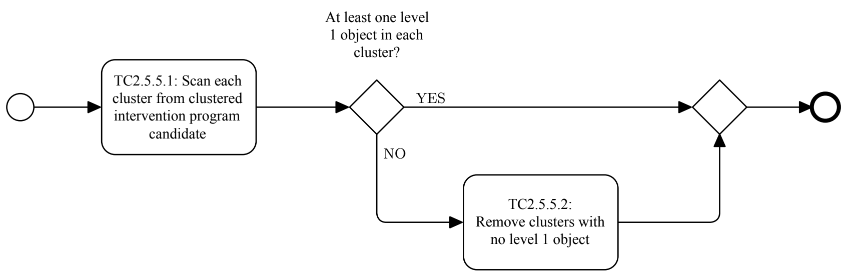



Figure 4.17.: Filtering of level 2 clusters

The process consists of two tasks: In task 2.5.5.1 each cluster is scanned for the object levels, to determine if at least one level 1 object is present. Then, in task 2.5.5.2, clusters without level 1 objects are removed. This finally gives a clustered intervention program, that consists of 1) clusters of size 1, that only include one level 1 object, and 2) clusters of larger size, that include at least one level 1 object, but possibly more level 1 and level 2 objects. However, interactions between objects have not been taken into account so far. If this is necessary, then the interactions are calculated in task TC2.6. Otherwise, the clustering procedure is finished.

### 4.2.6. Calculate interactions

If an interaction propagation exists, then the interaction is calculated. This is done via the process shown in Figure 4.18.

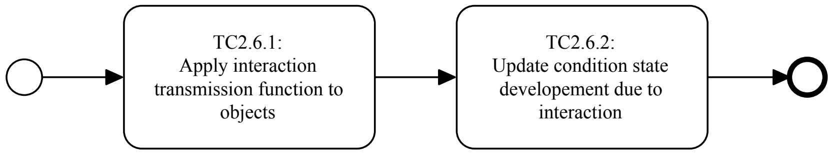



Figure 4.18.: Calculation of interactions

First, the interaction transmission function is applied to the object (TC2.6.1). This function (which will be presented in the corresponding mathematical formulation (chapter 5.2.6)) "transmits" interactions by updating the condition state development of the affected objects. With the newly updated condition state development, the process loop then continues at task TC2.1, with reapplying level 1 selection criteria.

## 4.3. Estimate effects on level of service

In this task (TC3), the effects on the level of service are calculated. This is important to the presented methodology, as the optimal intervention program in this methodology is based on a balance between the loss in level of service stemming from the interventions (which cause service disruptions) and the loss in level of service caused by non-optimal condition, by minimising the sum of 1) the intervention costs, 2) the costs for loss in level of service due to interventions, and 3) the costs for loss in level of service due to non-optimal condition.

The conceptual model for describing the service (and the loss thereof) is based on the assumption that all services can be described by the same schematic expression: a time integral of the flow of the good/service/units in/on the respective network. Mathematical details will be given in section 5.3. A shortened version can also be found in Kielhauser et al. (2016). The loss of service is measured using the same integral. In general, loss of level of service occurs due to the condition of the objects and the implications caused by this (leaks, resistance, partial closure, re-routing, etc.). Figure 4.19 gives an introduction to the proposed terminology on the example of a network consisting of one single object, while Figure 4.20 shows a small network.

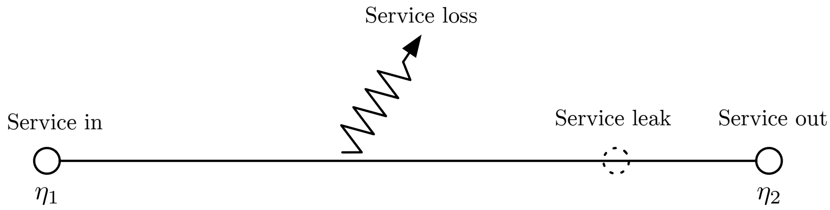



Figure 4.19.: Network loss terminology

Each object connects two nodes, $\eta_1$ and $\eta_2$ . In node $\eta_1$, there is a service input, in $\eta_2$ a service output. During the transmission of the service power, there is the possibility of a service loss along the object, which represents a loss of service power that is related to the length of the object. This loss is caused by “friction” (e.g.hydraulic friction, electric resistance, etc.). Additionally, there is also a possibility of leaks on the object, where service may also be lost. In this case, the loss is point-like. The sum of service loss and service leak is called loss in level of service. For the system to be in balance, the sum of service input, service output and loss in level of service has to be zero. This means, assuming Figure 4.19 depicts an extremely simple infrastructure network with only one producing node (the service provider, $\eta_1$ ) and only one receiving node (the customer, $\eta_2$ ), that the service provider has to produce not only the service used by the customer, but also the additional amount of service that is lost during the transportation.

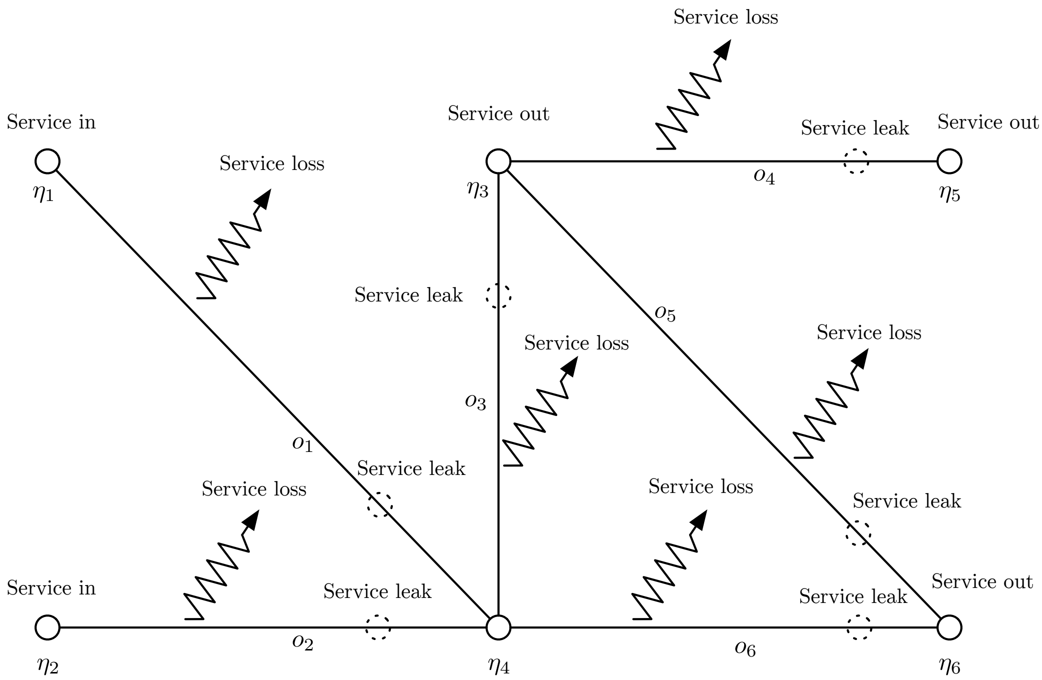



Figure 4.20.: Small network example

In Figure 4.20, a small network is depicted. It consists of two producing nodes $\eta_1$ and $\eta_2$, one intermediate node $\eta_4$, and three consuming nodes $\eta_3, \eta_5$, and $\eta_6$. These nodes are linked by the objects $o_1$ to $o_6$. The principle of the losses is the same, however, the losses can occur on each object. Therefore, for the system to be in balance, the sum over the whole network service has to be zero.

It can be seen that the in-feed service is to be shared between the network (where it has to compensate the losses) and the output. If the network "consumes" more service than expected this leads to less output service, assuming the input stays constant. On the other hand, if the input decreases (with the loss over the network being unchanged), the output service also decreases. Normally, both will happen simultaneously. First, if the network consumes more service (due to friction, leakage, etc.), the producer increases the in-feed service to compensate the losses and to supply a constant level of service. At some point, the maximum production capacity will be reached. Thus a further increase in network losses will lead to a loss in level of service, as the in-feed service power will keep constant, but the loss will increase. In order for the mathematical equations, that are presented in chapter 5.3, to hold true, the network is thought to start at the in-feed node, which means that service pressure generation stations (e.g. pressure stations or water reservoirs) are not seen as part of the network. .

The loss in level of service can be estimated using conductivity, which is a measure that describes the ease of flow through 1 length unit of an object having a cross section of $1^2$ length units. This measure is the inverse of the resistivity, as used in electrical engineering. The use of the conductivity is due to the fact that an object out of service has infinite resistivity (=zero conductivity), with the infinite being mathematically more difficult to handle than the zero.

The object slimness represents the ratio of length and the cross-section of the object, and combined with the conductivity gives the total conductance of that object.

The flow through the object is the last component needed to calculate the loss of service. To do this calculation, first, the flow in the whole network has to be calculated. The way of flow calculation is distinct for each network, and thus will be presented in the mathematical formulation. With the flow known, the service, and as such, the loss of service can be calculated.

An overview of the estimation of level of service process is shown in Figure 4.21.

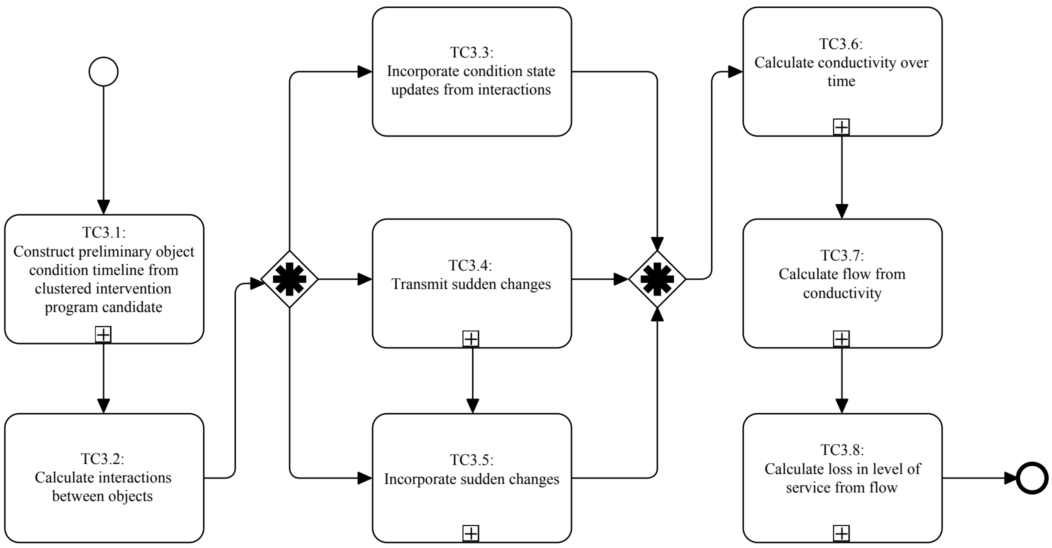



Figure 4.21.: Estimation of effects on level of service

First, the preliminary object condition timeline is constructed from the clustered intervention program (TC3.1). Then, the possible interactions are calculated between the object. This task is the same as TC2.6. After that, depending on the results of the interactions, three tasks may happen simultaneously. If condition state updates are necessary from the interventions, then they are incorporated in the condition state timeline in TC3.3. If sudden changes in condition occur, then they are transmitted and incorporated with tasks TC3.4 and TC3.5. With that, the condition state timeline for each object is determined. Then, the conductivity is calculated from the condition state over time (TC3.6). In the next task, the flow is calculated from the conductivity (TC3.7). This is necessary, as the flow on the network is determined by the combined conductivity of the objects and their position in the network. From the flow, the service then can finally be calculated (TC3.8), and this can then be translated into the loss in level of service. That also integrates the relative importance of the objects' location and role within the network. This extra step is necessary, as on each network, the level of service definition is different. The final result is the loss in level of service that is caused by the clustered intervention program, both due to the interventions themselves, and due to the resulting condition of the objects.

### 4.3.1. Construct preliminary object condition timeline from clustered intervention program candidate

In this task (TC3.1), the object condition timeline is calculated from the preliminary intervention program candidate. Depending on how the condition is modelled on the specific network, this can be in different forms. An overview of this process is shown in Figure 4.22.

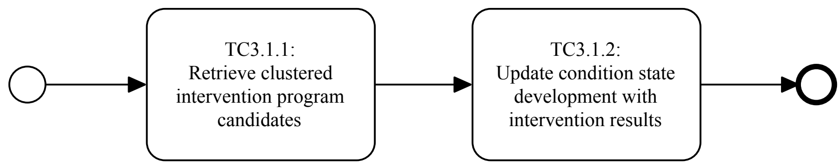



Figure 4.22.: Construction of preliminary object condition timeline

First, the clustered intervention program candidate sets are retrieved in task TC3.1.1, and then, the condition state development over time is updated in TC3.1.2.

### 4.3.2. Transmit sudden changes

In this task, sudden changes in object condition are transmitted. These sudden changes represent instantaneous changes in object condition, that can be transmitted to other objects as well. One simple example for this would be a pipe breaking due to bad condition, and the breakage also influencing nearby pipes, or a construction accident during an intervention. The process diagram for this task is shown in Figure 4.23.

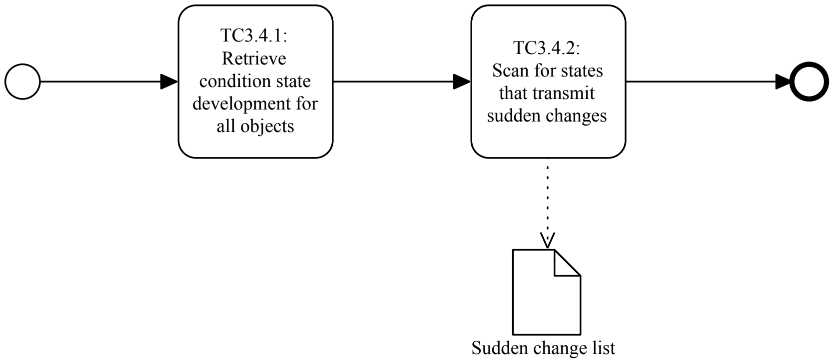



Figure 4.23.: Transmission of sudden changes

The process consists of two tasks: TC3.4.1, where the condition state development is retrieved for every object, and TC3.4.2, where the condition state development is scanned for states that transmit sudden changes. These sudden changes are based on the relative position of the objects to each other, as well as a transmission hierarchy to represent the fact that it is possible that there is a transmission of a sudden change in one direction between two objects, but not in the opposite direction. These sudden changes are then stored in a sudden change list.

### 4.3.3. Incorporate sudden changes

In this task, the sudden changes that emanate from different objects are then incorporated, i.e. the condition state development is then updated to also reflect the sudden changes in condition state. A process diagram of this task (TC3.5) is shown in Figure 4.24.

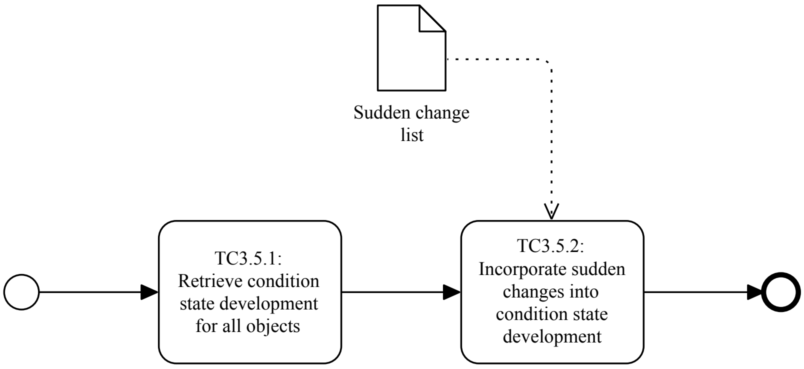


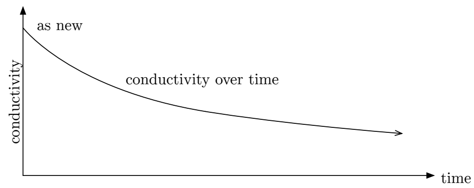

Figure 4.24.: Incorporation of sudden changes

The process consists of the tasks TC3.5.1, where the condition state development is retrieved for all objects, and task TC3.5.2, where the sudden changes are incorporated.

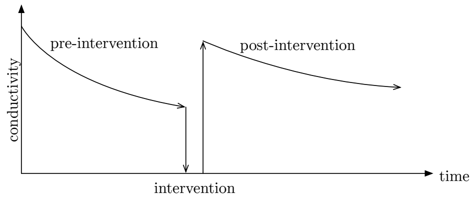
### 4.3.4. Calculate conductivity over time

In this task, the conductivity over time is calculated. This task is one of the main contributions of this thesis. The concept of conductivity is that the condition state of each object, regardless from which network it originates, can be expressed by this concept, thus enabling the direct comparison between networks. Thus, conductivity represents the state of the object, and as such each object has its own conductivity over time.

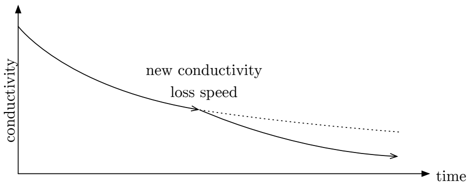
Over time, objects tend to deteriorate, i.e. suffer from a change in their state. These changes can be attributed to 1) gradual changes, that only depend on the object itself (these have been calculated in task TC3.1), and 2) interaction-caused changes, that affect the state of object Y if an intervention is done on object X, with $\{\mathrm{X}, \mathrm{Y} \in o_{n,m}\}$. These have been calculated in tasks TC3.2 to TC3.5. In this model, the object state is translated into conductivity, i.e. the "ease of flow" through the object. Changes in this object state describe processes, that reduce the ease of flow per time unit (e.g. the gradual deterioration of a road surface, that leads to a reduction in possible traffic speed, or the gradual deposition of sediment in sewer pipes, that reduces the flow speed). This reduction can be expressed in terms of conductivity over time. A schematic of this is shown in Figs. 4.25a-4.25d



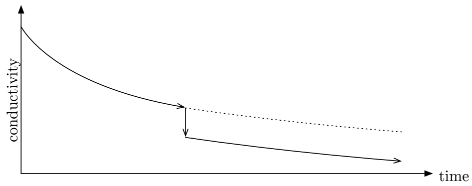

(a) Conductivity over time without intervention




(b) Conductivity over time with intervention




(c) Increase of conductivity loss speed




(d) Sudden change in conductivity

Figure 4.25.: Time dependency of conductivity

Figure 4.25a shows a decrease of conductivity over time, if no interventions are executed. In order to be able to represent physical deterioration, this curve should be monotonically decreasing (signifying that the state of an object and thus the conductivity can only decrease, but not increase without interventions) and have a lower bound at 0 (corresponding to the fact that a flow cannot be less than zero). The shape of the curve can be convex or concave, depending on the object properties.

If an intervention is executed, the shape of the conductivity curve resembles the one shown in Figure 4.25b. The conductivity will become 0 during the execution of the intervention, which signifies that the object is taken out of service for the intervention. Afterwards, the conductivity will be restored to a value, which may be the same, higher as, or lower than the as-new value, depending on the type of intervention, and then start decreasing again with a curve shape that may be similar or different.

If an interaction occurs, then the curve can assume two additional possible shapes: 1) If, for example the ground is disturbed after an intervention on a neighbouring object (but no direct damage is made), then the conductivity curve looks like shown in Figure 4.25c. In this case, there is no direct change in conductivity, but due to the ground disturbance, the object will deteriorate faster from that point in time, and also the conductivity will decrease faster as a consequence. 2) If the object is affected directly, the conductivity suffers from an instantaneous loss, but the curve continues parallel to the original curve. Additionally, also a combination of 1) and 2) is possible.

By combining the four curve shapes shown in Figures 4.25a to 4.25d, the condition state development can be converted into an according conductivity curve for all objects. The process diagram for this task (TC3.6) is shown in Figure 4.26.

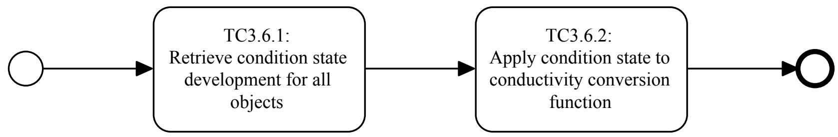



Figure 4.26.: Calculation of conductivity over time

In the first task TC3.6.1, the condition state development for all objects is retrieved. Then, in the second task TC3.6.2, a condition state conversion function (for more details, see the corresponding mathematical formulation section 5.3.4) is applied in order to convert to conductivity.

### 4.3.5. Calculate flow from conductivity

In this task, the flow in the networks is calculated from the conductivity. For all networks, the flow can be calculated from the service inputs, object properties and conductivities. The way of calculating the flow however, is distinct for each network but uses in all cases a methodology related to the balance rule presented in section 4.3. The mathematical formulations will be presented in chapter 5.3.5, the process flowchart is shown in Figure 4.27.

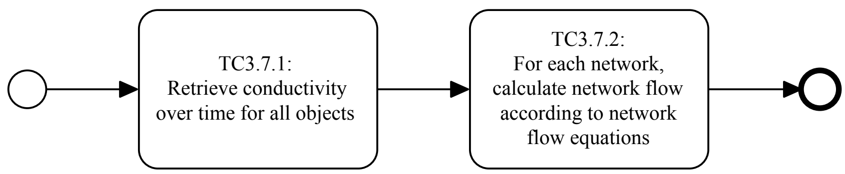



Figure 4.27.: Calculation of flow from conductivity

In the first task TC3.7.1, the conductivity over time is retrieved for all objects. Then, in the second task TC3.7.2, for each network, the flow is calculated using the appropriate methodology.

### 4.3.6. Calculate loss in level of service from flow

Finally, in this task, the loss in level of service is calculated. For all networks, this loss in level of service can be calculated from the flow and other available object properties, but the exact way of calculation depends on the network and the definition of loss in level of service. For example, in gas networks, as the level of service is defined in terms of minimal standards (see chapter 2.1.2), the loss in level of service can also be zero, if the standards are still met even if there is a reduced flow. The exact mathematical formulations for the determination of the loss in level of service from the flow are shown in the mathematical formulation chapter 5.3.6, the process diagram is shown in Figure 4.28.

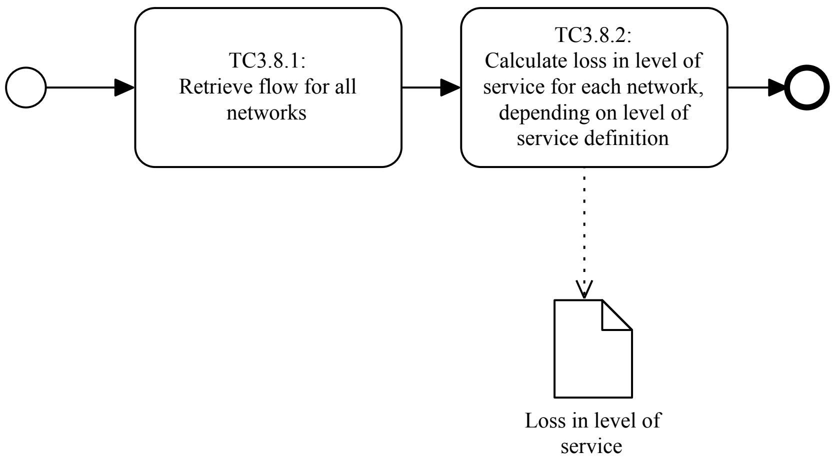



Figure 4.28.: Calculation of loss in level of service from flow

The first task TC3.8.1 retrieves the flow for all networks. Then in the second task TC3.8.2, the loss in level of service is calculated, depending on the network-specific definition of loss in level of service. With this task finalised, the effects on the level of service are estimated.

## 4.4. Evaluate clustered intervention program candidates

In this task, the clustered intervention programs are evaluated. For this, the "fitness" of each clustered intervention program has to be calculated. This is done via a fitness function (that is presented in the mathematical formulation section 5.4), that relates the intervention program to the goals that are set for the infrastructure. Additionally, penalties to the fitness may be applied. These penalties consider the fact, that some intervention program candidates have undesirable properties. For example, an intervention program candidate could exceed the budget, or another intervention program candidate could not fulfil minimum standards that are required for certain networks. These intervention programs are then penalised, i.e. their fitness is reduced, if they do not fulfil certain requirements. Then, the intervention program candidates are ranked according to their adjusted fitness. The process diagram is shown in Figure 4.29.

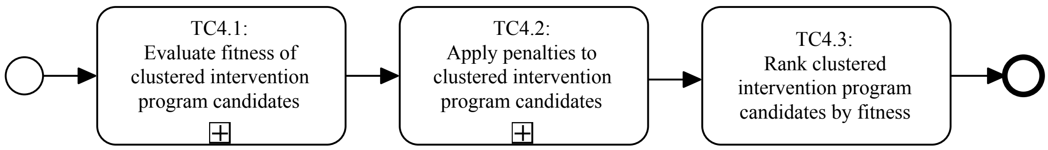



Figure 4.29.: Evaluation of clustered intervention program candidates

In the first task of this process (TC4.1), the fitness of each clustered intervention program candidate is calculated. Then, in task TC4.2, penalties are applied to the intervention program candidates, that violate any restriction. In task TC4.3, the intervention candidates are then ranked by their fitness. In the next sections, all three tasks will be presented concept-wise in more detail.

### 4.4.1. Evaluate fitness of clustered intervention program candidates

In this task, the fitness of each clustered intervention program candidate is calculated. The process diagram is shown in Figure 4.30.

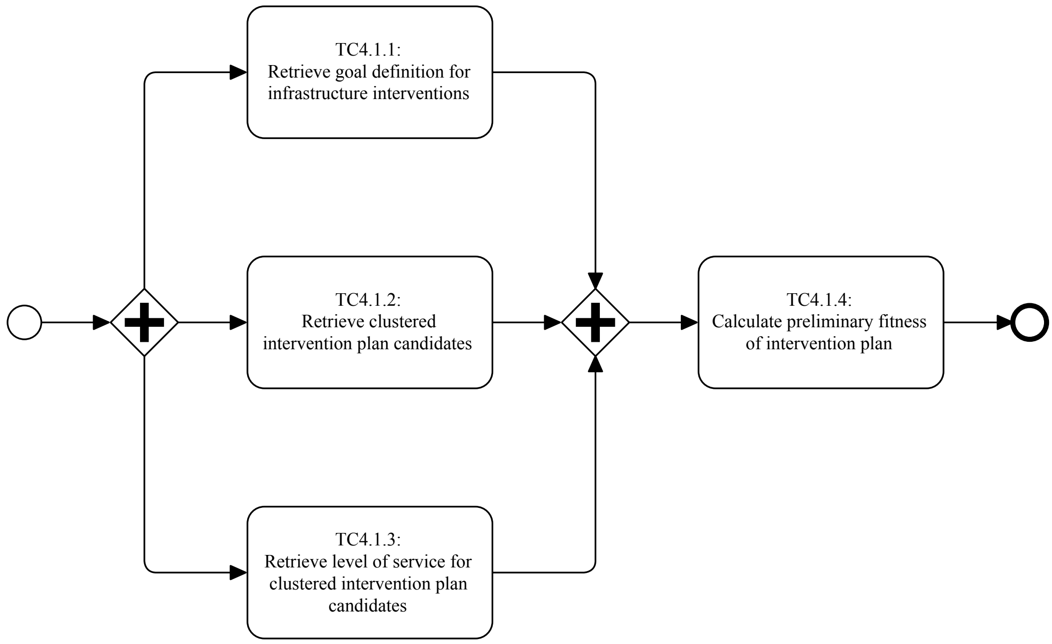



Figure 4.30.: Evaluation of fitness of clustered intervention program candidates

First, in task TC4.1.1, the goal definition for the interventions is retrieved. This goal definition has to be made outside of the presented methodology. In the total infrastructure management process, however, the definition of goals is associated to task IM4.1, which can be seen in Figure 3.2. For the presented methodology, it is assumed that the goal is set to minimise the sum of 1) the intervention costs, 2) the costs for loss in level of service due to interventions, and 3) the costs for loss in level of service due to non-optimal condition. In task TC4.1.2, the clustered intervention program candidates are retrieved, and in TC4.1.3, the associated level of service and the loss thereof is retrieved. All information is then combined and fed into the preliminary calculation of the fitness of the clustered intervention program candidate.

### 4.4.2. Apply penalties to clustered intervention program candidates

In this task, the intervention program candidates are scanned for restriction violation, and penalties are applied accordingly. This is an important part of the presented methodology, as here any restrictions that might affect the clustered intervention program candidates are taken into account. The restrictions can be divided into two groups: 1) absolute restrictions, i.e. restrictions that have to be met (e.g. a minimal legally required condition state), as any violation is prohibited. These restrictions are sometimes also called hard constraints. 2) relative restrictions, i.e. restrictions that still should be met, but a violation is not prohibited, but only strongly undesirable (e.g. a yearly budget limit, that in case of urgency can be raised through negotiations, as long as the long-term budget limit is still adhered to, in the sense of "moving over a portion of one years' budget to another year"). For the first group, the penalties are extremely high, whereas for the second group, the penalties are significantly lower. However, the assignment of groups and penalty factors is a management decision, that is not part of the presented methodology. To stay with the example of the yearly budget, the management has to decide, how "undesirable" the renegotiation of a certain years' budget is. The process diagram for the application of penalties is shown in Figure 4.31.

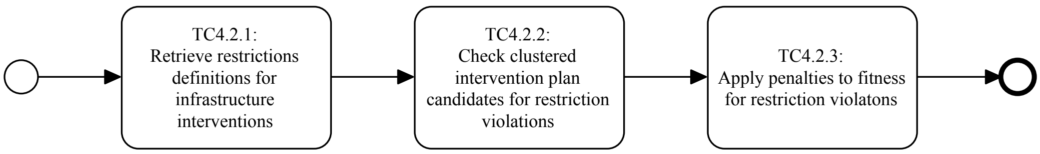



Figure 4.31.: Application of penalties

First, in task TC4.2.1, the restrictions are retrieved for each infrastructure network. Then, in task 4.2.2, the clustered intervention program candidates are checked for restriction violations. In the last task TC4.2.3, the penalties are applied to the fitness function value of those clustered intervention program candidates that violate restrictions. This then gives the final fitness for each clustered intervention program candidate, that enables the ranking performed in task TC4.3.

## 4.5. Adjust intervention program candidates

In this last task (TC5), the intervention program candidates have to be adapted in order to improve the candidates by applying changes to both the level 1 selection criteria (which come from the intervention strategy) in task TC5.1, and the marking rules for level 2 objects in task TC5.2. This is the last element of the whole optimisation setup, and the process of it is shown in Figure 4.32. The mathematical formulation of the evolution process is shown in the mathematical formulation section 5.5.

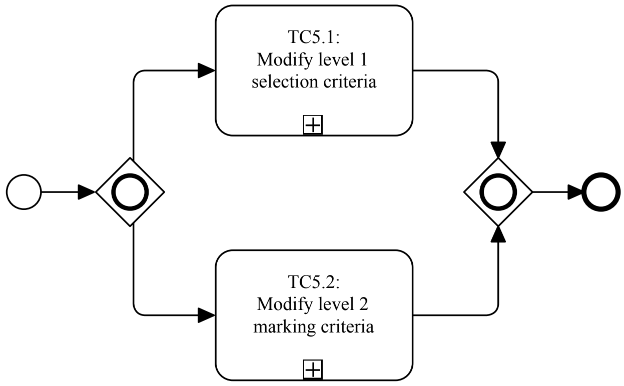



Figure 4.32.: Adjustment of intervention program candidates

### 4.5.1. Modify level 1 selection criteria

In this task, a modification function is applied to the current generation of clustered intervention program candidates (TC5.1.1), and from there, the modified level 1 selection criteria are extracted (TC5.1.2)

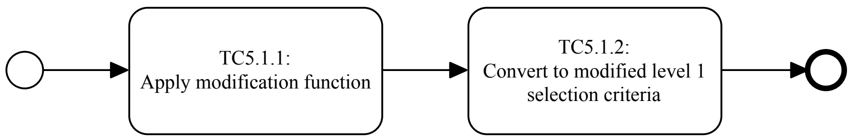



Figure 4.33.: Modification of level 1 selection criteria

### 4.5.2. Modify level 2 marking criteria

The same is done with the level 2 marking criteria: First, the modification function is applied (TC5.2.1), and then, the modified level 2 marking criteria are extracted.

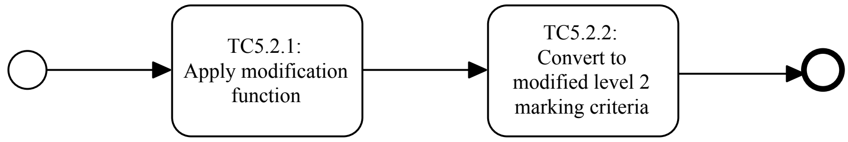



Figure 4.34.: Modification of level 2 marking criteria

This process is the last process, that is needed to form a full iteration loop. With the technical concept presented, the next chapter shows the mathematical formulations.

# 5. Mathematical formulation

In this chapter, the mathematical concept of the methodology is presented, that addresses the gaps shown in the introduction and the literature, and enables infrastructure managers to improve upon their current situation, by creating combined intervention programs that take into account not only one infrastructure network, but also the interactions between the networks and the possible benefits that can be created from intervention grouping. The goal of this chapter is to present the mathematical formulation corresponding to the process charts from chapter 4. The computer algorithm, that translates this mathematical formulation into executable code is shown in chapter 6. Again, this chapter uses the same numbering scheme as chapters 4 and 6 (i.e. for the technical concept in chapter 4.2.2, the corresponding mathematical formulation is in chapter 5.2.2, and the algorithmic implementation in chapter 6.2.2.), in order to facilitate comparison between the technical concept, mathematical formulation and algorithmic implementation. Therefore, it may happen that some chapters contain a lot of text in the respective chapters 4 or 6 but not in this chapter, or vice versa.

First a mathematical representation has to be defined, that encodes the intervention program candidate into a mathematically tractable form. For this, the following definition is used:

$$\Psi = \delta_{n,m,\kappa,t} \tag{5.1}$$

with

$\Psi \ldots$ Genome representing the intervention program,

$\delta_{n,m,\kappa,t} \ldots$ Binary indicator for object $o_{n,m}$ (object with ID $n$ from network $m$), for intervention type $\kappa$ at time point $t$

In other words, the decision variable is directly the type of intervention $\kappa$, on object $o_{n,m}$ at time point $t$, represented in a binary indicator, that has a value of 1, if intervention type $\kappa$ is executed on object $o_{n,m}$ at time point $t$, and 0, if not.

## 5.1. Create initial intervention program candidates

In the first task (TC1.1), the level 1 objects are preselected. The function used to determine if an object is selected for an intervention is referred to as a selector function $f^I$. The superscript $^I$ denotes level 1. The selector function is defined as a logical function, with $f^I = 1$ (true) when an object is selected, and 0 otherwise. For ease of reading, the indices $\kappa$ and $t$ from equation 5.1 are omitted in the following. A set of objects $o_{n,m}$ is determined based on the boundaries of the physical area to be analysed and the jurisdiction of the manager. Objects that are either outside the area to be analysed, or are the responsibility of another manager, are excluded. The set of all objects considered is denoted by the object vector $\vec{o}_{n,m}$ consisting of all objects $o_{n,m}$: $\vec{o}_{n,m} = (o_{1,1}, o_{2,1}, \ldots, o_{N,1}, o_{1,2}, \ldots, o_{N,2}, \ldots, o_{N,M})$. The selection of the objects is based on properties $\zeta_n^I$ of the object itself, and based on network properties $\xi_m^I$. This selector function is applied to $\vec{o}_{n,m}$ (the set of all objects $o_{n,m}$) in order to obtain the logical selection vector[1] for the level 1 objects $\vec{\delta}_{n,m}^I$. This function is the mathematically expressed intervention strategy.

$$\vec{\delta}_{n,m}^I = f^I\left(\vec{o}_{n,m}, \zeta_n^I, \xi_m^I\right) \tag{5.2}$$

To avoid confusion, the following notation will be used: $\vec{\delta^I}_{n,m}$ refers to the selection vector, whereas $\delta_{n,m}^I$ refers to an element of this vector. In the last step, this logical selection vector is stored to be used for further computations.

In the second task (TC1.2), the level 2 objects are marked. Similar to level 1, the function used to determine if an object is marked, is referred to as a selector function $f^{II}$. All the components of the selector function are the same, only with different values. Therefore, the indices have been changed from $I$ to $II$. The selector function is applied to $\vec{o}_{n,m}$ order to obtain the level 2 objects logical selection vector $\vec{\delta}_{n,m}^{II}$ :

[1] i.e. a vector of true (1) or false (0) that records which objects are selected by the selector function

$$\vec{\delta}^{II}_{n,m} = f^{II}\left(\vec{o}_{n,m}, \zeta^{II}_{n}, \xi^{II}_{m}\right) \tag{5.3}$$

The third task (TC1.3) is then simply the storage of $\vec{\delta}^{I}_{n,m}$ and $\vec{\delta}^{II}_{n,m}$.

## 5.2. Apply clustering procedure

In this task (TC2), the clustering procedure is applied, which will be mathematically presented in sections 5.2.2 to 5.2.5.

### 5.2.1. Select level 1 objects

In this task (TC2.1), the level 1 selector function will be applied again (Equation 5.2), in order to update the level 1 objects.

### 5.2.2. Calculate neighbourhood

This task (TC2.2) is the main task of the neighbourhood calculation, that is also one of the contributions of the presented methodology.

#### 5.2.2.1. Obtain temporal neighbourhood

At first, the temporal neighbourhood is calculated. The temporal neighbourhood of an object is defined by a timespan around the time-point, when an intervention is to be done. Mathematically, the temporal neighbourhood calculation can be described as follows:

$$nc_{n,m,j,k} = H\left(n_T - \left(nc_{j,k} - nd_{n,m}\right)\right) \tag{5.4}$$

with

$nc_{n,m,j,k} \ldots$ indicator, if object $o_{j,k}$ lies within temporal neighbourhood of the originating object $o_{n,m}$ (1 if yes, 0 if no),

$n_T \ldots$ temporal distance, $nc_{j,k} \ldots$ earliest time for intervention on object $o_{j,k}$,

$nd_{n,m} \ldots$ latest time for an intervention on object $o_{n,m}$.

$H(x)$ denotes the Heaviside function, which is a function that returns 1 for $x > 0$, and 0 otherwise. Combining the indicators $nc_{n,m,j,k}$ to a grand matrix gives the temporal neighbourhood matrix $\mathbf{N}_C$. Mathematically:

$$\mathbf{N}_C = \begin{bmatrix} nc_{1,1,1,1} & \cdots & nc_{1,1,j,1} & nc_{1,1,1,2} & \cdots & nc_{1,1,j,2} & \cdots & nc_{1,1,j,k} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ nc_{n,1,1,1} & \cdots & nc_{n,1,j,1} & nc_{n,1,1,2} & \cdots & nc_{n,1,j,2} & \cdots & nc_{n,1,j,k} \\ nc_{1,2,1,1} & \cdots & nc_{1,2,j,1} & nc_{1,2,1,2} & \cdots & nc_{1,2,j,2} & \cdots & nc_{1,2,j,k} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ nc_{n,2,1,1} & \cdots & nc_{n,2,j,1} & nc_{n,2,1,2} & \cdots & nc_{n,2,j,2} & \cdots & nc_{n,2,j,k} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ nc_{n,m,1,1} & \cdots & nc_{n,m,j,1} & nc_{n,m,1,2} & \cdots & nc_{n,m,j,2} & \cdots & nc_{n,m,j,k} \end{bmatrix} \qquad (5.5)$$

In other words, the temporal neighbourhood matrix $\mathrm{N}_C$ describes, if object $o_{n,m}$ (the rows) is temporally close to object $o_{j,k}$ (the columns) with a value of “1” in the respective field, and “0” otherwise.

#### 5.2.2.2. Calculate topological neighbourhood from level 1 objects

The topological neighbourhood of an object is based on the topological distance along the network. This distance is defined by the number of objects between two logical nodes. In that sense, two objects are neighbours if the network distance between their closest logical nodes is below a certain threshold. Mathematically, objects that are close (i.e. within a certain neighbourhood threshold) can be found as follows: First, the incidence matrix $\mathbf{C}_m$ (i.e. a matrix describing which edges are connected to which nodes) is converted to an adjacency matrix $\mathbf{L}_m$, which is just another way to describe a network:

$$\mathbf{L}_m = \mathbf{C}_m^\top \cdot \mathbf{C}_m - \operatorname{diag}\left(\mathbf{C}_m^\top \cdot \vec{1}\right) \tag{5.6}$$

with

$\boldsymbol{L}_m \ldots$ Adjacency matrix of network $m$,

$\boldsymbol{C}_m \ldots$ Incidence matrix of network $m$.

From there, all nodes reachable in a distance $k$ can be calculated by

$$\boldsymbol{K}_m = \operatorname{sgn}\left(\sum_{x=0}^{k} \boldsymbol{L}_m^x\right) \tag{5.7}$$

with

$\boldsymbol{K}_m \ldots$ Reachability matrix of network $m$ for $k$ steps,

and $sgn(x)$ representing the sign function[2]. Each element from $\boldsymbol{K}_m = [k_{m,i,j}]$ shows if a node is reachable from another node with a maximum of k steps. Combining those reachability matrices to a grand matrix, gives the neighbourhood matrix $\mathbf{N}_T$:

$$\mathbf{N}_T = \begin{bmatrix} \mathbf{K}_1 & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{K}_2 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{K}_M \end{bmatrix} \tag{5.8}$$

In this matrix both rows and columns represent individual objects, and objects X and Y with $\{\mathrm{X}, \mathrm{Y} \in \vec{o}_{n,m}\}$ are in topological neighbourhood, if the matrix cells $(\mathrm{X}, \mathrm{Y})$ or $(\mathrm{Y}, \mathrm{X})$ have a nonzero entry. Note that this matrix has to be filled with 0-matrices next to the individual $\mathbf{K}_m$-matrices because objects in different networks $m$ are not connected in a topological sense.

[2]The sign function is defined as follows: $sgn(x) = \begin{cases} x < 0: & -1 \\ x = 0: & 0 \\ x > 0: & 1 \end{cases}$

#### 5.2.2.3. Calculate distance neighbourhood from level 1 objects

As the sizes of objects can differ by orders of magnitudes, neighbourhoods can also be defined by distance along the network. This is an alternative neighbourhood definition which takes into account only the physical distance from each other along the network. For this, an object is defined as a neighbour, if it can be reached within a certain distance along the network.

Mathematically, the shortest path between all logical nodes $\eta$ of all objects has to be calculated (or loaded from the database if available).

$$\mathbf{D}_{m,\eta} = \mathrm{APSP}_m(m, \eta) \tag{5.9}$$

with

$\mathbf{D}_{m,\eta} \ldots$ All logical node pairs distance matrix for network $m$,

$\mathrm{APSP}_m \ldots$ All node pairs shortest path algorithm for networks as described in (Johnson, 1977).

The minimal distance between all object pairs is then the minimum of the minimal distances between each objects' logical nodes.

$$\mathbf{D}_m = \min\left(\mathrm{dist}\left(\mathbf{D}_{m,\eta}, \mathbf{D}_{m,\eta}\right) \middle|\, \eta_{n,m} \subset o_{n,m}\right) \tag{5.10}$$

with

$\mathbf{D}_m \ldots$ minimal distance matrix for all objects in network $m$,

$\mathrm{dist} \ldots$ distance function,

$\eta_m \ldots$ logical nodes of object $o_{n,m}$.

Comparing this minimal distance matrix with a distance threshold $d_{lim,m}$ for each network $m$ gives the neighbourhood matrix $\mathbf{D}_{d,m}$:

$$\mathbf{D}_{d,m} := \mathbf{D}_m \leq d_{lim,m} \tag{5.11}$$

Combining those distance matrices into a grand matrix, gives the neighbourhood matrix $\mathbf{N}_N$ :

$$\mathbf{N}_N = \begin{bmatrix} \mathbf{D}_{d,1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{D}_{d,2} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{D}_{d,M} \end{bmatrix} \tag{5.12}$$

#### 5.2.2.4. Calculate Voronoi neighbourhood from level 1 objects

Both, topological and distance neighbourhood definitions have the prerequisite that all objects have to belong to the same network. To overcome this limitation, the neighbourhood can also be defined by Voronoi cells. Voronoi cells $V_v$ consist of every point whose distance to $p_k$ is less or equal to any other point $p_{j \neq k}$. A Voronoi region $R_i$ for one object is then the set of all Voronoi cells emanating from the nodes of that object (see Figure 4.11). Combining those regions gives the set of all Voronoi regions $\vec{R}_{n,m}$ for all objects $o_{n,m}$ This can be used to define the neighbourhood as follows: objects X and Y are neighbouring, if object Y touches object X's Voronoi region with $\{\mathrm{X}, \mathrm{Y} \in \vec{o}_{n,m}\}$. The neighbourhood can then be defined as:

$$\mathbf{N}_V = \vec{R}_{n,m} \sqcap \vec{o}_{n,m} \tag{5.13}$$

with $\vec{R}_{n,m} \ldots$ Voronoi regions of objects $\vec{o}_{n,m}$,

$\sqcap \ldots$ dyadic spatial intersection, and

$\mathbf{N}_V \ldots$ neighbourhood matrix for Voronoi methodology.

In the last activity of the dynamic neighbourhood, all neighbourhoods are combined to a grand neighbourhood, by combining all neighbourhood matrices to the dynamic neighbourhood matrix $\mathbf{N}_D$:

$$\mathbf{N}_D = \mathbf{N}_C \wedge ((\mathbf{N}_T \vee \mathbf{N}_N) \vee \mathbf{N}_V) \tag{5.14}$$

with the symbol $\wedge$ denoting the logical "and", which is an operator that returns the value of "1" if both of the inputs are "1", and the symbol $\vee$ denoting the logical 'or', which is an operator that returns a value of ‘1’ if at least one input is ‘1’, i.e. ‘1’ and ‘0’ or ‘0’ and ‘1’ or ‘1’ and ‘1’. In words, two objects are neighbours if they are 1) temporal neighbours and 2) either topological, distance or Voronoi neighbours.

### 5.2.3. Determine close objects

In the next step, the so called close objects are determined. Those objects are objects that are located in the neighbourhood, which is defined by the dynamic neighbourhood matrix $\mathbf{N}_D$. This process ensures that only close objects, i.e. objects that are sufficiently near to level 1 objects are screened for being potential level 2 objects in the next step. Mathematically, the whole process can be expressed in one equation:

$$\vec{\delta}^{C,D}_{n,m} = \left( (\mathbf{N}_D \otimes \vec{o}_{n,m})^\top \cdot \vec{1} \right) \nrightarrow \vec{\delta}^{I}_{n,m} \tag{5.15}$$

with

$\vec{\delta}^{C,D}_{n,m}$ ... binary variable vector indicating if object $o_{n,m}$ is part of the close object set.

The superscript $^C$ denotes the close objects, the superscript $^D$ denoting the dynamic neighbourhood and the symbol $\nrightarrow$ denotes the material non-implication operator. This operator only returns a value of ‘1’ if the first input is ‘1’ and the second input is ‘0’. In this case: an object is only a close object for the neighbourhood ($\delta^{C,D}_{n,m} = 1$) if the object is within the neighbourhood of a level 1 object ((($\mathbf{N}_{T,k} \otimes \vec{\delta}^{I}_{n,m})^\top \cdot \vec{1}) = 1$) but is not by itself a level 1 object ($\delta^{I}_{n,m} = 0$). The operator $\otimes$ in this context denotes the expanded Hadamard product[3]. In the last activity, the selection vector is stored for further use.

### 5.2.4. Determine close level 2 objects

From this, the close level 2 objects are defined, by building the intersection between the close objects and the level 2 objects:

$$\vec{\delta}^{C,D,II}_{n,m} = \vec{\delta}^{C,D}_{n,m} \cap \vec{\delta}^{II}_{n,m} \tag{5.16}$$

[3] i.e. $\begin{bmatrix} a_{1,1} & a_{1,2} & a_{1,3} \\ a_{2,1} & a_{2,2} & a_{2,3} \\ a_{3,1} & a_{3,2} & a_{3,3} \end{bmatrix} \otimes \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} a_{1,1} \cdot b_1 & a_{1,2} \cdot b_1 & a_{1,3} \cdot b_1 \\ a_{2,1} \cdot b_2 & a_{2,2} \cdot b_2 & a_{2,3} \cdot b_2 \\ a_{3,1} \cdot b_3 & a_{3,2} \cdot b_3 & a_{3,3} \cdot b_3 \end{bmatrix}$

with $\vec{\delta}_{n,m}^{C,D,II}$ ... binary variable vector indicating if object $o_{n,m}$ is part of the close level 2 object set

### 5.2.5. Group objects

In this task, the level 1 and level 2 objects, which have been identified in the previous steps, are combined into intervention clusters, i.e. sets of interventions that are executed together. Mathematically:

$$\mathbf{I}_D = \text{DBSCAN}\left(\vec{\delta}_{n,m}^{I} \wedge \vec{\delta}_{n,m}^{C,D,II}, \text{Eps}, \text{MinPts}\right) \tag{5.17}$$

with

$\mathbf{I}_D$ ... intervention cluster matrix. The rows correspond to all objects $o_{n,m}$, and the columns correspond to the clusters. A "1" in a field signifies, that the object $o_{n,m}$ is part of the cluster in the respective column, a "0" shows that the object is not part of the cluster.

DBSCAN ... Clustering function according to (Ester et al., 1996),

Eps ... Distance variable, representing a search area around points,

MinPts ... Minimal number of points, that make up a cluster (normally MinPts = 2)

#### 5.2.5.1. Filter level 2 clusters

In this task, the clusters are filtered for level 2 object - clusters only, that are excluded from the intervention program. This is done again by the material non-implication operator. Mathematically:

$$\mathbf{I}_D' = \mathbf{I}_D \nrightarrow \vec{\delta}_{n,m}^{C,D,II} \tag{5.18}$$

with $\mathbf{I}_D'$ ... filtered intervention cluster matrix.

### 5.2.6. Calculate interactions

The interactions are also calculated in section 5.3.2. To improve readability, the mathematical formulation will be presented there.

## 5.3. Estimate effects on level of service

The mathematical model for describing the service (and the loss thereof) is based on the assumption that all aforementioned services can described by the same schematic expression: a time integral of the flow of the good/service/units in/on the respective network $m$. This is necessary to be able to combine all networks in one mathematical expression in order to facilitate the interaction calculation between the networks. In these networks however, the naming and usage of variables is not consistent across networks, i.e. sometimes the same word or variable is used to mean different things on different networks. For example, the variable $Q$ is used for charge in electrical engineering, but for flow in hydraulic engineering. Therefore, in the presentation of the mathematical model, the variable names have been changed to $A, B, C \ldots$ in order of their appearance to avoid confusion. The basic equation 5.19 shows the schematic expression of the service $A$:

$$A_m = \int_t B_m(t)\, dt \tag{5.19}$$

In order to simplify explanations, the following terms shall be introduced:

Service power $B_m$: The derivative of the provided service with respect to time, i.e. the service per time unit

$$B_m = \frac{d}{dt}\,(A_m) \tag{5.20}$$

Service pressure $C_m$: The quotient of service power and service flow $D_m$

$$C_m = \frac{B_m}{D_m} \tag{5.21}$$

Service flow $D_m$: The amount of service units that flows through a given cross section per unit time

$$D_m = \frac{E_m}{t} \tag{5.22}$$

Service unit $E_m$: The product of service flow and time

$$E_m = D_m \cdot t \tag{5.23}$$

From equation 5.19, it can be seen that the service provided is an integral of service power over time. Therefore, the loss of service can be measured using the same integral. In general, loss of level of service occurs due to the condition of the objects and the implications caused by this (leaks, resistance, partial closure, re-routing, etc.). Figure 5.1 gives an introduction to the proposed terminology on the example of a network consisting of one single object, by amending the conceptual Figure 4.19 with the variables from the mathematical formulation. Figure 5.2 then shows the application to a general network.

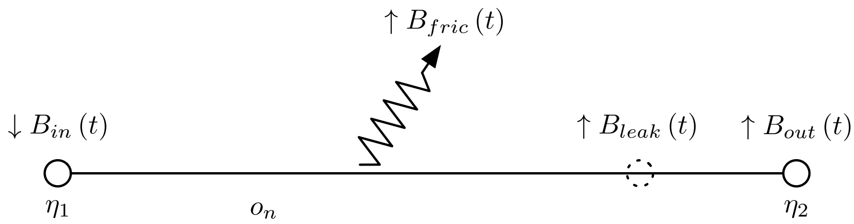



Figure 5.1.: Losses on a single object

Each object $o_n$ connects two nodes, $\eta_1$ and $\eta_2$. In node $\eta_1$, there is a service power input $B_{in}(t)$, in $\eta_2$ a service power output $B_{out}(t)$. During the transmission of the service power, there is the possibility of $B_{fric}(t)$ friction along the object, which represents a loss of service power that is related to the length of object $o_n$. This loss is usually caused by a loss in service pressure. Additionally, there is also a possibility of leaks $B_{leak}(t)$ on the object, where service power may also be lost. In this case, the loss is caused by a loss of service units. The sum of $B_{fric}(t)$ and $B_{leak}(t)$ is referred to as lost service power $B_{loss}(t)$. For the system to be in balance, the following equation holds true:

$$B_{in}(t) = \underbrace{B_{fric}(t) + B_{leak}(t)}_{B_{loss}(t)} + B_{out}(t) \tag{5.24}$$

This means, assuming Figure 5.1 depicts a simple infrastructure network with only one producing node (the service provider, $\eta_1$ ) and only one consuming node (the customer, $\eta_2$ ), that the service provider has to produce not only the service $B_{out}(t)$ used by the customer, but also the additional amount of service power $B_{loss}(t)$ that is lost during the transportation.

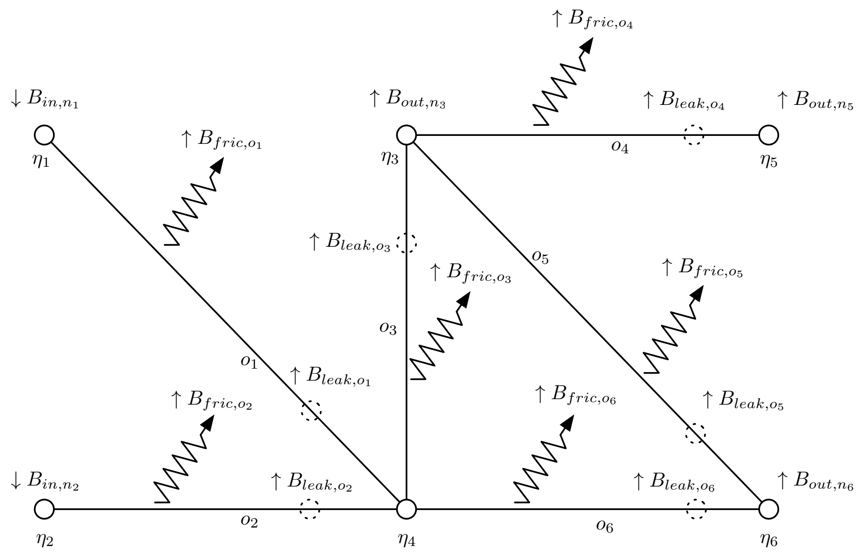



Figure 5.2.: Losses on the network

In Figure 5.2, a small network is depicted. It consists of two producing nodes $\eta_1$ and $\eta_2$, one intermediate node $\eta_4$, and three consuming nodes $\eta_3, \eta_5$, and $\eta_6$. These nodes are linked by the objects $o_1$ to $o_6$. The principle of the losses is the same, however, the losses can occur on each object. Therefore, for the system to be in balance, the following equation holds true:

$$\sum_{\eta} B_{in,\eta}(t) = \sum_{o} \left( \underbrace{B_{fric,o}(t) + B_{leak,o}(t)}_{B_{loss,o}(t)} \right) + \sum_{\eta} B_{out,\eta}(t) \tag{5.25}$$

By examining Eq. 5.25, it can be seen that the in-feed service power is to be shared between the network (where it has to compensate the losses) and the output. If the network, which due to an increasing $B_{loss}$ in the network, consumes more service power than expected this leads to less output service power $B_{out}$, assuming the input $B_{in}$ stays constant. On the other hand, if the input $B_{in}$ decreases (with the loss over the network $B_{loss}$ being unchanged), the output service power also decreases. Normally, both will happen simultaneously. First, if the network consumes more service power (due to friction, leakage, etc.), the producer increases the in-feed service power to compensate the losses and to supply a constant level of service. At some point, the maximum production capacity will be reached. Thus a further increase in network losses will lead to a loss in level of service, as the in-feed service power will keep constant, but the loss will increase.

With the loss of service defined in terms of service power, the service power state and the loss of service power can be estimated for each network. To facilitate reading, the index (t) for each time point has been omitted. Following basic physical relations, the general form of the service power equation is

$$B_m = f(\gamma_{n,m}, \sigma_{n,m}, D_{n,m}) \tag{5.26}$$

with

$\gamma_{n,m} \ldots$ conductivity term for object $o_{n,m}$

$\sigma_{n,m} \ldots$ object slimness

$D_{n,m} \ldots$ service flow through object $o_{n,m}$

$B_m \ldots$ service power in network $m$.

### 5.3.1. Construct preliminary object condition timeline from clustered intervention program candidate

In this task, the preliminary object condition timeline is constructed from the clustered intervention program. This is done via conductivity in task TC3.4. Therefore, the detailed mathematical formulation can be found in section 5.3.4.

### 5.3.2. Transmit sudden changes

Mathematically, the transmission of sudden changes (see Figure 4.25d) is captured using a transmission matrix **S**, which captures both of these types of changes. This transmission matrix is defined as follows:

$$\mathbf{S} = \begin{bmatrix} s_{11} & s_{12} & \dots & s_{1j} \\ s_{21} & s_{22} & \dots & s_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ s_{i1} & s_{i2} & \dots & s_{ij} \end{bmatrix} \; with \; \begin{cases} \forall\, i = j & : \quad s_{ij} \leq 1 \\ \forall\, i \neq j & : \quad s_{ij} \in \{0..1\} \end{cases} \; and\; i,j \in \left\{1 ... \sum n \sum m\right\} \tag{5.27}$$

In words, the element $s_{ij}$ in the transmission matrix **S** describes the adverse effect that is transmitted from object $i$ to object $j$. Therefore, the indices $i$ and $j$ run through all objects $o_{n,m}$.

For the diagonal elements (i.e. where $i = j$), the individual values have to be 0 (signifying no interaction of the object with itself), outside of the diagonal, the individual values can range between 0 and 1, with a value of $s_{ij} = 1$ meaning that the object $j$ is rendered totally inoperable by an intervention on object $i$.

The transmission element $s_{ij}$ itself can be calculated as follows:

$$s_{i,j} \forall \{i \neq j\} = f\left(\tau_{n,m}, \operatorname{dist}(i,j)\right) \tag{5.28}$$

with

$\tau_{n,m} \dots$ transmission factor for object $o_{n,m}$,

$\operatorname{dist}(i,j) \dots$ distance between objects $i$ and $j$.

In other words, the transmission element is calculated as a function of a transmission factor and a distance between the affected objects. This transmission factor takes into account both the potential interaction between the objects, as well as an interaction hierarchy that represents the fact that it is possible that there is a transmission of a sudden change in one direction between two objects, but not in the opposite direction, i.e. $s_{i,j} \neq s_{j,i}$.

### 5.3.3. Incorporate sudden changes

To incorporate sudden changes, the decision vector $\vec{\delta}_{n,m,\kappa,t}$ is combined with the transmission matrix to describe the sudden change of conductivity due to interaction with other objects as:

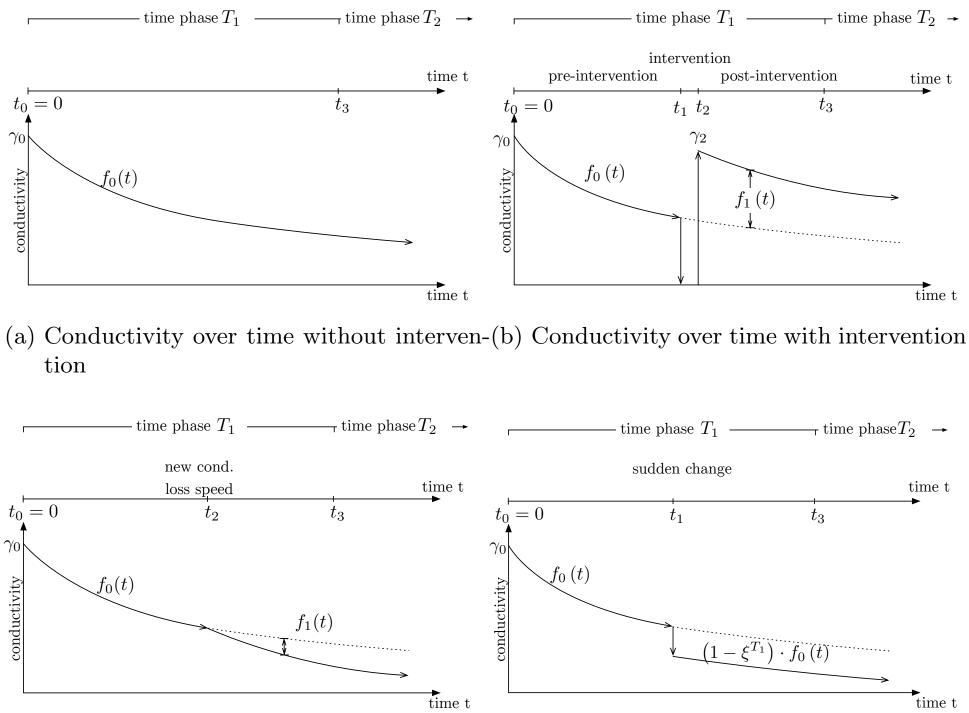
$$\vec{\xi}_{n,m,t} = min\left(\mathbf{S}^{\intercal} \cdot \vec{\delta}_{n,m,\kappa,t}, \vec{1}\right) \tag{5.29}$$

with

$\vec{\xi}_{n,m,t} \ldots$ Transmission vector of the effects to objects $\vec{o}_{n,m}$, with the individual elements representing the received adverse effects from all other objects). As Equation 5.29 sums up all interactions, these interactions have to be capped by a “1”, due to the fact that an object cannot be rendered more than totally inoperable (which is defined in section 5.3.2 as a value of “1”)

### 5.3.4. Calculate conductivity over time

After incorporating the sudden changes, the conductivity over time can be calculated. For better understandability of the used variables, the concept shown in Figure 4.25 is amended by the variables in Figure 5.3.




(a) Conductivity over time without intervention

(b) Conductivity over time with intervention

(c) Increase of conductivity loss speed

(d) Sudden change in conductivity

Figure 5.3.: Variables used in conductivity calculation

To be able to calculate the conductivity of the object, the above-mentioned gradual and sudden changes in conductivity have to be combined into one equation, which is:

$$
\begin{aligned}
\gamma_{n,m}(t) \quad = \quad & \left(f_{0,n,m}(t) + \sum\nolimits_{\omega} \left(\delta_{n,m}^{T_k} \cdot f_{\omega,n,m}(t) \cdot H\left(t - t_{(3\omega-1)}\right)\right)\right. \\
- \quad & \sum\nolimits_{\omega} \left(\delta_{n,m}^{T_k} \cdot \mathrm{boxcar}\left(t, t_{(3\omega-2)}, t_{(\omega k-1)}\right) \cdot \sum\nolimits_{\omega} \left(\delta_{n,m}^{T_\omega} \cdot f_{\omega,n,m}(t) \cdot H\left(t - t_{(3\omega-1)}\right)\right)\right)\Big) \\
\cdot \quad & \sum\nolimits_{\omega} \left(\left(1 - \xi_{n,m}^{T_\omega}\right) \cdot H\left(t - t_{(3\omega-1)}\right)\right)
\end{aligned}
\tag{5.30}
$$

with

$\gamma_{n,m}(t)\ldots$ conductivity of object $o_{n,m}$ at time $t$,

$\delta_{n,m}^{Tk}\ldots$ binary variable indicating if an intervention is executed on object $o_{n,m}$ at time phase $T_\omega$ ,

$boxcar(x,a,b)\ldots$ Boxcar function, defined as: $boxcar(x,a,b) = \begin{cases} x & for\; a \leq x \leq b \\ 0 & else \end{cases}$

With this equation, the conductivity of the object can be described formally, on a per-object-basis, allowing for distinct conductivity functions for each object that can also be fundamentally different (i.e. from different functional families such as exponential, rational, etc.) as long as the function is monotonically decreasing over time.

### 5.3.5. Calculate flow from conductivity

To allow focussing on the global methodology, the interpretation of the different variables on the infrastructure network will be omitted. In general, all conductivity measures are implemented in a flow equation (Eq. 5.31).

$$\mathbf{M}\cdot\vec{P} = \begin{pmatrix} m_{11} & -m_{12} & \ldots & -m_{1\eta} \\ -m_{21} & m_{22} & & -m_{2\eta} \\ \vdots & & \ddots & \vdots \\ -m_{\eta 1} & -m_{\eta 2} & \ldots & m_{\eta\eta} \end{pmatrix} \cdot \begin{pmatrix} P_1 \\ P_2 \\ \vdots \\ P_\eta \end{pmatrix} = \begin{pmatrix} D_1 \\ D_2 \\ \vdots \\ D_\eta \end{pmatrix} = \vec{D} \tag{5.31}$$

with

$\mathbf{M}\ldots$ network characteristic matrix,

$\vec{P}\ldots$ pressure vector,

$m_{ij}(\text{with}\, i=j)\ldots$ sum of conductance of all objects connected to node $(i \in 1\ldots\eta)$, $m_{ij}(\text{with } i \neq j)\ldots$ conductance between nodes $i$ and $j$ , $(i,j \in 1..\eta)$, $D_\eta\ldots$ current flowing in/out of node $\eta$, and $\vec{D}\ldots$ flow vector. The conductance is simply the ratio of every object's conductivity to its slimness. The network characteristic matrix is able to represent the structure of the network topology, including flow direction or different directional capacities.

### 5.3.6. Calculate loss in level of service from flow

In this task (TC3.6), the loss in level of service is calculated from the flow. From the methodology point of view, the loss in level of service is measured in costs $G_{LOS,m}$. The general formulation for the costs is:

$$G_{LOS,m} = G_{LOS,fix,m} + \int_0^t \left(f\left(B_{m,in}(t) \cdot g_{prod,m}\right)\right) dt - \int_0^t \left(f\left(B_{m,out}(t) \cdot g_{rcv,m}\right)\right) dt \tag{5.32}$$

with

$G_{LOS,m} \ldots$ costs occurred by the loss in level of service for network $m$,

$G_{LOS,m,fix} \ldots$ fixed costs for operating the network,

$B_{m,in}(t) \ldots$ service power input for network $m$,

$B_{m,out}(t) \ldots$ service power output for network $m$,

$g_{prod,m} \ldots$ costs per service power unit produced,

$g_{rcv,m} \ldots$ revenue per service power unit received.

In other words, the loss in level of service is expressed as the difference between the sum of the fixed costs plus the per-unit service power generation cost minus the service power revenue per service power unit received.

## 5.4. Evaluate clustered intervention program candidates

In this task, the clustered intervention program candidates are evaluated, based on the fitness of the intervention program candidates and certain penalties for exceedance of restrictions. First, the fitness is calculated, and then penalties are applied if applicable. This also constitutes the optimisation problem, that is minimised in order to find the optimal intervention program.

### 5.4.1. Evaluate fitness of clustered intervention program candidates

In this section, the mathematical model is described, that expresses the fitness function $F$ in a mathematical form:

$$\min F = G_{int}\left(\Psi\right) + \sum_{m} G_{LOS,m} \tag{5.33}$$

The fitness function minimises the sum of 1) intervention costs, and 2) sum of loss in level of service costs.

The intervention costs $G_{int}(\Psi)$ can be written out as:

$$G_{int}(\Psi) = \alpha_g \cdot \sum_{j} \left(c_j + \left(\left(\left(\mathbf{I}'_D \otimes \left(c_{n,m}\right)^{\top}\right) \otimes \left(u_{n,m}\right)^{\top}\right) \cdot \vec{1}\right)\right) \tag{5.34}$$

with

$\alpha_g \ldots$ grouping benefit (i.e. the reduction of costs due to grouping of interventions),

$c_j \ldots$ setup costs for intervention cluster $j$,

$c_{n,m} \ldots$ unit costs without setup costs (e.g. costs per meter) for each intervention on each object, and

$u_{n,m} \ldots$ size of the object.

### 5.4.2. Apply penalties to clustered intervention program candidates

In this task, the penalties are applied to the clustered intervention program candidates, so that the final fitness can be calculated:

$$F'\left(\Psi\right) = P\left(\Psi\right) + F\left(\Psi\right) \tag{5.35}$$

with

$F'(\Psi)\ldots$ penalty-adjusted fitness, and

$P(\Psi)\ldots$ penalty for chromosome $\Psi$.

In general, the penalties come from the violation of restrictions. In this formulation, two different types of restrictions can be accounted for: 1) global restrictions and 2) temporal restrictions. The former are in place during the whole calculation period, the latter on a time-step by time-step basis.

Mathematically:

$$R(\Psi) \leq R_{lim} \tag{5.36}$$

with

$R(\Psi)\ldots$ restricted global feature (e.g. the total intervention cost, or a maximum failure probability) of the intervention program candidate represented by chromosome $\Psi$, and

$R_{lim}\ldots$ restriction limit (e.g. the global intervention budget limit), and

$$R(\Psi, t) \leq R_{lim}(t) \tag{5.37}$$

with

$R(\Psi, t)\ldots$ restricted temporal feature (e.g. the intervention cost per year $t$) of the intervention program candidate represented by chromosome $\Psi$, and

$R_{lim}(t)\ldots$ restriction limit (e.g. the intervention budget limit per year $t$).

The total penalty can then be calculated as:

$$\begin{aligned} P(\Psi) &= \zeta \cdot F(\Psi) \cdot H\left(H\left(\textstyle\sum_t \left(H\left(R_{int}(\Psi, t) - R_{lim}(t)\right)\right)\right)\right. \\ &+ \left. H\left(R(\Psi) - R_{lim}\right)\right) \end{aligned} \tag{5.38}$$

with $\zeta\ldots$ penalty factor. The multiple occurrences of the Heaviside function in Equation 5.38 stem from the rules of summation for the Heaviside function.

## 5.5. Adjust intervention program candidates

In this task, the intervention program candidates are adjusted for the next iteration loop. The exact formulation of this adjustment is, however, strongly dependent on the type of iteration loop used. For example, gradient based iteration techniques calculate the local gradient and adjust the decision variables in gradient direction, whereas in genetic algorithms, the next iteration loop is initiated with genetic crossover and mutation operations. Therefore, the subsections "Modify level 1 selection criteria" and "Modify level 2 selection criteria" are omitted in the mathematical formulation chapter, but are presented in chapter 6, where the actual algorithm implementation is shown.

# 6. Algorithmic implementation

In this chapter, the algorithmic implementation of the concept and mathematical representation (as shown in chapters 4 and 5) is presented, that transfers the concept into an executable program. The goal of this chapter is to present an algorithmic implementation, that is detailed enough to be able to directly be programmed, but without being restricted to a specific programming language. Again, this chapter uses the same numbering scheme as chapters 4 and 5 (i.e. for the technical concept in chapter 4.2.2, the corresponding mathematical formulation is in chapter 5.2.2, and the algorithmic implementation in chapter 6.2.2.), in order to facilitate comparison between the technical concept, mathematical formulation and algorithmic implementation. Therefore, it may happen that some chapters contain a lot of text in the respective chapters 4 or 5, but not in this chapter, or vice versa.

The algorithmic implementation is based on a genetic algorithm setup. The genetic algorithm implementation was chosen due to the mathematical problem behind the optimisation, i.e. assigning, for each year, objects to intervention groups (Note the inverted formulation. This is due to the fact, that an intervention program "pairs" every object with an intervention group (that also could consist of one object only) in every year, if a "do-nothing-intervention" is also included.) Using that formulation, it can be seen that the mathematical problem corresponds to the weighted set cover problem, which is an extended version of one of Karp's 21 NP-complete problems (Karp, 1972). The set cover portion corresponds to the task to assign each object for every year to either the "set" of do-nothing-interventions, or to an intervention cluster. The weighting portion of the problem relates to the fact that each executed intervention cluster changes the condition of the network, and such gives, depending on which objects are assigned to the intervention cluster, a different level of service (and therefore costs for loss in level of service), as well as different intervention costs. These different costs are the "weights" of the set. Thus the mathematical problem to solve is the weighted set cover problem, which is NP-complete. Therefore, a heuristic approach is deemed appropriate find a solution in an adequate time. This is also recommended by Szimba and Rothengatter (2012).

In the literature review, Figure 2.1 on page 29 shows an overview of possible heuristics being considered. Due to the large size of a solution candidate (i.e. a full list of interventions and clustering information), it is deemed necessary to use a heuristic with memory, as the search space is highly multidimensional and non-smooth, and thus an algorithm without memory is more likely to get stuck on local minima. This excludes the heuristic families of *local search algorithms*, *direct algorithms*, *variable neighbourhood search*, *estimation of distribution algorithm*, and *GRASP* from consideration. *Tabu search* is also excluded, as it is based on a limited memory. *Ant colony optimisation* was also excluded, because this type of optimisation requires the solution being able to be effectively represented as a path through a graph, which is not the case for the weighted set cover problem. *Particle swarm optimisation* was excluded, as the algorithm is based on a real-numbered search space, which is not present in the weighted set cover problem. A transformation into a real-numbered search space would be possible, but as this requires additional computational effort, the particle swarm optimisation was also excluded from the considered heuristics. This leaves the family of evolutionary algorithms as a set to choose a heuristic from. From the evolutionary algorithms, the genetic algorithm approach was chosen, as it is well documented, can be easily adapted to the mathematical problem, and due to the fact that genetic algorithms were successfully applied to similar (but only single-network-based) problems by Miyamoto et al., 2000; Halfawy et al., 2008; Deshpande et al., 2010; Mathew and Isaac, 2013.

Genetic algorithms optimise a chromosome $\Xi$ (which is the algorithmic representation of the intervention program $\Psi$, as defined in Equation 5.1) in terms of the fitness function $F$ (Equation 5.33). Figure 6.1 shows an overview of the algorithm.

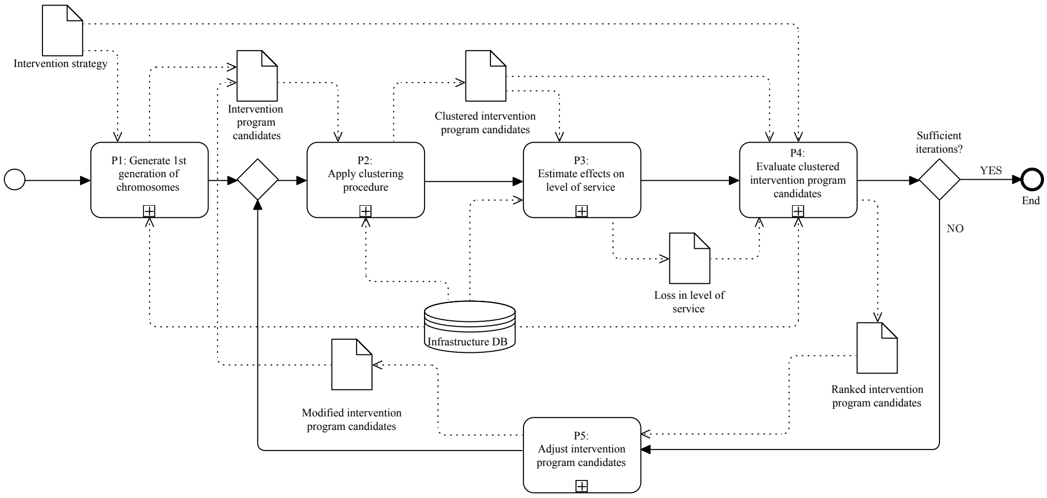



Figure 6.1.: Global algorithm overview

In the first task (P1), the first generation of chromosomes is generated. Each of these chromosomes represent one (unclustered) intervention program candidate. These unclustered intervention program candidates are then transferred to the second task (P2), where the clustering procedure is applied. This task groups the preselected intervention program candidates into clustered intervention program candidates by evaluating their spatial, topological and temporal closeness of the interventions and grouping them to clusters, that are executed jointly. Then, the clustered intervention program candidates are transferred to task P3, where the effects on the level of service of each clustered intervention program candidate are calculated, together with the loss in level of service for each network. In task P4, the clustered intervention program candidates, together with the losses in level of service are evaluated in respect to the fitness function $F'$ (Equation 5.35). Then, the clustered intervention program candidates are ranked according to their fitness. If the number of iterations is sufficient, the iterative loop is terminated. Otherwise, the ranked clustered intervention program candidates are fed into task P5, where the next generation of chromosomes is generated, using evolutionary functions. A detailed description of the five tasks is given in the following sections.

## 6.1. Create initial intervention program candidates

In this task, the first generation of chromosomes is generated. The intervention strategy as input is transferred into an initial set of unclustered intervention program candidates. The process is shown in Figure 6.2.

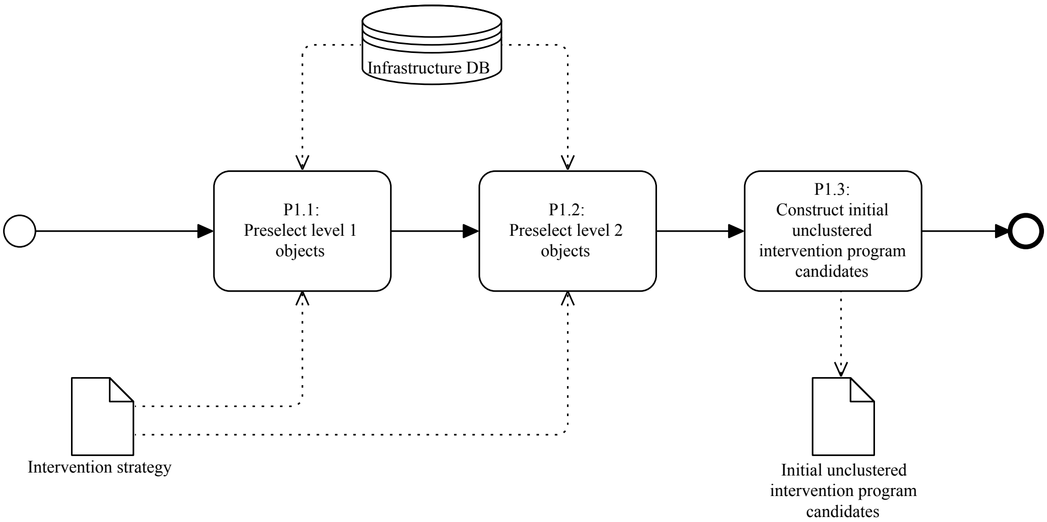



Figure 6.2.: Creation of initial intervention program candidates

The task consists of three subtasks. In task P1.1, level 1 objects are preselected, according to the chosen intervention strategy. For this, the selector function (Equation 5.2) is applied to all objects from the infrastructure database. In task P1.2, level 2 objects are preselected by applying the selector function for level 2 objects (Equation 5.3) to the infrastructure database. In the last task (P1.3), the preselected objects are then combined into initial unclustered intervention program candidates, which are then supplied to the next step of the process, that clusters the intervention program candidates.

## 6.2. Apply clustering procedure

In this task, the unclustered intervention program candidates are combined into clusters that are executed jointly. The process diagram of this task is shown in Figure 6.3.

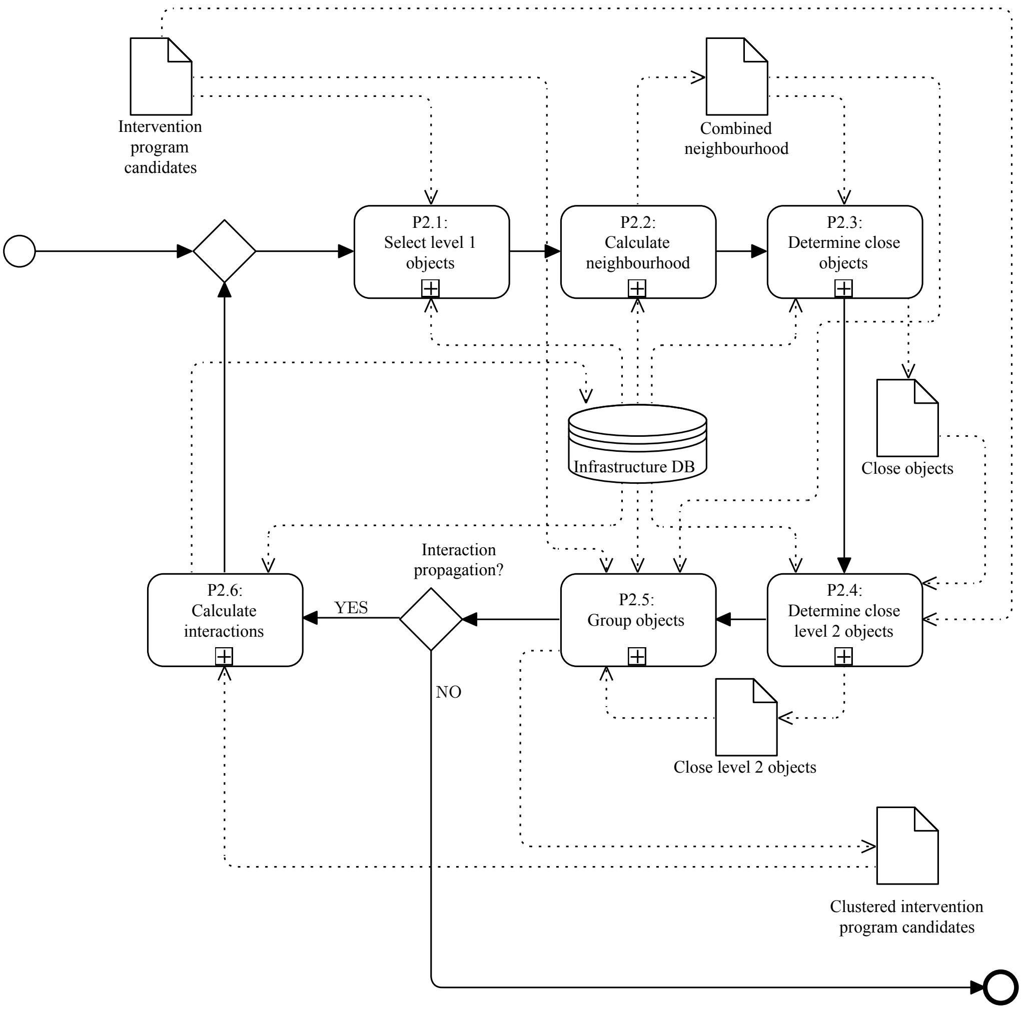



Figure 6.3.: Clustering procedure

In the first task (P2.1), the level 1 objects are selected. Then, (task P2.2), the neighbourhood around these level 1 objects is calculated, according to Equations 5.6 to 5.14. Out of the combined neighbourhood, the close objects are selected in task P2.3. These close objects are then scanned for level 2 objects in task P2.4, i.e. it is determined which objects are both close and level 2 objects. The close level 2 objects are then combined with the level 1 objects into intervention clusters in task P2.5. If intervention propagation is accounted for (i.e. if it is assumed that interventions on objects cause adverse effects on other objects), then the interactions are calculated in task P2.6. Otherwise, the loop terminates and results with a set of clustered intervention program candidates.

### 6.2.1. Select level 1 objects

In this task, the level 1 objects are definitively selected. This task is necessary, as due to interactions, the condition state of certain objects might change, and thus objects may then be in a state that leads them to be newly selected as level 1 objects. The process diagram is shown in Figure 6.4.

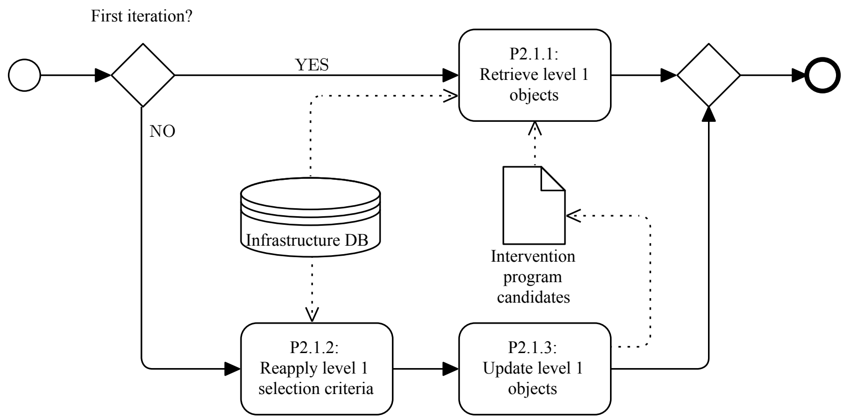



Figure 6.4.: Selection of level 1 objects

First, it is checked, whether it is the first iteration loop in the clustering procedure, or, if due to interaction propagation, the clustering procedure already is in the second or more iteration loop. If it is the first iteration loop, then the level 1 objects are simply retrieved from the unclustered intervention program candidates in task P2.2.1. If it is not the first iteration loop, then the level 1 selection criteria (Equation 5.2) are reapplied to the infrastructure database in task P2.1.2 in order to update the list of level 1 objects (which is done in task P2.1.3). With the level 1 objects finally selected, the neighbourhood area can now be calculated.

### 6.2.2. Calculate neighbourhood

In this task, the neighbourhoods (temporal, topological, distance, and Voronoi) are calculated. The process is shown in Figure 6.5.

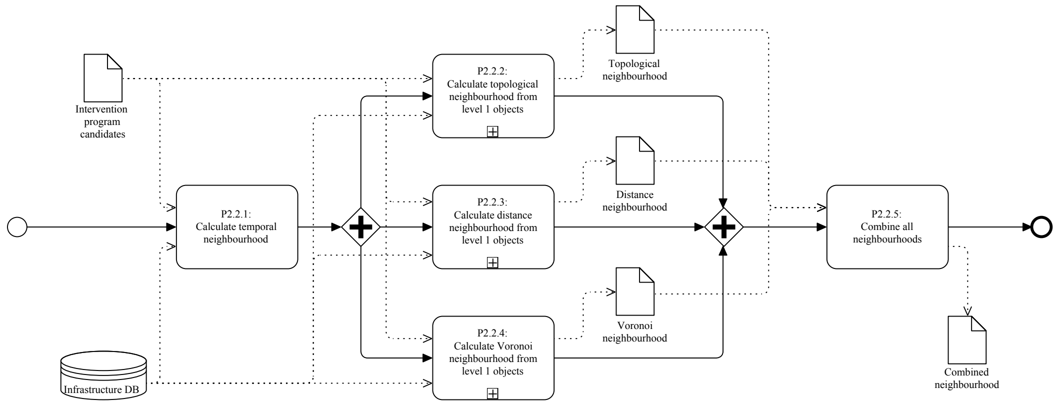



Figure 6.5.: Calculation of neighbourhood

#### 6.2.2.1. Obtain temporal neighbourhood

First, the temporal neighbourhood is calculated (task P2.2.1) from the unclustered intervention program candidates and the infrastructure database, using the process shown in chapter 4.2.2. Then, the topological neighbourhood (task P2.2.2), the distance neighbourhood (task P2.2.3), and the Voronoi neighbourhood (task P2.2.4) are calculated, all using the unclustered intervention program candidates and the infrastructure database as input. From there, the neighbourhoods are combined in task P2.2.5, which yields the combined neighbourhood, that is then used in tasks P2.3 and P2.5 (see Figure 6.3) for clustering. A detailed description of tasks P2.2.2 to P2.2.4 is given in the next sections.

#### 6.2.2.2. Calculate topological neighbourhood from level 1 objects

In this task, the topological neighbourhood is calculated for all level 1 objects. The process diagram is shown in Figure 6.6.

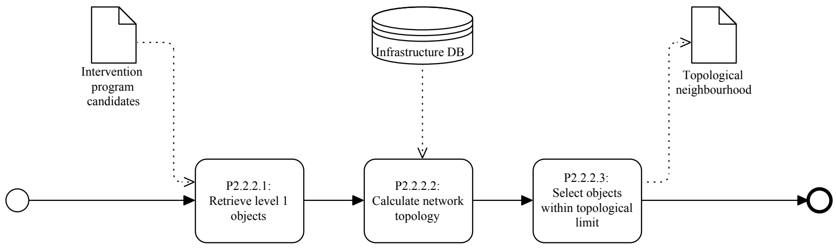



Figure 6.6.: Calculation of topological neighbourhood

First, the level 1 objects are retrieved from the intervention program candidates in task P2.2.2.1. Then, the network topology is calculated, using Equations 5.6 to 5.8 from chapter 5.2.2.2. In the last task P2.2.2.3, the topological neighbourhood is exported.

#### 6.2.2.3. Calculate distance neighbourhood from level 1 objects

In this task, the distance neighbourhood is calculated for all level 1 objects. The process diagram is shown in Figure 6.7.

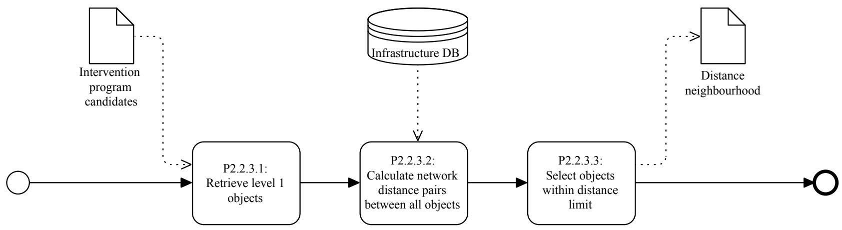



Figure 6.7.: Calculation of distance neighbourhood

First, the level 1 objects are retrieved from the intervention program candidates in task P2.2.3.1. Then, the network distance is calculated, using Equations 5.9 to 5.12 from chapter 5.2.2.3. In the last task P2.2.3.3, the distance neighbourhood is exported.

#### 6.2.2.4. Calculate Voronoi neighbourhood from level 1 objects

In this task, the Voronoi neighbourhood (as defined in section 4.2.2.4) is calculated for all level 1 objects. The process diagram is shown in Figure 6.8.

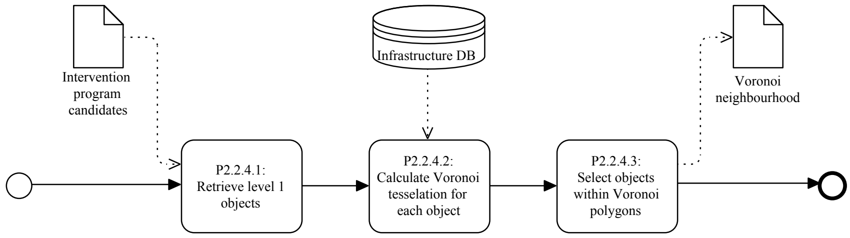



Figure 6.8.: Calculation of Voronoi neighbourhood

First, the level 1 objects are retrieved from the intervention program candidates in task P2.2.4.1. Then, a Voronoi tessellation is calculated for each object, using Equation 5.13 from chapter 5.2.2.4. In the last task P2.2.4.3, the Voronoi neighbourhood is exported.

### 6.2.3. Determine close objects

In this task, the close objects are finally determined. Figure 6.9 shows the process diagram.

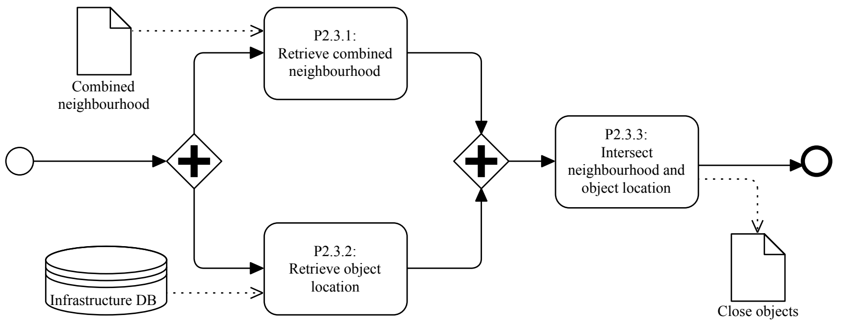



Figure 6.9.: Determination of close objects

First, the combined neighbourhood (task P2.3.1) and the object location (task P2.3.2) are retrieved. Then, both are intersected in task P2.3.3 in order to give the set of close objects. This step is necessary to be separated from the next task (P2.4) in order to reduce calculation time, as both neighbourhood and object location are spatial information, that can efficiently be intersected.

The intersection (i.e. the close objects) are then passed on to the next task (P2.4)

### 6.2.4. Determine close level 2 objects

In this task, the level 2 objects are selected from the close objects. The process diagram is shown in Figure 6.10.

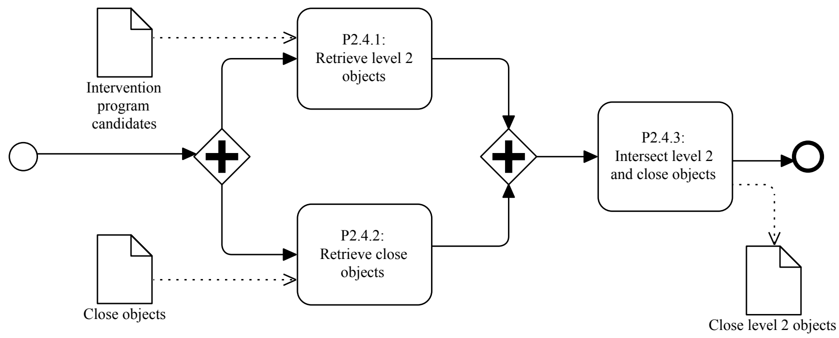



Figure 6.10.: Determination of close level 2 objects

First, the level 2 objects are retrieved from the intervention program candidates (task P2.4.1), and the close objects are retrieved in task P2.4.2. Then, both are intersected in order to find those level 2 objects that are also close objects (task P2.4.3). Then, the close level 2 objects are exported.

### 6.2.5. Group objects

In this task, the interventions from the unclustered intervention program are clustered into intervention clusters. The process diagram is shown in Figure 6.11.

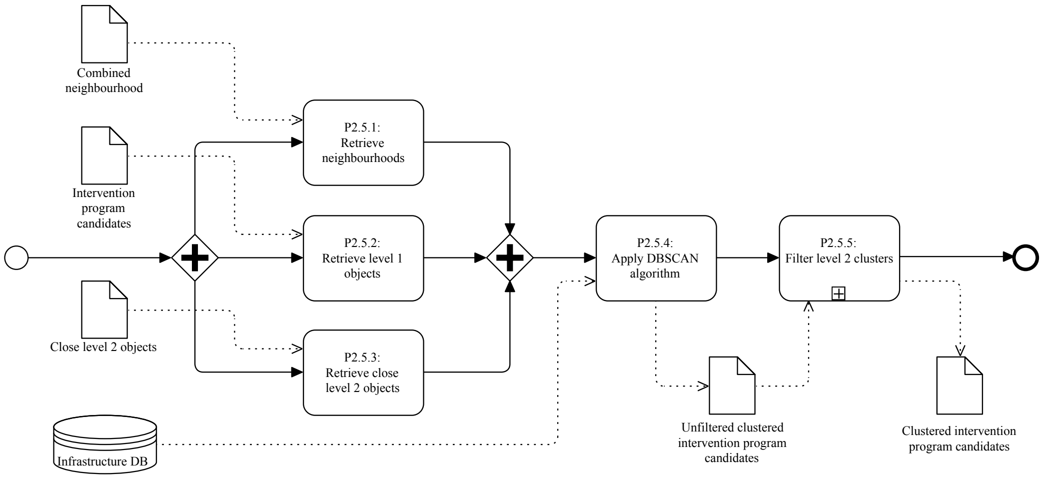



Figure 6.11.: Grouping of objects

First, the neighbourhoods (task P2.5.1), the level 1 objects (task P2.5.2), and the close level 2 objects (task P2.5.3) are retrieved. Then, the DBSCAN algorithm (Equation 5.17) is applied to the objects in task P2.5.4. This gives the unfiltered clustered intervention program candidates. These are then filtered in task P2.5.5 to yield the clustered intervention program candidates.

#### 6.2.5.1. Filter level 2 clusters

In this task, the unfiltered clustered intervention program candidates are filtered for level 2 only clusters. This is necessary, as per definition each cluster must contain at least one level 1 object. The process diagram is shown in Figure 6.12.

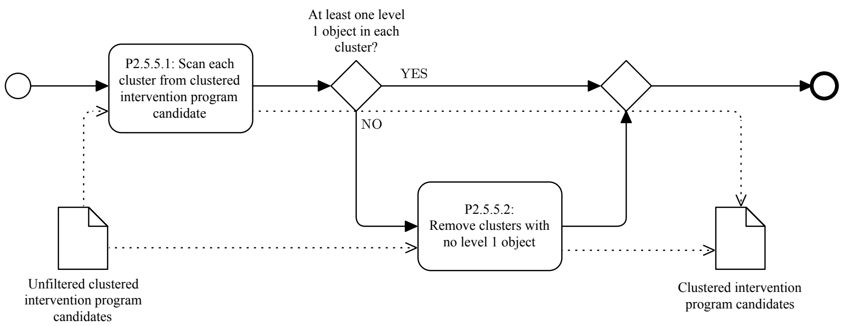



Figure 6.12.: Filtering of level 2 clusters

First, each cluster from each intervention program candidate is scanned (P2.5.5.1). Then, if each cluster contains at least one level 1 object, the filtering is finished. If there are clusters without level 1 objects, these clusters are removed from the unfiltered clustered intervention program candidates in task P2.5.5.2.

### 6.2.6. Calculate interactions

If there are interaction propagations to be considered in the creation of intervention program candidates (i.e. if it should be considered that the execution of interventions could affect other objects, e.g. an accident during excavation), the interactions are calculated in this task. The process is shown in Figure 6.13.

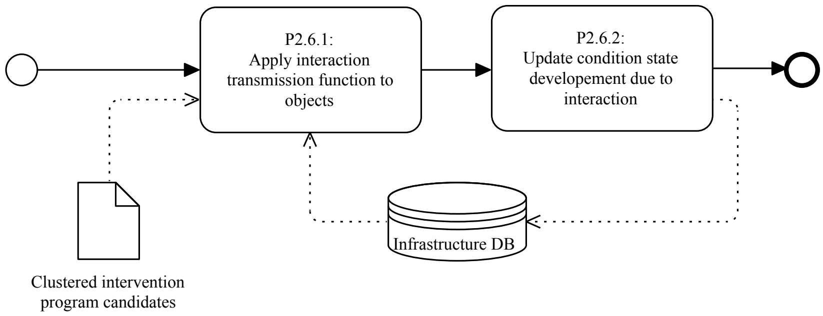



Figure 6.13.: Calculation of interactions

First, the interaction transmission function (task P2.6.1) according to Equation 5.27 is applied to the objects from the clustered intervention program candidates. This leads to an update in the condition state development of the objects, which is incorporated into the infrastructure database in task P2.6.2.

## 6.3. Estimate effects on level of service

In this task, the effects on the level of service caused by the clustered intervention program are calculated. The process diagram is shown in Figure 6.14.

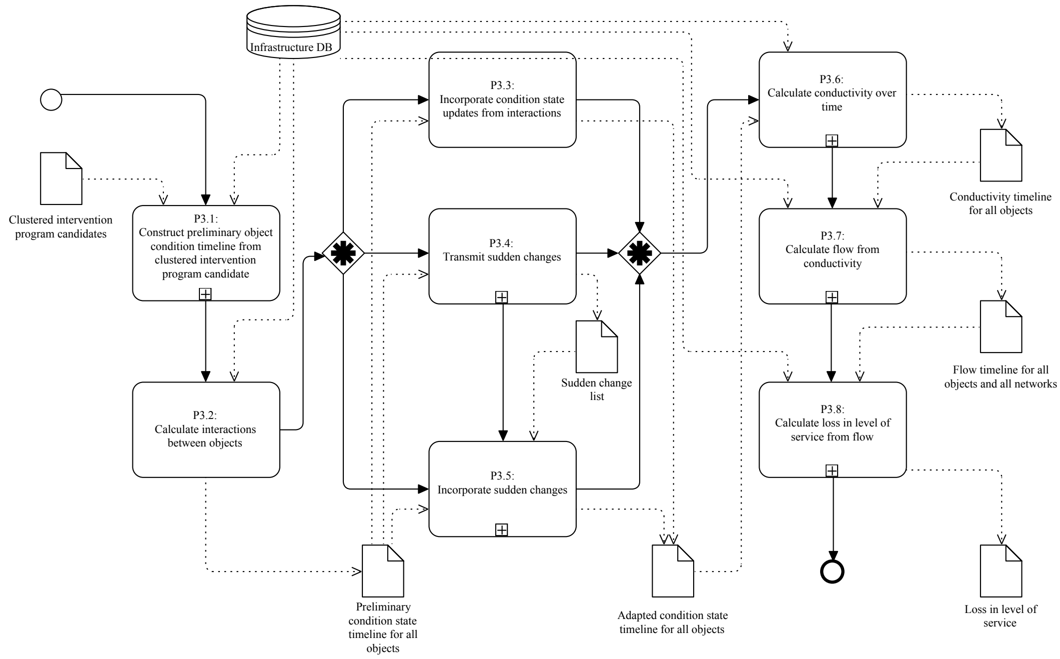



Figure 6.14.: Estimation of effects on level of service

First, the preliminary object condition timeline is constructed (task P3.1). This is done to combine the interventions and the deterioration retrieved from the infrastructure database to give a condition state development over time. Then, the interactions that emanate from these timelines are calculated in task P3.2. With this, a preliminary condition state timeline for all objects can be calculated. Depending on the interactions, the condition state timeline is updated from the interactions (task P3.3), sudden changes are transmitted from objects (task P3.4) and sudden changes are received from objects and incorporated into the condition state timeline (task P3.5). This gives the adapted condition state timeline for all objects. With that, the conductivity timeline (i.e. the change of conductivity over time which is determined by the condition state timeline, but depending on network and object type as well as object parameters) can be calculated for each object (task P3.6). With that, the flow timeline in each network can be calculated using the object conductivity timeline as a basis (task P3.7). From the flow timeline, the loss in level of service can be calculated (task P3.8) and passed on to the next task (P4). A detailed description of the tasks is given in the next sections.

### 6.3.1. Construct preliminary object condition timeline from clustered intervention program candidate

In this task, the preliminary object condition timeline is calculated for each object from the clustered intervention program candidate. The process diagram is shown in Figure 6.15.

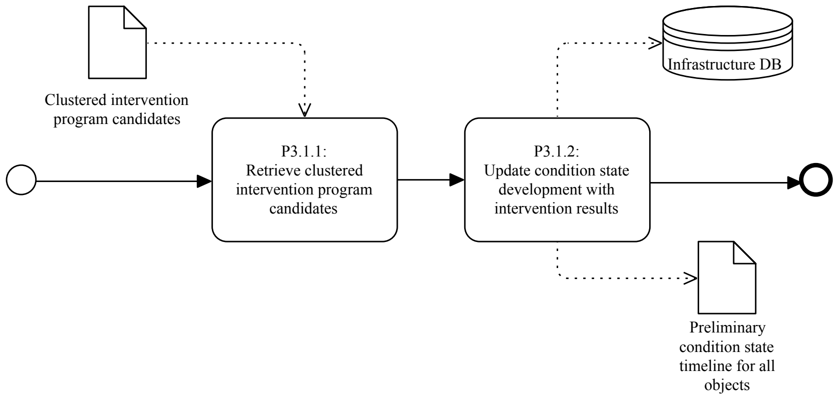



Figure 6.15.: Construction of preliminary object condition timeline

First, the clustered intervention program candidates are retrieved in task P3.1.1. Then, the condition state development for each object is updated with the intervention results in the infrastructure database.

### 6.3.2. Transmit sudden changes

In this task, the sudden changes are determined, that emanate from the objects due to their condition state development. The process diagram is shown in Figure 6.16.

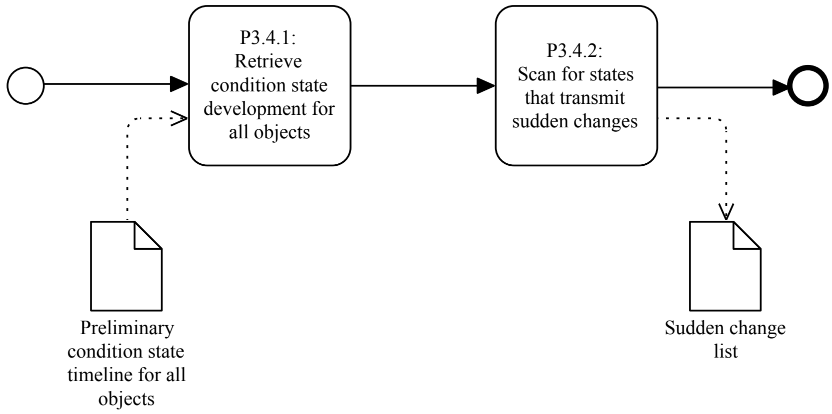



Figure 6.16.: Transmission of sudden changes

First, the preliminary condition state development is retrieved in task P3.4.1. Then, in task P3.4.2, the condition state development of each object is scanned for states that lead to a transmission of sudden changes, which are collected in a sudden change list, which is calculated based on Eq. 5.28 and includes a transmission hierarchy between the objects.

### 6.3.3. Incorporate sudden changes

In this task, the sudden changes that emanate from the objects due to their condition state development are incorporated into the affected objects. The process diagram is shown in Figure 6.17.

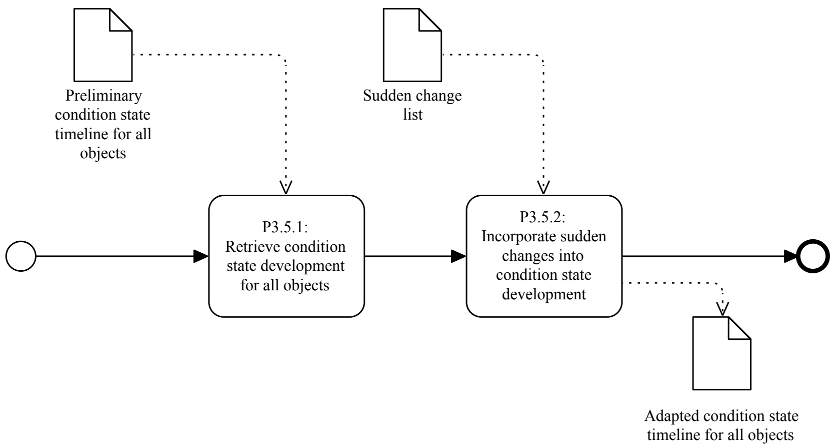



Figure 6.17.: Incorporation of sudden changes

First, the condition state development for all objects is retrieved in task P3.5.1. Then, the sudden change list is retrieved and incorporated into the condition state development in task P3.5.2. This yields the adapted condition state timeline for all objects.

### 6.3.4. Calculate conductivity over time

In this task, the conductivity over time is calculated for each adapted condition state timeline for all objects for all intervention program candidates. The process diagram is shown in Figure 6.18.

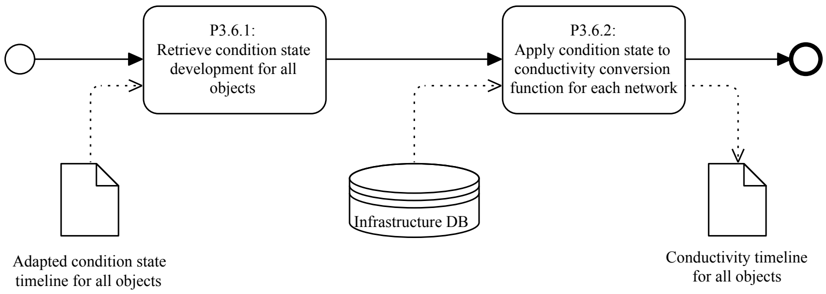



Figure 6.18.: Calculation of conductivity over time

First, the condition state development is retrieved for all objects (task 3.6.1). Then, for each object, according to the specifics of the object and network (which are provided by the infrastructure database), the condition state is converted to a conductivity timeline for each object for each network for each intervention program candidate (task P3.6.2). Then, the conductivity timeline is passed on to the flow calculation in task P3.7.

### 6.3.5. Calculate flow from conductivity

In this task, the flow for each network is calculated. The process diagram is shown in Figure 6.19.

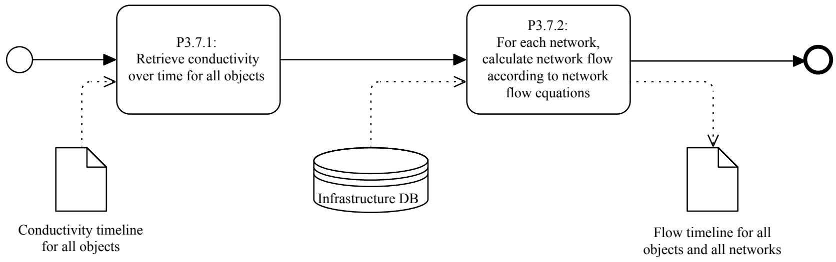



Figure 6.19.: Calculation of flow from conductivity

First, the conductivity timelines for all objects are retrieved in task P3.7.1. Then, for each network, the flow is calculated over time according to the equation 5.31, taking into account the different flow models for each network (task P3.7.2). This yields the flow timeline for all objects and all networks.

### 6.3.6. Calculate loss in level of service from flow

In this task, the loss in level of service is calculated from the flow timeline. The process diagram is shown in Figure 6.20.

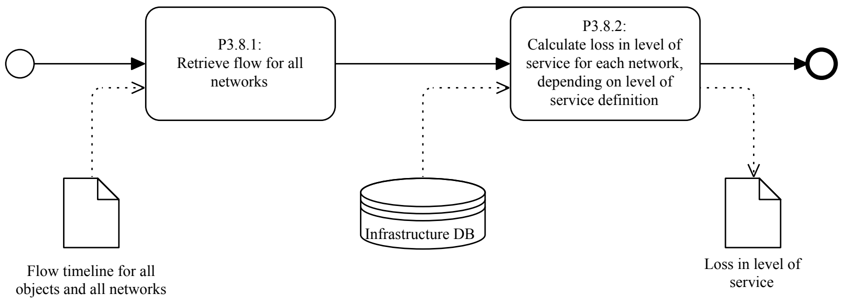



Figure 6.20.: Calculation of loss in level of service from flow

First, the flow for all networks is retrieved in task P3.8.1. Then, for each network, the loss in level of service is calculated over time, according to the equation 5.32, taking into account the level of service definition provided by the infrastructure database. This gives the loss in level of service for all networks, and the whole time period investigated.

## 6.4. Evaluate clustered intervention program candidates

This task is the central part of the genetic algorithm implementation of the methodology. Here, the fitness of the intervention program candidates is evaluated, in order to achieve a ranking that is then used in task P5 to construct a new generation of intervention program candidates. The process diagram for this is shown in Figure 6.21.

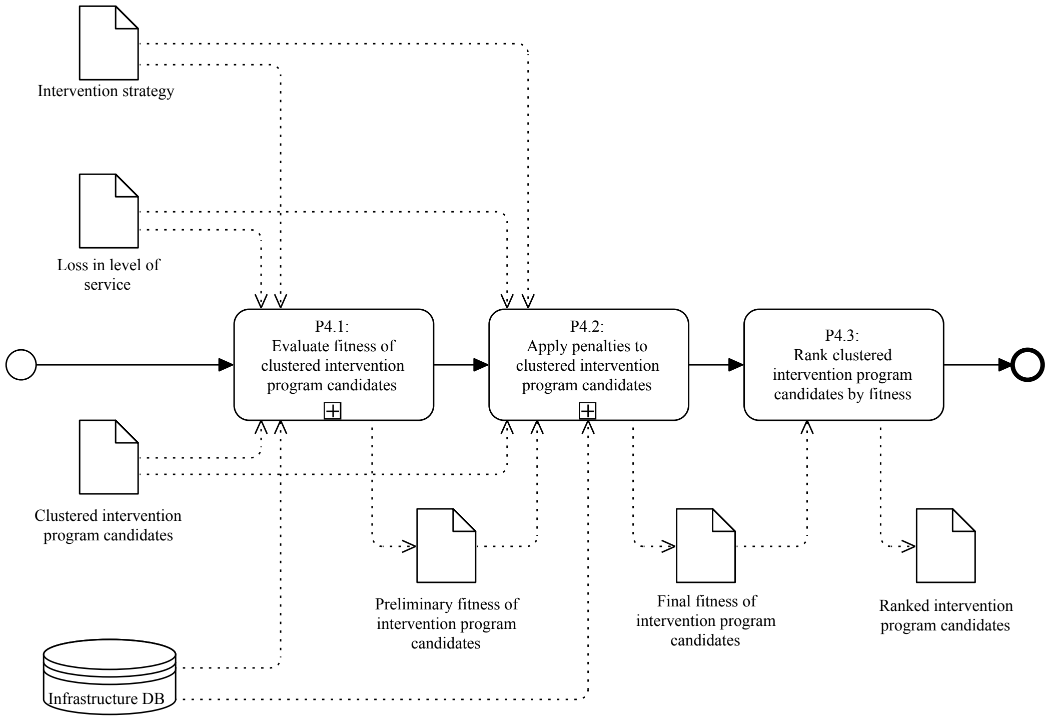



Figure 6.21.: Evaluation of clustered intervention program candidates

The goal of this task is to evaluate the “fitness” of the clustered intervention program candidates, while taking into account penalties and perform a ranking to be used in the generation of the next evolutionary step. First, in task P4.1, the fitness of the intervention program candidates is evaluated, taking into account the intervention strategy, the loss in level of service, and additional infrastructure information from the infrastructure database. This generates the preliminary fitness of the intervention program candidates. Then, in task P4.2, penalties are applied to those intervention program candidates, that violate rules given by the intervention strategy, such as a minimal allowable condition state. Then, the fitness is adjusted according to the penalty, and the final fitness is calculated. From there, in task P4.3, the intervention program candidates are ranked by their fitness.

### 6.4.1. Evaluate fitness of clustered intervention program candidates

In this task, the fitness of the clustered intervention program candidates is calculated. The process diagram is shown in Figure 6.22.

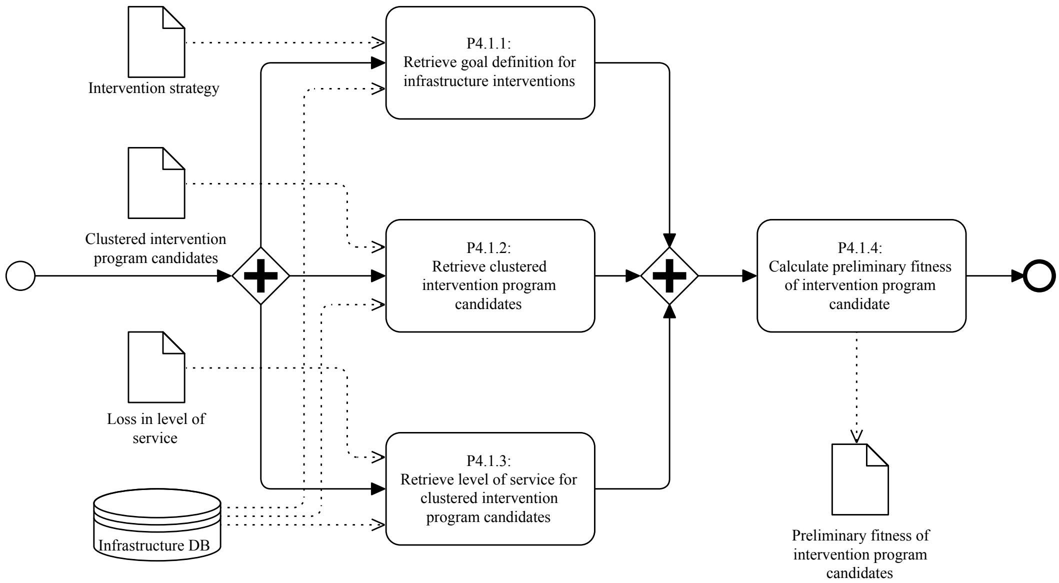



Figure 6.22.: Evaluation of fitness of clustered intervention program candidates

First, the goal definition (task P4.1.1), the clustered intervention program candidates (task P4.1.2) and the level of service for the clustered intervention program (task P4.1.3) are retrieved. Then, in task P4.1.4, the preliminary fitness of the intervention program is calculated. The fitness is defined (as in Equation 5.33) as the sum of intervention costs and costs attributed to the loss in level of service over time.

### 6.4.2. Apply penalties to clustered intervention program candidates

This task calculates and applies penalties to the preliminary fitness of the intervention program candidates, if there are restriction violations present. The process diagram is shown in Figure 6.23.

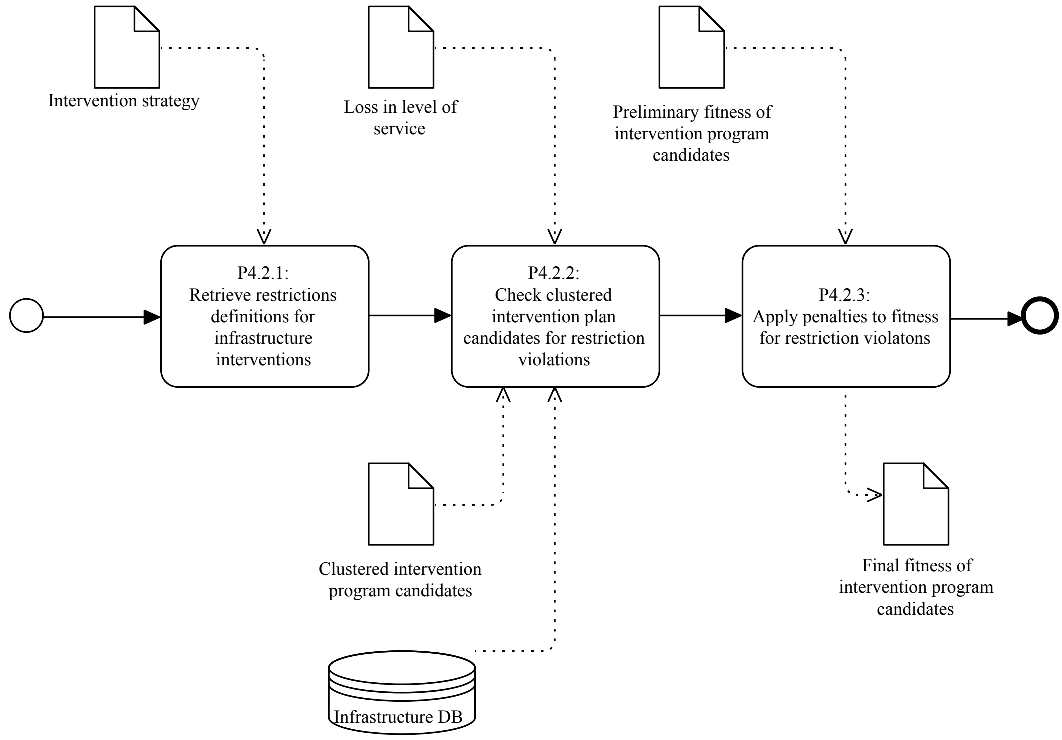



Figure 6.23.: Application of penalties

First, the restrictions definitions are retrieved from the intervention strategy in task P4.2.1. Then, in task P4.2.2, the clustered intervention program, together with the loss in level of service, and additional information from the infrastructure database, are checked for restriction violations. If any restriction violations are found, the preliminary fitness is adapted in task P4.2.3 by applying penalties in order to obtain the final fitness of the intervention program candidates.

## 6.5. Adjust intervention program candidates

In this task, the intervention program candidates are adjusted according to the genetic algorithm methodology in order to produce a new generation for the next iteration round. The process diagram is shown in Figure 6.24.

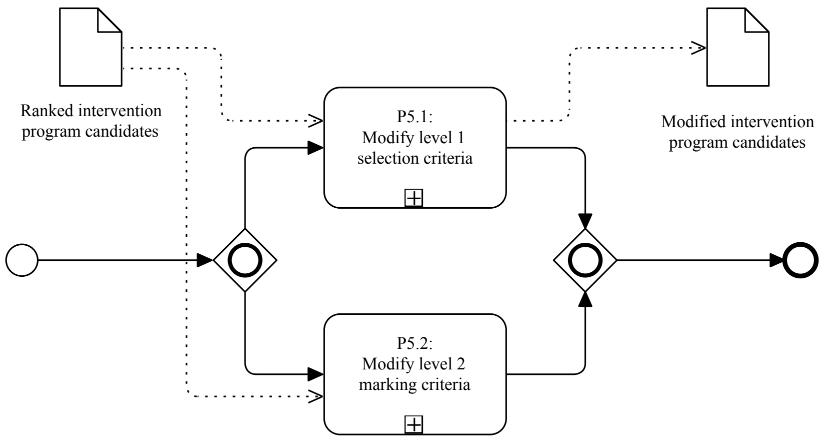



Figure 6.24.: Adjustment of intervention program candidates

The task modifies simultaneously both level 1 (task P5.1) and level 2 (task P5.2) criteria for marking level 1 and level 2 objects, which then gives a modified intervention program candidate. However due to the modification, the grouping is no longer valid (as objects change), and thus the grouping information is discarded.

### 6.5.1. Modify level 1 selection criteria

In this task, the level 1 selection criteria are modified according to the genetic algorithm evolutionary function. The process diagram is shown in Figure 6.25.

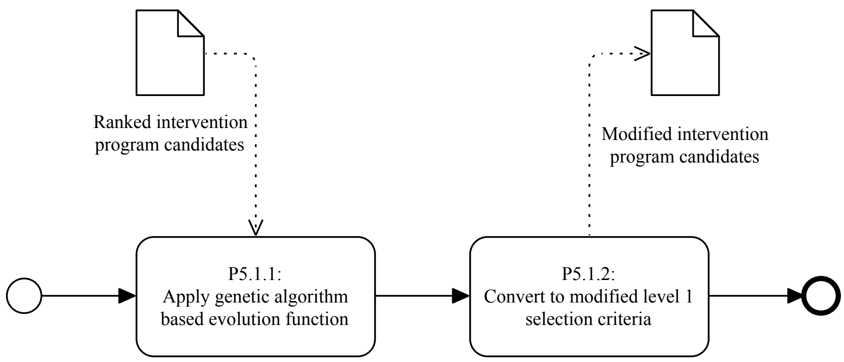



Figure 6.25.: Modification of level 1 selection criteria

First, the ranked intervention program candidates are retrieved, and the evolution function is applied (task P5.1.1). This evolution consists of three parts: 1) the elitism part, where the best ranked intervention program candidates are taken over without change into the next generation, 2) the mutation part, where the intervention program candidates are randomly changed, and 3) the crossover function, where parts of two intervention program candidates are exchanged, with the likelihood of exchange being dependent on the ranking. Then, the results of the evolution function are converted to modified level 1 selection criteria in task P5.1.2.

### 6.5.2. Modify level 2 marking criteria

In this task, the level 2 marking criteria are modified according to the genetic algorithm evolutionary function. The process diagram is shown in Figure 6.26.

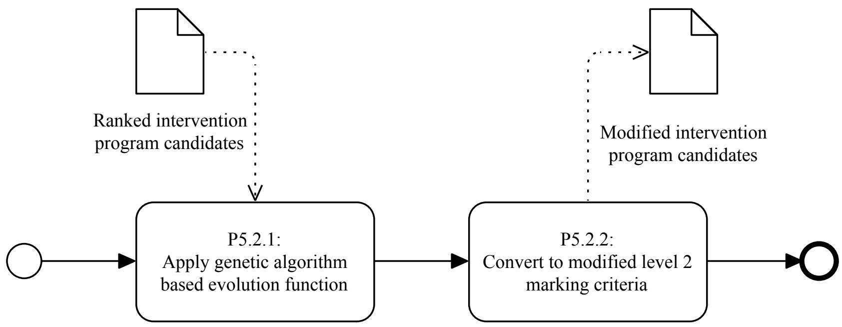



Figure 6.26.: Modification of level 2 marking criteria

This task is identical to task P5.1, with the only difference, that instead of the level 1 selection criteria, the level 2 marking criteria are adapted.

# 7. Example

In this chapter, the methodology presented in chapter 4 to 6 is applied to five urban infrastructure networks, in order to demonstrate the practical applicability of the concept.

It can be seen as an extended “proof of concept”, that applies the methodology to a test on a real-world problem, i.e. a problem with the size and network topology of a real world network. The example, however, has been made to be computationally feasible on a standard laptop computer. In order to accomplish this, the amount of accuracy and the computational time have to be balanced. The balancing was performed so that the main parts of the methodology (i.e. the grouping, the level of service calculations and the interactions) are calculated fully, while the supporting functions use simplified algorithms in order to keep the computational time at an acceptable level.

First, the urban area and the network, along with data, assumptions and simplifications used for the example application are described in section 7.1. Then, in section 7.2, the results of the optimisation are given, together with a sensitivity analysis. Finally, in section 7.3, the results are discussed from a practical perspective. The general discussion of the presented methodology from a scientific point of view is then given in chapter 8.

## 7.1. Situation description

In this chapter, the urban area is described, that is used in the example application. First in section 7.1.1, the data available for the networks such as object size, length, age, condition etc. is described. Unfortunately, there is neither information about age nor condition on the road network and as such the data is not directly useable without amendments. Therefore, the data completion process, that was used to fill gaps in the road data is described in section 7.1.2. Then, in section 7.1.3, the remaining information that is needed to run the optimisation algorithm is given. This encompasses information about the supply and demand on the networks, some assumptions that have to be taken (mainly representing management decisions or assumed costs), and the simplifications made in order to reduce computational effort.

### 7.1.1. Provided data

In this section, the available data of the five different networks are described as is, but without the measures taken to complete the dataset. These measures are described in section 7.1.2.

The urban area investigated for the example application is part of a city with a population of approx. 30'000 and a population density of approx. 1'000 people per sq. km. Figure 7.1 shows an overview of the investigated area.


Figure 7.1.: Overview of the investigated area

The investigated area has a population of approximately 1'200. The urban landscape in the investigated area consists of a mix of detached, semi-detached and multi-story apartment houses, as well as farms and office buildings. In the next sections the data provided is described on a network-by-network basis. The five networks with data provided were 1) the electricity network, 2) the gas network, 3) the road network, 4) the sewer network and 5) the water network. All network data is provided in the digital appendix in a spatial database format.

#### 7.1.1.1. Electricity

The electricity network of the investigated area, consisting of 2'220 objects, is shown in Figure 7.2.


Figure 7.2.: Overview of the electricity network

The data provided consists of the information fields given in table 7.1. The first three fields contain database keys, the fourth field contains the object ID, the other fields contain information about the objects itself. The full dataset can be found in the digital appendix. A summary is given in table 7.2.

Table 7.1.: Provided electricity network data

| Number | Field name | Description | |
|---|---|---|---|
| 1 | gid | key column | primary key for this table |
| 2 | fid | key column | foreign key for other database |
| 3 | tid | key column | foreign key for other database |
| 4 | name_numme | Object ID | object identification (letter-number combination AAA00000) |
| 5 | trasse_art | cable run type | only one value: “Kabeltrasse” (cable run) |
| 6 | trassebrei | cable run width | width in mm, ranges from 100-1200 |
| 7 | baujahr | construction year | ranges from 1943-2013 |
| 8 | lagebestim | position accuracy | 2 values: “ungenau” (imprecise), “genau” (precise) |
| 9 | status | operative status | all objects are “in Betrieb” (operative). |
| 10 | betreiber | operator | all objects belong to one operator |
| 11 | the_geom | geometry information | encoded as HEX-character string, not human-readable |

It can be seen in table 7.1, that the data for the objects of the electricity network contain information about size, location, type, operator, and age as well as a binary condition indicator (working/non-working).

Table 7.2.: Electricity network data summary

| Number of objects | 2’220 | | | |
|---|---|---|---|---|
| | Min | Median | Mean | Max |
| Length [m] | 0.21 | 3.73 | 9.38 | 458.51 |
| Width [mm] | 100 | 500 | 486 | 1’200 |
| Construction year | 1943 | 1983 | 1986 | 2013 |

Looking at the data summary (Table 7.2), it can be seen that the 2’220 objects are consisting of a range of very short cable runs to long cable runs, with a median length of 3.73 $m$, and a mean length of 9.38 $m$, suggesting more short objects and less long objects.

#### 7.1.1.2. Gas

The gas network of the investigated area, consisting of 349 objects, is shown in Figure 7.3.

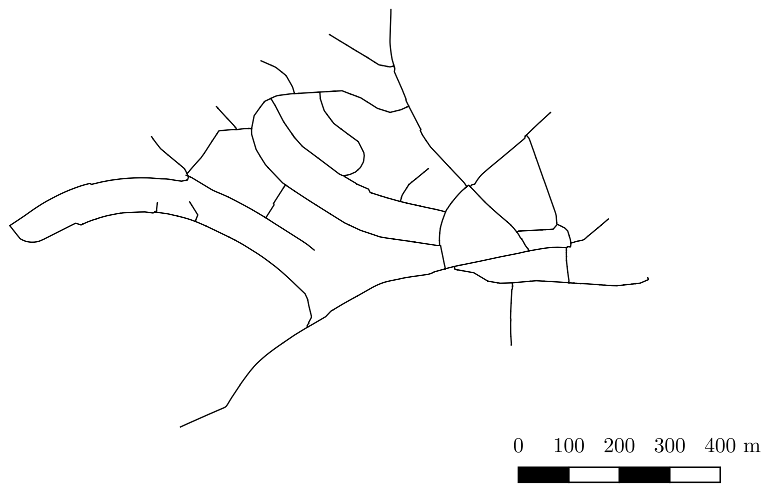



Figure 7.3.: Overview of the gas network

The data provided consists of the information fields given in table 7.3. The first three fields contain database keys, with the second field also acting as the object ID, the fields 4 to 10 and 12 contain information about the objects itself, and field 11 shows the date of the last information change. The full dataset can be found in the digital appendix. A summary is given in table 7.4.

Table 7.3.: Provided gas network data

| Number | Field name | Description | |
|---|---|---|---|
| 1 | gid | key column | primary key for this table |
| 2 | ogc_fid | key column | foreign key for other database, also acts as object identificator (integer number) |
| 3 | tid | key column | foreign key for other database |
| 4 | funktion | function | 2 values: "Versorgungsleitung" (supply pipe), "Hauptleitung" (main pipe) |
| 5 | material | pipe material | 3 values: "Kunststoff" (plastic), "Guss" (ductile cast iron), "Stahl" (steel) |
| 6 | durchmesse | pipe diameter | width in mm, ranges from 63-200 |
| 7 | genauigkei | position accuracy | 2 values: "ungenau" (imprecise), "genau" (precise) |
| 8 | baujahr | construction year | ranges from 1975-2011 |
| 9 | status | operative status | all objects are "in Betrieb" (operative). |
| 10 | eigentueme | owner | all objects belong to one operator |
| 11 | letzte_aen | last data change | ranges from 2011-01-01 to 2014-01-02 |
| 12 | the_geom | geometry information | encoded as HEX-character string, not human-readable |

It can be seen in table 7.3, that the data for the objects of the gas network contain information about size, location, type, owner, and age as well as a binary condition indicator (working/non-working).

Table 7.4.: Gas network data summary

| Number of objects | 349 | | | |
|---|---|---|---|---|
| | Min | Median | Mean | Max |
| Length [m] | 0.11 | 9.68 | 18.93 | 374.49 |
| Diameter [mm] | 63 | 150 | 140 | 200 |
| Construction year | 1975 | 1983 | 1986 | 2011 |

Looking at the data summary (Table 7.4), it can be seen that the 349 objects are consisting of a range of very short pipes to long pipes, with a median length of 9.86 $m$, and a mean length of 18.93 $m$, suggesting more short objects and less long objects.

#### 7.1.1.3. Roads

The road network of the investigated area, consisting of 102 objects, is shown in Figure 7.4.

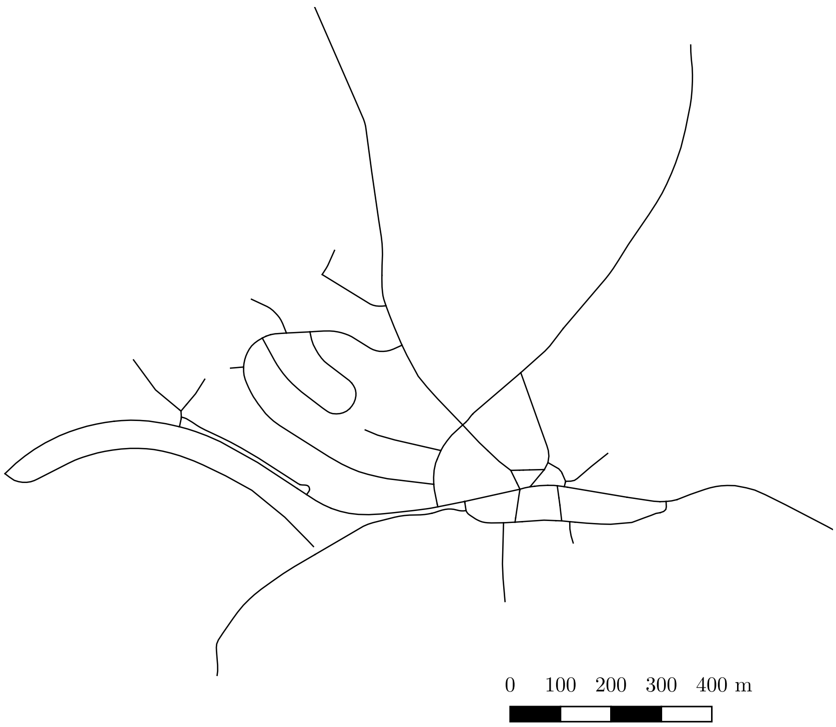



Figure 7.4.: Overview of the road network

The data provided consists of the information fields given in table 7.5. The first three fields contain database keys, the fourth field contains the object ID, the fields 5 to 11 contain information about the objects itself. The full dataset can be found in the digital appendix. A summary is given in table 7.6.

Table 7.5.: Provided road network data

| Number | Field name | Description | |
|---|---|---|---|
| 1 | gid | key column | primary key for this table |
| 2 | old_gid | key column | foreign key for other database |
| 3 | sub_gid | key column | foreign key for other database |
| 4 | osm_id | ID | openStreetMap ID |
| 5 | name | road name | as shown on street signs |
| 6 | type | road type | 4 values:<br>“secondary”,<br>“tertiary”,<br>“residential”,<br>“unclassified” |
| 7 | oneway | logical indicator for one-way road | no objects are one-way roads |
| 8 | bridge | logical indicator for bridge | no objects are bridges |
| 9 | tunnel | logical indicator for tunnel | no objects are tunnels |
| 10 | maxspeed | speed limit in $km/h$ | 4 values:<br>30,<br>50,<br>60,<br>80 |
| 11 | the_geom | geometry information | encoded as HEX-character string, not human-readable |

It can be seen in table 7.5, that the data for the objects of the road network contain information about road type, indicators for one-way, bridge or tunnel (however with no one-way, bridge, or tunnel section in the dataset) as well as information about the speed limit. Unfortunately, there is neither information about the age nor about the condition state available.

Table 7.6.: Road network data summary

| Number of objects | 102 | | | |
|---|---|---|---|---|
| | Min | Median | Mean | Max |
| Length [m] | 0.29 | 31.58 | 92.30 | 1’130.22 |
| Speed limit [km/h] | 30 | 30 | 38.5 | 80 |

From the road network summary table 7.6, it can be seen that the network consists of short (0.29 $m$) to long objects (1.1 $km$), with the speed limit having a median of 30 $km/h$ and a mean of 38.5 $km/h$, as the larger part of the network is made up of residential roads.

#### 7.1.1.4. Sewer

The sewer network of the investigated area, consisting of 214 objects, is shown in Figure 7.5.

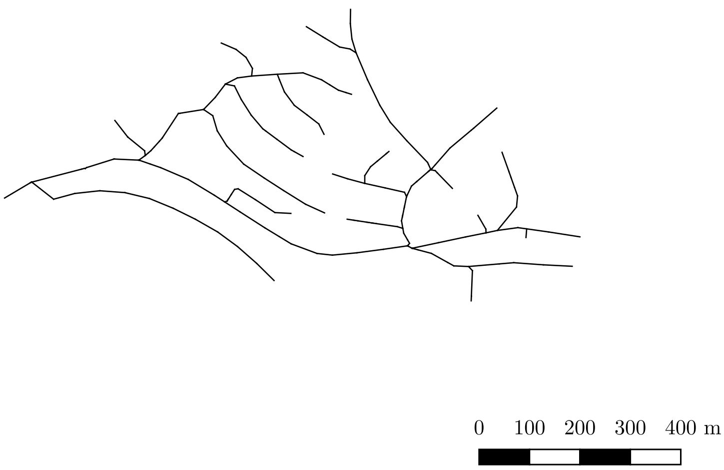



Figure 7.5.: Overview of the sewer network

The data provided consists of the information fields given in table 7.7. The first field contains the database key and acts as the object ID, the fields 2 to 10 contain information about the objects itself. The full dataset can be found in the digital appendix. A summary is given in table 7.8.

Table 7.7.: Provided sewer network data

| Number | Field name | Description | |
|---|---|---|---|
| 1 | gid | key column | primary key for this table, also acting as object identificator (integer number) |
| 2 | profiltyp | pipe profile type | all objects are “Kreisprofil” (circular). |
| 3 | profilbrei | pipe width | width in mm, ranges from 150-1’100 |
| 4 | profilhoeh | pipe height | height in mm, ranges from 150-1’100 |
| 5 | material | pipe material | 4 values: “armierter Beton” (reinforced concrete), “Spezialbeton” (special concrete), “Polyvinylchlorid”, “Faserzement” (fibrous cement) |
| 6 | funktion_h | hydraulic function | all objects are “Hauptsammelkanal” (main collection pipe). |
| 7 | status | operative status | all objects are “in Betrieb” (operative). |
| 8 | baujahr | construction year | ranges from 1973-2006 |
| 9 | baulicher_ | condition state class (5 classes) | 2 of 5 classes present: Z4 - “keine Mängel” (no defects), Z3 - “leichte Mängel” (small defects) |
| 10 | the_geom | geometry information | encoded as HEX-character string, not human-readable |

It can be seen in table 7.7, that the data for the sewer network contains information about pipe type, size and material (although only circular pipe profiles are in the dataset), information about the hydraulic function, the status, the construction year and the condition state of the object.

Table 7.8.: Sewer network data summary

| Number of objects | 214 | | | |
|---|---|---|---|---|
| | Min | Median | Mean | Max |
| Length [m] | 0.05 | 20.59 | 24.23 | 100.79 |
| Pipe diameter [mm] | 150 | 450 | 510 | 1'100 |
| Construction year | 1973 | 1976 | 1979 | 2006 |
| Condition state [Z4→Z0, Z4 is best] | 3 | 4 | 3.97 | 4 |

Looking at the data summary (Table 7.8), it can be seen that the 214 objects are consisting of a range of very short pipe sections to long pipes, with a median length of 20.59 $m$, and a mean length of 24.23 $m$, suggesting a normal distribution of pipe lengths. As the oldest objects in the sewage system are from 1973 (with an assumed approximate lifetime of 80 years) an expected year of renewal would be 2053-2060. Therefore, it is expected to have few, if any interventions on sewer objects in this example.

#### 7.1.1.5. Water

The water network of the investigated area, consisting of 185 objects, is shown in Figure 7.6.

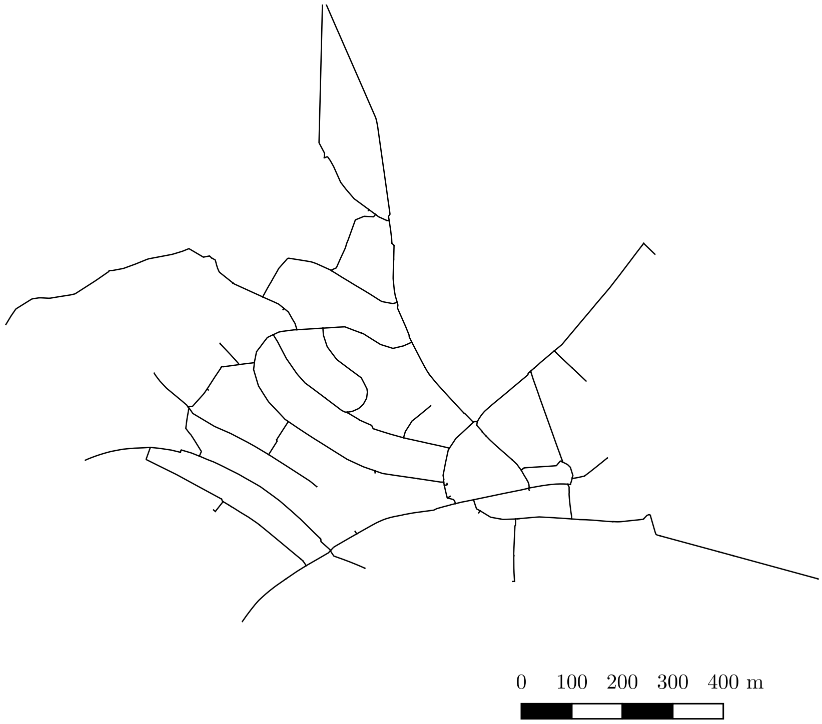



Figure 7.6.: Overview of the water network

The data provided consists of the information fields given in table 7.9. The first three fields contain database keys with the second field acting as the object ID, the fields 4 to 9 contain information about the objects itself. The full dataset can be found in the digital appendix. A summary is given in table 7.10.

Table 7.9.: Provided water network data

| Number | Field name | Description | |
|---|---|---|---|
| 1 | gid | key column | primary key for this table |
| 2 | ogc_fid | key column | foreign key for other database, also acting as object identificator (integer number) |
| 3 | _tid | key column | foreign key for other database |
| 4 | durchmesse | pipe diameter | diameter in mm, ranges from 50-500 |
| 5 | baujahr | construction year | ranges from 1942-2012 |
| 6 | status | operative status | all objects are "in Betrieb" (operative). |
| 7 | funktion | hydraulic function | 2 values: "Versorgungsleitung" (supply pipe), "Hauptleitung" (main pipe) |
| 8 | material | pipe material | 3 values: "Kunststoff" (plastic), "Guss" (ductile cast iron), "unbekannt" (unknown) |
| 9 | the_geom | geometry information | encoded as HEX-character string, not human-readable |

It can be seen in table 7.9, that the data for the water network objects contain information about pipe size and material (although only circular pipe profiles are in the dataset), information about the hydraulic function, the status, and the construction year.

Table 7.10.: Water network data summary

| Number of objects | 185 | | | |
|---|---|---|---|---|
| | Min | Median | Mean | Max |
| Length [m] | 0.05 | 24.28 | 49.55 | 458.63 |
| Pipe diameter [mm] | 50 | 150 | 150.4 | 500 |
| Construction year | 1942 | 1982 | 1983 | 2012 |

Looking at the data summary (Table 7.10), it can be seen that the 185 objects are consisting of a range of very short pipe sections to long pipes, with a median length of 24.28 $m$, and a mean length of 49.55 $m$, suggesting more shorter pipes than longer ones. One interesting fact is, that the water network is substantially longer than the sewer network. This is because the water network (but not the sewer network) also serves two neighbouring settlements. This can also be seen in Figures 7.6 and 7.5, where the pipes extend to the top centre and top left for the water network, but not for the sewer network.

#### 7.1.1.6. Summary

Summarising, the data that is available, is in most cases sufficient to generate an intervention program. For the electricity, gas, and water network, there is age information as well as a binary condition state available (working/non-working). For the sewer network, there is a 5-state condition available, together with age information. However, the data about the road network is not sufficient to generate an intervention program, as neither age nor condition is available. The demand and supply data, that is needed for calculating the level of service is presented in section 7.1.3.

### 7.1.2. Data completion

In order to overcome the problem of having no condition information about the road network, the road condition state data was simulated. For this, the Kumaraswamy distribution (Jones, 2009) was used. This distribution is closely related to the beta distribution (i.e. a double-bounded distribution, with two shape parameters), has the same basic shape properties, however with advantages in mathematical tractability. A double-bounded distribution is necessary, as the road condition in Switzerland is recorded on a continuous scale between 0 and 5, so a distribution estimation should also be double-bounded in order to avoid invalid numbers (i.e. out-of-scale) during the random generation process. In Table 7.11 the parameters that were used, are presented.

Table 7.11.: Kumaraswamy distribution properties

| Parameter | Value | Description |
|---|---|---|
| $a$ | 3.2 | first shape parameter |
| $b$ | 5.7 | second shape parameter |
| $scale$ | 5.0 | scaling factor, as the probability function has bounds [0;1], and the condition state has bounds [0;5] |

### 7.1.3. Assumptions and simplifications

With the available data, including the completion performed as described in section 7.1.2, the network input data is sufficient to be able run the calculation. However, some assumptions have to be made in order to give definite values to the generic functions described in chapters 4 to 6. Additionally, in order to balance the computational effort, certain simplifications have been made.

In this section, both assumptions and simplifications will be presented. First, the assumptions and simplifications made for the different networks are presented in section 7.1.3.1, for example the deterioration model used, the limit states for interventions, etc.

Then, the assumptions and simplifications not related to specific networks are presented in section 7.1.3.2, for example the grouping distance, as presented in equation 5.17. Finally, a summary is presented in section 7.1.3.3.

#### 7.1.3.1. Network-related assumptions and simplifications

In this section, the assumptions and simplifications are described, that were taken with respect to the network. These are 1) the representation of the condition, 2) the calculation of the conductivity, given a certain condition, 3) the calculation of flow from the single-object conductivity and 4) the calculation of both level of service and intervention costs. All are listed by network type. Assumptions and simplifications that are taken with respect to management decisions or others that cannot be attributed to one network are presented in section 7.1.3.2.

**Electricity** As shown in section 7.1.1.1, the available data provided both age data and condition (although only in operational/non operational). Therefore the condition is represented in an exponential condition function:

$$CS_{elec,t} = e^{-\lambda_{elec} \cdot t} \tag{7.1}$$

with: $CS_{elec,t} \ldots$ condition state for electricity network object, $\lambda_{elec} \ldots$ ageing factor for electricity network. The value of $\lambda_{elec}$ has been calculated to yield a value of 0.05 for $CS_{elec}$ for an age of 44.7 years, thus $\lambda_{elec} = 0.067$.

The calculation of conductivity is based on a linear interpolation of the base conductance (calculated from the physical parameters of a new conductor), and a loss of 15% of conductance at a CS value of 0.04 (which would give an age of 48 years). After 48 years, the conductivity is deemed as 0. The base conductance is provided in the digital appendix, as an extra data field added to the electricity network data.

The flow calculation for the electricity network is based on Kirchhoff's equations, and is calculated independently for every time step, with object granularity, i.e. consideration of each objects' unique conductance. The Kirchhoff equations are solved in the program via the *resistorArray* functions.

The costs for interventions on the electricity network were assumed to be length-dependent, based on $350\, mu/m$, and are given in the digital appendix, as an extra data field added to the electricity network data.

The costs for loss in level of service are given as:

$$C_{LOS,el} = \left( \int_0^t \left( B_{el,in}(\gamma_{n,el}(t), \delta_{n,el}) \right) dt - \int_0^t \left( B_{el,out}(\gamma_{n,el}(t), \delta_{n,el}) \right) dt \right) \cdot c_{loss,el} \tag{7.2}$$

with $C_{LOS,el} \ldots$ costs for loss in level of electricity service, $c_{loss,el} \ldots$ cost per unit electric energy that is lost during the transmission.

It is assumed as a simplification, that the producer can supply all demands, i.e. there is no production shortage if demand increases. In other words, if the losses in the network increase, the producer is able to compensate, however at a certain cost. Additionally, "ghost conductors" are added, that supply the disconnected consumers. For both, the losses on the network and the consumers that have to be supplied via the ghost network due to disconnection from the normal network costs, namely $c_{loss,el}$ occur that are proportional to the energy (i.e. the integral of power over time). In that sense, the loss in level of service equals to the amount of unserved energy. The value of $c_{loss,el}$ is set to 0.40 $mu/kWh$.

For example, if a consumer is disconnected from the normal network and he has to be supplied via the ghost network, the full amount of energy demand for this customer is regarded as a loss in level of service. Also, if the condition of the network deteriorates, the extra power needed to overcome the higher resistance is an additional loss in level of service.

The demand data (on a per-node-basis) is given as a column in the node table of the electricity network that is provided in the digital appendix. The demand is based on the population times an average electricity demand of 790 $kWh$ per person and year.

**Gas** As shown in section 7.1.1.2, the available data provided both age data and condition (although only in working/non working). Therefore the condition is represented in an exponential condition function:

$$CS_{gas,t} = e^{-\lambda_{gas} \cdot t} \tag{7.3}$$

with: $CS_{gas,t} \ldots$ condition state for gas network object, $\lambda_{gas} \ldots$ ageing factor for gas network. The value of $\lambda_{gas}$ has been calculated to yield a value of 0.05 for $CS_{gas}$ for an age of 46.8 years, thus $\lambda_{gas} = 0.064$.

The calculation of conductivity is based on a linear interpolation of the base conductance (calculated from the physical parameters of a new pipe), and a loss of 2% of conductance at a CS value of 0.04 (which would give an age of 50 years). After 50 years, the conductivity is deemed as 0. The base conductance is provided in the digital appendix, as an extra data field added to the gas network data.

The flow calculation for the gas network is based on the approximation equations by Ayala et al. (2013), is calculated independently for every time step, with object granularity, i.e. consideration of each objects' unique conductance and solved in the program via the *resistorArray* functions.

The costs for interventions on the gas network were assumed to be length-dependent, based on $350\, mu/m$, and are given in the digital appendix, as an extra data field added to the gas network data.

The costs for loss in level of service are given as:

$$C_{LOS,gas} = \left( \int_0^t \left( B_{gas,in}(\gamma_{n,gas}(t), \delta_{n,gas}) \right) dt - \int_0^t \left( B_{gas,out}(\gamma_{n,gas}(t), \delta_{n,gas}) \right) dt \right) \cdot c_{loss,gas} \tag{7.4}$$

with $C_{LOS,gas} \ldots$ costs for loss in level of gas service, $c_{loss,gas} \ldots$ cost per unit gas power (product of flow and pressure) that is lost during the transmission.

It is assumed as a simplification, that the producer can supply all demands, i.e. there is no production shortage if demand increases. In other words, if the losses in the network increase, the producer is able to compensate, however at a certain cost. Additionally, "ghost pipes" are added, that supply the disconnected consumers. For both, the losses on the network and the consumers that have to be supplied via the ghost network due to disconnection from the normal network costs, namely $c_{loss,gs}$ occur that are proportional to the product of gas volume and pressure. In that sense, the loss in level of service equals to the amount of unserved gas at a pressure. The value of $c_{loss,gas}$ is set to 0.90 $mu/m^3@1bar$.

For example, if a consumer is disconnected from the normal network and he has to be supplied via the ghost network, the full amount of gas demand for this customer is regarded as a loss in level of service. Also, if the condition of the network deteriorates, the extra pressure needed to overcome the higher resistance is an additional loss in level of service.

The demand data (on a per-node-basis) is given as a column in the node table of the gas network that is provided in the digital appendix. The demand is based on the population times an average gas demand of $625\, m^3$ per person and year.

**Roads** As shown in section 7.1.1.3, the available data did not provide enough information to calculate a meaningful intervention program as neither age nor condition was available. Therefore, condition state data was simulated in section 7.1.2. Condition is available at a continuous scale, ranging from 0 to 5. In order to simplify calculation, this continuous scale is brought to the same form as the above presented networks by simply dividing by 5, and assuming an exponential deterioration function:

$$CS_{road,t} = e^{-\lambda_{road} \cdot t} \tag{7.5}$$

with: $CS_{road,t} \ldots$ condition state for gas network object, $\lambda_{road} \ldots$ ageing factor for gas network. The value of $\lambda_{road}$ has been calculated to yield a value of 0.05 for $CS_{road}$ for an age of 27.2 years, thus $\lambda_{road} = 0.11$.

The calculation of conductivity is based on the road type, with the following values given in table 7.12.

Table 7.12.: Assumed road capacities

| Road type | Capacity [Veh/hr] |
|---|---|
| unclassified | 500 |
| residential | 1000 |
| tertiary | 2000 |
| secondary | 4000 |

The flow calculation for the road network is based on a min cost (with travel time as cost) - max flow formulation, is calculated independently for every time step, with object granularity, and solved in the program via the *relax-IV* algorithm.

The costs for interventions on the road network were assumed to be length-dependent, are based on $350\,mu/m$ and are given in the digital appendix, as an extra data field added to the road network data.

The costs for loss in level of service are given as:

$$
\begin{aligned}
C_{LOS,rd} \quad = \quad & c_{travel} \cdot \int_0^t \Big(B_{rd,opt}(\gamma_{opt,rd}) \cdot \Big(1 \quad + \left(\frac{B_{rd,opt}(\gamma_{opt,rd}) - B_{rd,out}(\gamma_{n,rd}(t), \delta_{n,rd})}{B_{rd,out}(\gamma_{n,rd}(t), \delta_{n,rd})}\right) \\
& \qquad\qquad\qquad\qquad\qquad\qquad + \left(\frac{B_{rd,out}(\gamma_{opt,rd}) - B_{rd,out}(\gamma_{n,rd}(t), \delta_{n,rd})}{B_{rd,out}(\gamma_{n,rd}(t), \delta_{n,rd})}\right)\Big)\Big)\, dt \\
& + c_{loss_{rd}} \cdot \qquad \int_0^t \left(\frac{B_{rd,opt}(\gamma_{opt,rd}) - B_{rd,out}(\gamma_{n,rd}(t), \delta_{n,rd})}{B_{rd,out}(\gamma_{n,rd}(t), \delta_{n,rd})}\right) dt
\end{aligned}
\tag{7.6}
$$

with $c_{travel,rd} \ldots$ average travel time cost per hour, $c_{loss,rd} \ldots$ additional costs for impossible trips, $B_{rd,opt} \ldots$ traffic power in an optimal case (i.e. no closed roads), $B_{rd,out} \ldots$ traffic power in actual case (i.e. with closed roads), $\gamma_{opt,rd} \ldots$ conductivity of network in optimal state, and $\gamma_{n,rd} \ldots$ conductivity of network in actual state. In the first integral, the travel cost is calculated as the travel cost for the optimal network (first expression, where the mobility is calculated with a perfect network, i.e. where all trips are possible and executed on a network in perfect condition) augmented with two factors: 1) the first expression after the "1+", which calculates the rate of possible trips on the prefect network compared to the actual possible trips due to closed objects (note the different indices in the numerator), which considers the impossible trips due to network condition, and 2) the last expression in the first integral, that compares the actual possible traffic on an optimal network to the actual possible traffic on the actual network (i.e. considers only the possible trips, but with the actual road condition compared to an optimal one). The last integral adds additional costs for those trips that are totally impossible. The value of $c_{travel}$ is set to 23.29 $mu/hr$, in line with *SN 641822a*. The value of $c_{loss,rd}$ is set to 15 $mu/impossible\ trip$.

For example, if a point in the road network is unreachable, the loss in the level of service is 15 $mu/person$ that desires to travel to this point. If a person has to take a detour, the additional travel time is multiplied with 23.29 $mu/hr$ to give the loss in level of service.

As a simplification, the traffic pattern was assumed to be that the whole population leaves the urban area in the morning, and returns in the evening. This is seen as reasonable, as the town the urban area is part of is known as a commuter town, where the vast majority leaves in the morning and returns in the evening. The amount of persons leaving is given on a per-node-basis in the digital appendix.

**Sewer** As shown in section 7.1.1.4, the available data provided both age data and condition. However, the network is in exceptionally good condition, which makes an estimation of a deterioration function exceptionally difficult, especially as even the oldest pipes are in the best condition state. In order to be able to demonstrate the functioning of the methodology, it is assumed that the condition is (as in the other networks, for ease of comparability) represented in an exponential condition function:

$$CS_{sew,t} = e^{-\lambda_{sew} \cdot t} \tag{7.7}$$

with: $CS_{sew,t} \ldots$ condition state for sewer network object, $\lambda_{sew} \ldots$ ageing factor for sewer network. The value of $\lambda_{sew}$ has been calculated to yield a value of 0.05 for $CS_{sew}$ for an age of 76.8 years, thus $\lambda_{sew} = 0.039$.

The calculation of conductivity is based the maximum capacity of the sewer pipes, using the Prandtl-Colebrook nomogram for fully filled circular tubes in conjunction with the fill level curve adjustment diagram according to Kroiss (2007), the pipe diameter, an assumed slope of 4‰ and a value of $k_b = 1.5$ (calculated from the physical parameters of a new conductor). The values are provided as extra column in the digital appendix. It is assumed that the water that cannot be transported leads to overflows out of the manholes.

The flow calculation for the sewer network is, as a simplification based on a max gradient - max flow formulation, is calculated independently for every time step, with object granularity, which is solved in the program via the *relax-IV* algorithm.

The costs for interventions on the sewer network were assumed to be length-dependent, based on $350\,mu/m$, and are given in the digital appendix, as an extra data field added to the sewer network data.

The costs for loss in level of service are given as:

$$C_{LOS,sw} = \int_0^t \left(B_{sw,in}(\gamma_{n,sw}(t), \delta_{n,sw}) - B_{sw,out}(\gamma_{n,sw}(t), \delta_{n,sw})\right) dt \cdot c_{poll,sw} \tag{7.8}$$

with $C_{LOS,sw} \ldots$ costs for loss in level of sewer service, $c_{poll,sw} \ldots$ cost per $m^3$ sewer overflow.

The value of $c_{poll,sw}$ is set to 0.0001 $mu/m^3$. This reflects the approach that in sewer management, leakage is tolerated to a certain point. Nevertheless, a value larger than zero has to be assumed due to mathematical reasons. In that sense, the loss in level of service is the amount of water leaking or overflowing, times the pollution costs.

The demand data (i.e. the amount of produced wastewater, on a per-node-basis) is given as a column in the node table of the sewer network that is provided in the digital appendix. The demand is based on waterwork data, with a total of $89'562\,m^3$ per year, calculating to an average sewage production of $245\,m^3$ per person and year.

**Water** As shown in section 7.1.1.5, the available data provided both age data and condition (although only in working/non working). Therefore the condition is represented in an exponential condition function:

$$CS_{water,t} = e^{-\lambda_{water} \cdot t} \tag{7.9}$$

with: $CS_{water,t} \ldots$ condition state for water network object, $\lambda_{water} \ldots$ ageing factor for gas network. The value of $\lambda_{water}$ has been calculated to yield a value of 0.05 for $CS_{water}$ for an age of 49.9 years, thus $\lambda_{gas} = 0.060$.

The calculation of conductivity is based on a linear interpolation of the base conductance (calculated from the physical parameters of a new pipe), and a loss of 2% of conductance at a CS value of 0.04 (which would give an age of 54 years). After 54 years, the conductivity is deemed as 0. The base conductance is provided in the digital appendix, as an extra data field added to the water network data.

The flow calculation for the water network is based on the approximation equations by Ayala et al. (2013), is calculated independently for every time step, with object granularity, and is solved in the program via the *resistorArray* functions.

The costs for interventions on the water network were assumed to be length-dependent, based on $350\,mu/m$, and are given in the digital appendix, as an extra data field added to the water network data.

The costs for loss in level of service are given as:

$$C_{LOS,water} = \left( \int_0^t \left( P_{water,in}(\gamma_{n,water}(t), \delta_{n,water}) \right) dt - \int_0^t \left( P_{water,out}(\gamma_{n,water}(t), \delta_{n,water}) \right) dt \right) \cdot c_{loss,water} \tag{7.10}$$

with $C_{LOS,water} \ldots$ costs for loss in level of water service, $c_{loss,water} \ldots$ cost per unit water power (product of flow and pressure) that is lost during the transmission.

The demand data is given as a column in the node table of the sewer network that is provided in the digital appendix. The demand is based on an average water demand of $62.5\,m^3$ per person and year.

The value of $c_{loss,water}$ is set to 0.11 $mu/m^3@1bar$.

#### 7.1.3.2. Non-network-related assumptions

In this section, the non-network-related assumptions are presented, in order of their appearance in the methodology (see chapters 4 to 6).

The first assumption to be made is the form of the chromosome that encodes the intervention program. The complexity of the chromosome determines to a large part the complexity of the whole optimisation routine. As the calculation of the interactions and flow in the network is object-based and performed for every time step, the complexity of the chromosome is reduced. For this example, the chromosome is defined as:

$$\Xi = \left\{ L^I_{elec}, L^I_{gas}, L^I_{road}, L^I_{water}, L^I_{sewer}, L^{II}_{elec}, L^{II}_{gas}, L^{II}_{road}, L^{II}_{water}, L^{II}_{sewer} \right\} \tag{7.11}$$

with

$L^I_m \ldots$ intervention threshold for level 1 for network $m$, and

$L^{II}_m \ldots$ intervention threshold for level 2 for network $m$.

The chromosome defines an intervention *strategy* that subsequently produces an intervention program. The optimisation is then defined as follows:

It is assumed that the objects of each infrastructure undergo an intervention *at latest*, if they reach a certain age (that expresses the condition), regardless of their surroundings (i.e. level 1). It is also assumed that if there are interventions on other objects nearby, interventions on objects of different networks can be added to the intervention cluster if they already have reached another certain age (i.e. level 2). Clusters can only be started by level 1 objects.

The goal of the optimisation is now to determine the optimal age for the intervention threshold for level 1 for each network and the optimal age for the intervention threshold for level 2 for each network, i.e. 5 pairs of ages, one for each network.

Optimality is judged by the thresholds that produce a cost-minimal intervention program taking into account intervention costs, interactions, and costs due to loss in level of service.

In simpler terms, the procedure can be described as follows: The basis of the optimisation is a certain intervention strategy. If this intervention strategy is combined with the actual state of the network, an intervention program is produced. (e.g. assume the strategy would be to replace an object at an age of 25. Then, if a network object is now at an age of 12, the intervention would be in year $25 - 12 = 13$. This would be the intervention program. If the age of the object would be 24 now, the intervention would be in year $25 - 24 = 1$. ) The intervention program then causes a certain state of the object over time, that incurs different costs (costs for level of service). The optimisation routine now changes the strategy in order to minimise the sum of costs for interventions plus the sum of costs over time for the level of service. In that sense, the optimisation routine starts with an intervention strategy, that (with the actual state of the network) produces an intervention program, and with this intervention program the level of service for the networks, over all 30 years, is calculated. The sum of costs (intervention plus level of service) is then the "fitness" of the strategy. Using a genetic algorithm approach, the strategy is then modified in order to improve the fitness, i.e. reduce the total cost. In order to reduce the complexity, a simple strategy was chosen, that does not discern between different materials on each network (in other words, all objects start at their respective age, that varies from object to object, but the speed at which objects age was assumed to be equal for all objects of one network). This will be further discussed in the example discussion section.

The next value to be assumed is the temporal neighbourhood timeframe $n_T$, as shown in figure 4.7. This value is assumed to be $n_T = 3yrs$, i.e. interventions can be moved up to three years if a grouping is beneficial from the algorithm point of view.

Then, the topological and distance limit, as defined in equation 5.7 (parameter $k$) and equation 5.11 (parameter $d_m$) have to be assumed. The topological distance limit is assumed to be $k = 2$, and the distance limit is assumed to be $d_m = 20\,m$. With that the neighbourhoods can be determined.

For the *DBSCAN* clustering procedure, two additional values have to be assumed. The first one, parameter $MinPts$ from equation 5.17 is trivially set to $MinPts = 2$, as this value describes the minimum number of objects that should be grouped together. The second parameter, *Eps* is related to the maximum distance, two objects can be apart in order to still be considered for a joint intervention execution. This parameter is set to $Eps = 60\,m$. As a reminder, this parameter is an input to the DBSCAN algorithm, and is not related to the distance limit $d_m$.

The next assumption to be made pertains to the interaction between the objects. As has been mentioned in Eq. 5.28, a certain hierarchy between the networks can be accounted for, given that the hierarchy is well-defined. The interaction follows the hierarchy shown in Figure 7.7, and was assumed using burying depth of the networks.

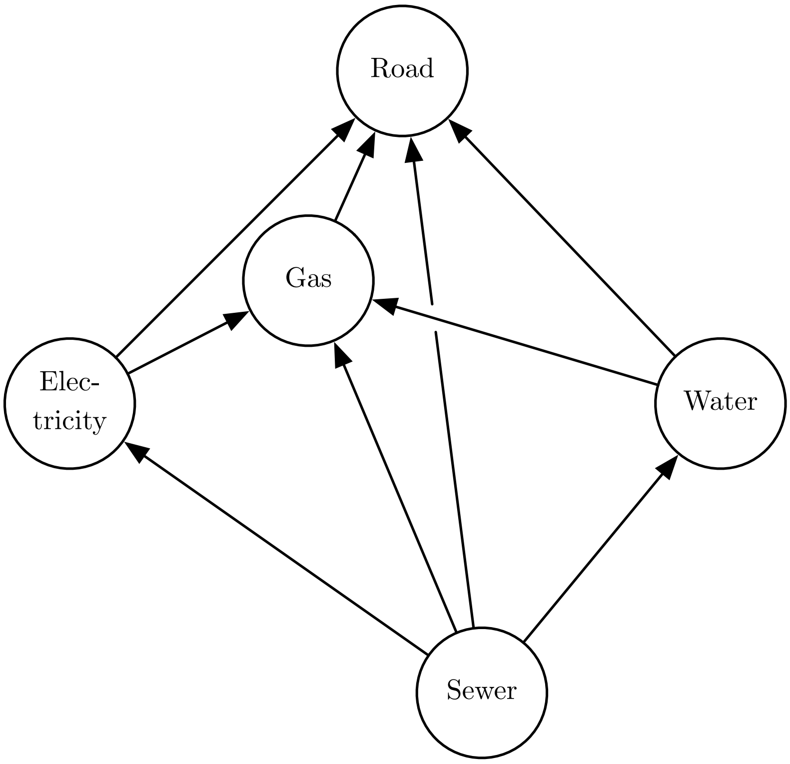



Figure 7.7.: Interaction hierarchy

This means that interactions between networks (not within a network) are assumed to happen in the following way: road objects receive interactions from all other networks (as all other networks in the example are buried underneath the road); gas network objects receive interactions from electricity, water, and sewer networks; electricity network objects receive interactions from the sewer network; and water network objects receive interactions from the sewer network as well. The sewer network does not receive any interactions from other networks, as it is the deepest buried network of the five networks investigated. The values of the interaction transmission matrix are calculated with Equation 5.28. As the interaction matrix is too large to be displayed in print either here or in the appendix ($\sim 9 \cdot 10^6$ data points), a data file with the information is provided.

The same holds true for the demand/supply and base conductivity data for the investigated networks. As mentioned before in section 7.1.3.1, they are appended in the respective network tables given in the digital appendix.

The last values to be defined are the cluster setup cost (i.e. the cost for setting up an intervention cluster and coordination of the single interventions, see Equation 5.34) and the grouping benefit (i.e. the amount of money saved by, for example, only opening the road once, or only having to set up a detour once). The cluster setup cost is set to $c_j = 20'000\, mu$, and the grouping benefit is set to $\alpha_g = 0.7$.

As the optimisation is based on the total cost, that also includes the level of service, penalties are omitted in this example.

The evolution functions for the genetic algorithm are directly taken from (Scrucca, 2013).

With these assumptions, the example is ready to be calculated. For convenience, all assumptions are summarised in table 7.13.

Additionally, the summary also lists in table 7.15 the simplifications to increase calculation speed.

#### 7.1.3.3. Summary

In the following table, all assumptions are summarised.

| Network | Item | Assumed value | Unit |
|---|---|---|---|
| Electricity | Deterioration function | exponential | |
| | Average replacement age | 44.7 | years |
| | Conductivity loss | linear with CS | |
| | Max conductivity loss | 15 | % |
| | Age with 0 conductivity | 48 | years |
| | Flow calculation | resistorArray | algorithm |
| | Intervention costs | 350 | $mu/m$ |
| | Level of service costs | $C_{LOS,el} = \left(\int_0^t \left(B_{el,in}(\gamma_{n,el}(t), \delta_{n,el})\right) dt - \int_0^t \left(B_{el,out}(\gamma_{n,el}(t), \delta_{n,el})\right) dt\right) \cdot c_{loss,el}$ | |
| | $c_{loss,el}$ | 0.4 | $mu/kWh$ |
| Gas | Deterioration function | exponential | |
| | Average replacement age | 46.8 | years |
| | Conductivity loss | linear with CS | |
| | Max conductivity loss | 2 | % |
| | Age with 0 conductivity | 50 | years |
| | Flow calculation | resistorArray | algorithm |
| | Intervention costs | 350 | $mu/m$ |
| | Level of service costs | $C_{LOS,gas} = \left(\int_0^t \left(B_{gas,in}(\gamma_{n,gas}(t), \delta_{n,gas})\right) dt - \int_0^t \left(B_{gas,out}(\gamma_{n,gas}(t), \delta_{n,gas})\right) dt\right) \cdot c_{loss,gas}$ | |
| | $c_{loss,gas}$ | 0.9 | $mu/m^3@1bar$ |
| Road | Deterioration function | exponential | |
| | Average replacement age | 27.2 | years |
| | Capacity | Road type / Capacity [Veh/hr]:<br>unclassified 500<br>residential 1000<br>tertiary 2000<br>secondary 4000 | |
| | Flow calculation | relax-IV | algorithm |
| | Intervention costs | 350 | $mu/m$ |
| | Level of service costs | $C_{LOS,rd} = c_{travel} \cdot \int_0^t \left(B_{rd,opt}(\gamma_{opt,rd}) \cdot \left(1 + \left(\frac{B_{rd,opt}(\gamma_{opt,rd}) - B_{rd,out}(\gamma_{n,rd}(t), \delta_{n,rd})}{B_{rd,out}(\gamma_{n,rd}(t), \delta_{n,rd})}\right) + \left(\frac{B_{rd,out}(\gamma_{opt,rd}) - B_{rd,out}(\gamma_{n,rd}(t), \delta_{n,rd})}{B_{rd,out}(\gamma_{n,rd}(t), \delta_{n,rd})}\right)\right)\right) dt + c_{loss_{rd}} \cdot \int_0^t \left(\frac{B_{rd,opt}(\gamma_{opt,rd}) - B_{rd,out}(\gamma_{n,rd}(t), \delta_{n,rd})}{B_{rd,out}(\gamma_{n,rd}(t), \delta_{n,rd})}\right) dt$ | |
| | $c_{travel}$ | 23.29 | $mu/hr$ |
| | $c_{loss,rd}$ | 15 | $mu/impossible\,trip.$ |

Table 7.13.: Assumptions for the example application part 1

| Network | Item | Assumed value | Unit |
|---|---|---|---|
| Sewer | Deterioration function | exponential | |
| | Average replacement age | 76.8 | years |
| | Conductivity | Prandtl-Colebrook, slope=4‰, $k_b = 1.5$ | |
| | Flow calculation | relax-IV | algorithm |
| | Intervention costs | 350 | $mu/m$ |
| | Level of service costs | $C_{LOS,sw} = \int_0^t \left(B_{sw,in}(\gamma_{n,sw}(t), \delta_{n,sw}) - B_{sw,out}(\gamma_{n,sw}(t), \delta_{n,sw})\right) dt \cdot c_{poll,sw}$ | |
| | $c_{poll,sw}$ | 0.0001 | $mu/m^3$ |
| Water | Deterioration function | exponential | |
| | Average replacement age | 49.9 | years |
| | Conductivity loss | linear with CS | |
| | Max conductivity loss | 2 | % |
| | Age with 0 conductivity | 54 | years |
| | Flow calculation | resistorArray | algorithm |
| | Intervention costs | 350 | $mu/m$ |
| | Level of service costs | $C_{LOS,water} = \left(\int_0^t \left(P_{water,in}(\gamma_{n,water}(t), \delta_{n,water})\right) dt - \int_0^t \left(P_{water,out}(\gamma_{n,water}(t), \delta_{n,water})\right) dt\right) \cdot c_{loss,water}$ | |
| | $c_{loss,water}$ | 0.11 | $mu/m^3$@$1bar$ |
| General | Chromosome definition | $\Xi = \left\{L^I_{elec}, L^I_{gas}, L^I_{road}, L^I_{water}, L^I_{sewer}, L^{II}_{elec}, L^{II}_{gas}, L^{II}_{road}, L^{II}_{water}, L^{II}_{sewer}\right\}$ | |
| | Temporal grouping distance | $n_T = 3$ | years |
| | Topological distance limit | $k = 2$ | |
| | Distance limit | $d_m = 20$ | m |
| | MinPts | 2 | |
| | Eps | 60 | m |
| | Interaction matrix | provided as data file | |
| | Demand | provided as data file | |
| | Supply | provided as data file | |
| | Base conductivity | provided as data file | |
| | Group setup cost | $c_j = 20'000$ | $mu$ |
| | Grouping benefit | $\alpha_g = 0.7$ | |
| | Evolution functions | according to (Scrucca, 2013) | |

Table 7.14.: Assumptions for the example application part 2

In the following table, the calculation granularity and the simplifications for each methodology component are listed.

Table 7.15.: Simplifications for the example application

| Component | Calculation granularity | Simplifications |
|---|---|---|
| object condition / age | individually calculated for each object and time step | exponential deterioration function |
| intervention decision | two thresholds per network | assumption that all objects from one network are similar enough to have the same threshold |
| clustering | individually calculated for each object and time step | 2-parameter model (DBSCAN) |
| interactions | individually calculated for each object and time step | only one level of interaction propagation |
| object conductivity | individually calculated for each object and time step | linear relation to condition, so in total exponential relation |
| network flow | individually calculated for each network and time step, considering each object's conductivity | simplified flow calculation functions |
| demand | individually given for each output node | demand constant over time |
| supply | individually calculated for each input node and time step | demand plus network loss can always be satisfied |
| loss in level of service | individually calculated for each network and time step | linear relation between loss in level of service and associated costs |
| intervention costs | individually for each object | linear relation to length |
| intervention setup costs | individual for each cluster | cluster size-independent |

## 7.2. Results

In this section, the results of the optimisation are presented, that have been executed on the example network, with explanations of the results, and a presentation of the intervention program that is derived from the optimisation.

### 7.2.1. Intervention program

As described in more detail in the section about the optimisation results on page 175, the result of the iteration remained stable for 50 generations. Thus it was assumed that a near-optimum was found. The intervention program is summarised in Table 7.16 and Figure 7.8. Table 7.17 shows an excerpt of the intervention program. The full intervention program is (due to size) provided in the digital appendix.

Table 7.16.: Intervention program summary table

| Year | Interventions | | | | | Total | Clustering | | |
|---|---|---|---|---|---|---|---|---|---|
| | Electricity | Gas | Road | Sewer | Water | | Uncl. objects | Clustered objects | No. of Clusters |
| 1 | 213 | 11 | 1 | 0 | 12 | 237 | 10 | 227 | 7 |
| 6 | 618 | 106 | 10 | 0 | 1 | 735 | 4 | 731 | 2 |
| 11 | 580 | 120 | 35 | 0 | 15 | 750 | 7 | 743 | 10 |
| 16 | 269 | 28 | 59 | 0 | 0 | 356 | 10 | 346 | 12 |
| 21 | 214 | 26 | 3 | 0 | 21 | 264 | 5 | 259 | 11 |
| 26 | 41 | 6 | 9 | 0 | 43 | 99 | 7 | 92 | 10 |

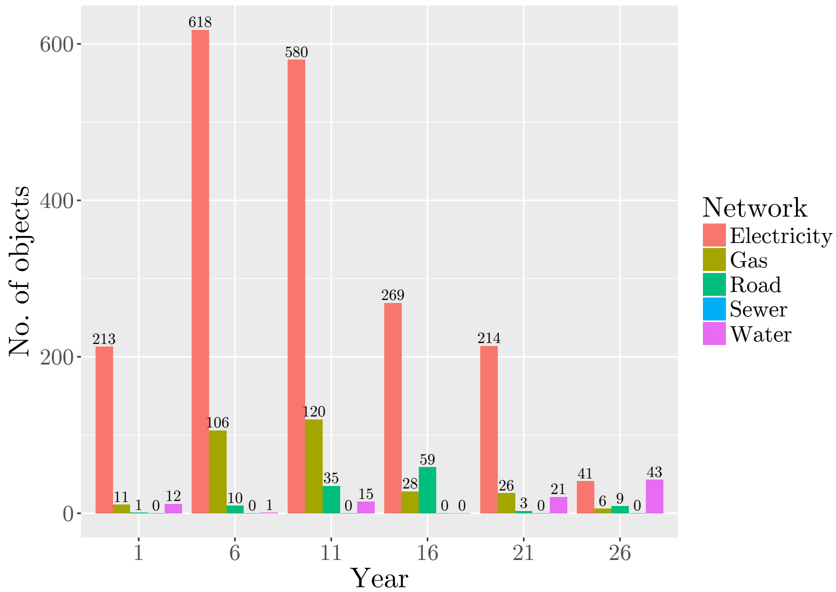



Figure 7.8.: Intervention program summary figure

The excerpt of the intervention program shows how the intervention program is structured. The first column shows the object identifier, the second column shows the

Table 7.17.: Intervention program excerpt

| Object ID | Network | Cluster ID | Intervention year | Cluster number | Time to un-coordinated intervention | Nominal intervention cost | Actual intervention cost |
|---|---|---|---|---|---|---|---|
| E29100 | Electricity | C1-Y1 | 1 | C1 | 3 | 24170.82 | 16919.57 |
| W3222 | Water | C1-Y1 | 1 | C1 | 0 | 23993.58 | 16795.51 |
| E33999 | Electricity | C5-Y1 | 1 | C5 | 0 | 23050.08 | 16135.06 |
| E33884 | Electricity | C1-Y6 | 6 | C1 | 6 | 20860.99 | 14602.69 |
| G1205 | Gas | C1-Y6 | 6 | C1 | 3 | 21690.62 | 15183.43 |
| G2975 | Gas | C1-Y6 | 6 | C1 | 2 | 24188.04 | 16931.63 |
| G3060 | Gas | C1-Y6 | 6 | C1 | 3 | 22917.69 | 16042.38 |
| G5490 | Gas | C1-Y6 | 6 | C1 | 1 | 20149.71 | 14104.80 |
| G3179 | Gas | C1-Y11 | 11 | C1 | 1 | 20912.04 | 14638.43 |
| R1230 | Road | C1-Y11 | 11 | C1 | 1 | 23428.06 | 16399.64 |
| W1006 | Water | C4-Y11 | 11 | C4 | 0 | 22686.62 | 15880.63 |
| W2196 | Water | C4-Y11 | 11 | C4 | 0 | 22835.79 | 15985.05 |
| R228 | Road | R228-Y11 | 11 | R228 | 4 | 21448.49 | 21448.49 |
| G3191 | Gas | C1-Y16 | 16 | C1 | 2 | 21900.69 | 15330.48 |
| R260 | Road | C2-Y16 | 16 | C2 | 0 | 21059.90 | 14741.93 |
| R1285 | Road | C4-Y16 | 16 | C4 | 1 | 23106.45 | 16174.52 |
| R243 | Road | C5-Y16 | 16 | C5 | 0 | 23500.26 | 16450.18 |
| R1141 | Road | C7-Y16 | 16 | C7 | 0 | 21735.91 | 15215.14 |
| W3897 | Water | C2-Y21 | 21 | C2 | 1 | 21280.85 | 14896.60 |
| W3527 | Water | C2-Y26 | 26 | C2 | 5 | 21469.24 | 15028.47 |
| W3763 | Water | C5-Y26 | 26 | C5 | 1 | 21220.40 | 14854.28 |

network the object belongs to. The third column shows the cluster ID (e.g. C1-Y11). This identifier has two parts, separated with a dash. The first part denotes the cluster number (e.g. C1) or if an intervention on an object is executed individually, the object ID (e.g. R228). The second part consists of the letter "Y" and the year number, in which the intervention is executed (e.g. Y11). This is then separated in the next two columns (intervention year; cluster number). The following column shows "time to uncoordinated intervention", i.e. the remaining years until an intervention would be executed without considering grouping into intervention clusters.

The last two columns show the nominal and actual intervention costs. The nominal intervention costs are the intervention costs that would occur if an intervention on an object is executed individually. The actual intervention costs include the calculated benefits from grouping. For the object R228, which is executed individually, these two costs are therefore identical.

Note that there is no level of service in the intervention program. This is due to the fact that the increase of the level of service cannot be determined for a single object. Imagine a simple network that consists only of two identical objects that in parallel connect the source with the target, and in an ideal network state, the demand can be fulfilled. Imagine also, that both objects have an intervention executed on them at the same time, that brings them back from a total failure (i.e. no flow) into "as new" state. Therefore, the level of service is now returned to 100%. But if only one of both is returned to "as new" and the other stays defunct, it not so easy to say how much the level of service has increased. If the demand is so low that one object is sufficient, then the level of service is returned to 100%. However if both objects are necessary to fulfil the demand, the level of service is only brought back to 50%. In that sense, the level of service increase cannot be stated for a single object, as the demand fulfilment (i.e. the level of service) depends on the other object and its condition. However, the level of service can be expressed and displayed for the whole network, which is done in section 7.2.4.

However, the column "Time to uncoordinated intervention" also gives an idea about the differences to an unclustered intervention program. The closer this is to zero, the better. Additionally, only those values that are above 3 years (as the temporal neighbourhood threshold was chosen to be $n_T = 3\,yrs$), are interventions that are level 2 interventions. Looking at the excerpt table, only 3 of 21 interventions are level 2, i.e. significantly predated.

The intervention program excerpt can be read as follows: In year 1, the objects E29100, W3222, and E33884 have an intervention, with the objects E29100 and W3222 being executed in the same cluster (C1-Y1), and E33884 in a different cluster (C5-Y1). For cluster C1-Y1, object W3222 acts as a "seed", as the time to an uncoordinated intervention is 0, i.e. without coordination an intervention on this object would be performed anyway. In the same sense, object E33884 "seeds" cluster C5-Y1. It has to be noted that there are more objects in the respective clusters, so there could also be multiple seeds for each cluster (which are, however, not shown in the excerpt).

An example area of the intervention program is shown in Figure 7.9. This example should demonstrate what is happening in the background of the algorithm, without needing to resort to a GIS software that is needed to fully show the whole network. Therefore the example is rather small (only one junction), but demonstrates the mechanisms of grouping in a user-friendly way. Still, the complexity of the networks in this one junction is already high.

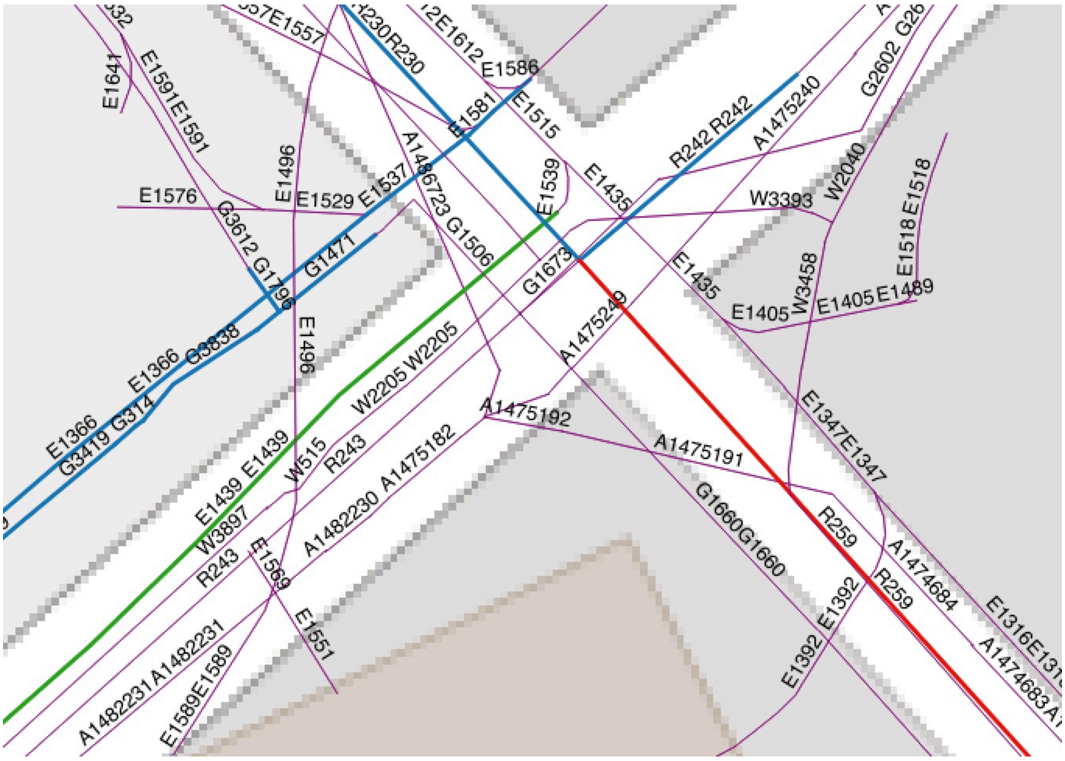



Figure 7.9.: Small intervention program area, green = year 1, red=year 6, blue=year 11

In the figure a junction is shown. The objects are marked with their respective t_gid identifier (i.e. all electricity objects start with "E", all gas objects with "G", all road objects with "R" all sewer objects with "A" and all water objects with "W"). The interventions are coloured by years, with interventions in year 1 being shown in green, interventions in year 6 in red, and interventions in year 11 in blue. Objects without intervention are shown with a thin violet line. In this example it can be seen that the intervention is set up in such a way that the junction in the centre is always connected. In the intervention in year 1, only the object E1439 has an intervention (being part of the bigger cluster C1-Y1, that is to the left of the zoomed picture), leaving the road on the lower left corner supplied via the objects E1589, E 1596, and E1496. In year 6, an intervention is executed on the road from the lower right corner, just until the junction (R259), being a non-clustered intervention. Then, in year 11, a bigger intervention cluster (C1-Y11) is executed. Here, the roads from the top left and right corner (R230, R242) have an intervention, together with the gas network objects G3419, G314, G3838, G1471, and G1796, and the electricity objects E1366, E1537, and E1581. In this cluster, the gas network objects have a *time to uncoordinated intervention* of 0-2 years, meaning they initiated the cluster. Road object R230 is also within 3 years of an intervention and thus a level 1 object. Road object R242 is not within 3 years of an intervention, but within 4 years, and is therefore also added to the intervention cluster. Electricity objects E1366, E1537 and E1581 are also level 1 objects, with exact 0 years to an uncoordinated intervention. In that sense, it is even possible to not deviate from an object-optimal strategy and still be able to have the benefits of a joint execution of an intervention.

When looking back at the summary table, one thing that is noticeable is that the interventions are grouped in 5-year blocks although the temporal timeframe is set to $n_T = 3\,yrs$. This can also be seen in Figure 4.7. Although the dotted lines only span a range of $n_T = 3\,yrs$, an additional range is included by the fact that the level 2 threshold enables objects to be also included and thus an "empty space" with no interventions is created after the temporal timeframe.

It is also noticeable that there are no interventions on sewer pipes at all. This is, however, expected, (as already stated in the situation description) as the oldest sewer pipe is just 44 years old (see Table 7.8), and with a calculated replacement age of 79 resp. 80 years, there are no interventions in the 30-year calculation period.

On the electricity network there is in general a high number of interventions, that peak in year 6. This is also expected, as the mean age of the electricity objects is 33 years (Table 7.2), and the replacement age is at 47 resp. 42 years. Thus the mean of the replacement year distribution is expected around the years 9-12, which fits the distribution in Figure 7.8.

When looking at the clustering information, it can be noticed that the number of unclustered objects (i.e. objects that are not combined with other objects into clusters) is in the one digit to low two digit range. This means that almost all objects could be combined into intervention clusters, i.e. the benefits of clustering are large.

### 7.2.2. Optimisation results

In this section, the development of the fitness, i.e. the path to finding a near-optimal solution is evaluated. As a genetic algorithm optimisation is a stochastic procedure, the final result is at least a near-optimal solution, but can also be the genuine optimum. Therefore it is necessary to evaluate the development of the fitness value, as this gives certain insights in the closeness to the genuine optimum. In Figure 7.10, the evolution of the fitness is shown by iteration.

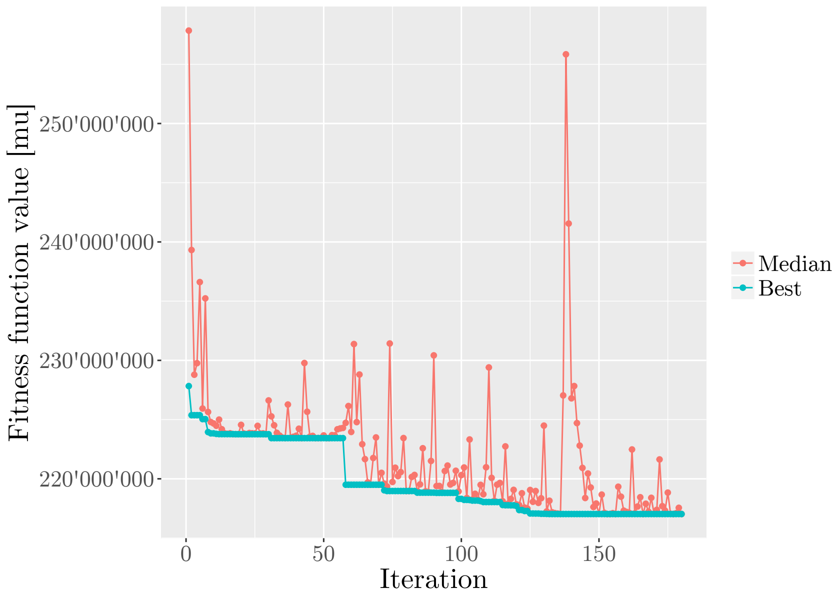



Figure 7.10.: Fitness function value

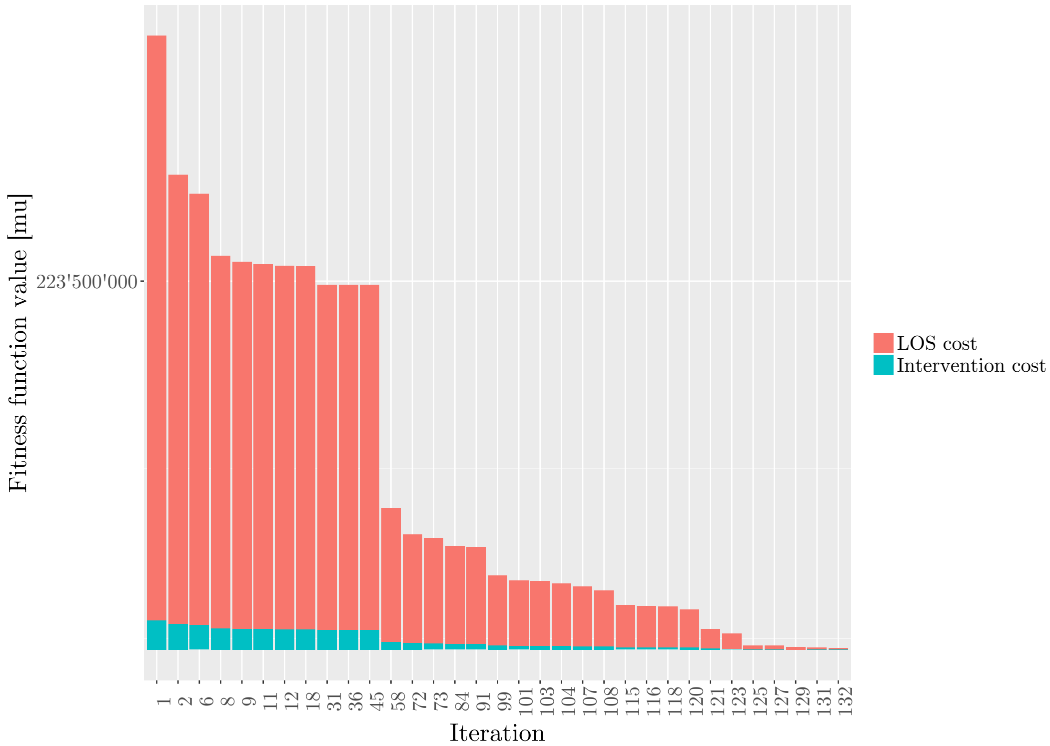
On the x-axis, the number of the iteration is shown, on the y-axis the value of the fitness function. The turquoise line shows the best value of each iteration, and the red line shows the median fitness of all individual chromosomes in each generation. In the first phase, the best fitness function value (turquoise line) decreases slightly. Then, after iteration 62, there is a sharp decrease in the fitness function value. Following that, the decrease slows down, and after iteration 132, no further decrease can be seen for the best fitness function value (turquoise line).

The median value (red line) is varying a lot. As this line plots the median fitness of all chromosomes inside each generation, the median value is a measure of the diversity in chromosomes. The more apart the best and the median line lines are, the more different the single chromosomes (and their fitness) are. The fact that the median line varies a lot suggests that there is sufficient diversity in the chromosome set, which in turn suggests that the likelihood of being caught in a local optimum is reduced.

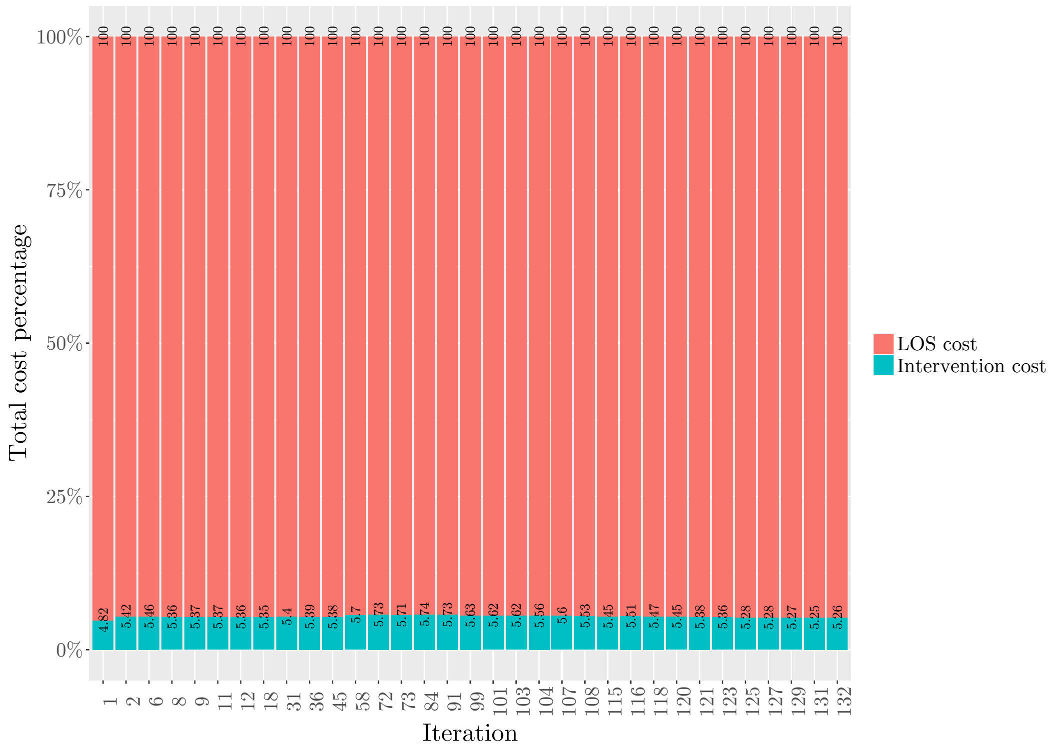
Additionally, the best fitness remains stable for 50 generations (iteration 132-182) suggests that, even with sufficient chromosome diversity, no further optimisation is possible, i.e. a near-optimal solution that is also likely to be the genuine optimum is found.

### 7.2.3. Total cost

In this section, the result in terms of total costs is evaluated. Figure 7.11a shows a plot of the total costs (i.e. the fitness) on the y-axis, and the iteration, at which the fitness changes at the x-axis. The costs are split in the intervention cost and level of service cost. However, due to the scaling, the relative part of the intervention cost cannot be seen easily. Therefore, the same graph has been normalised and is shown in Figure 7.11b.




(a) Scaled with fitness function




(b) Normalised

Figure 7.11.: Total cost split vs. fitness

It can be seen in Figure 7.11a, that the main component of the cost is attributed to the level of service. However, due to the difference in bar height (which stems from the overall fitness function value), the figure is difficult to read. Therefore, the values have been normalised to a percentage (i.e. the percentage of level of service cost vs. intervention cost) in Figure 7.11b. There it can be seen, that the percentage of intervention cost starts with first a value of 4.82%, then intermediately going up to 5.73% in iteration 84 before reducing again to 5.26% from iteration 132 on, suggesting that the differences in the percentages of level of service cost only are a minor contribution and thus no indicator for the overall fitness, i.e. the actual network configuration plays an important role in the optimality of the intervention program.

### 7.2.4. Level of service

In this section the level of service over time is presented, that results from the executed intervention program. However, as the road is (according to the impact hierarchy presented in Figure 7.7) receiving interactions from all networks (as all other networks are buried underneath the road), the diagram of the level of service is hardly readable due to the fact that during an intervention on e.g. a water network object, the flow is interrupted for a very short period of time (usually in hours), whereas the construction site (that affects the road traffic) is impeding traffic for several days. This would lead to differences in the level of service change in orders of magnitude, i.e. level of service changes on all networks except the road network would barely be visible. Therefore, an index was built, in order to make the change in level of service more visible. The index was constructed by assuming that for each network the level of service in year 1 has a level of service index (LOS index) of “1”, and if there is no service at all, the LOS index is “0”. Figure 7.12 shows the achieved level of service index.

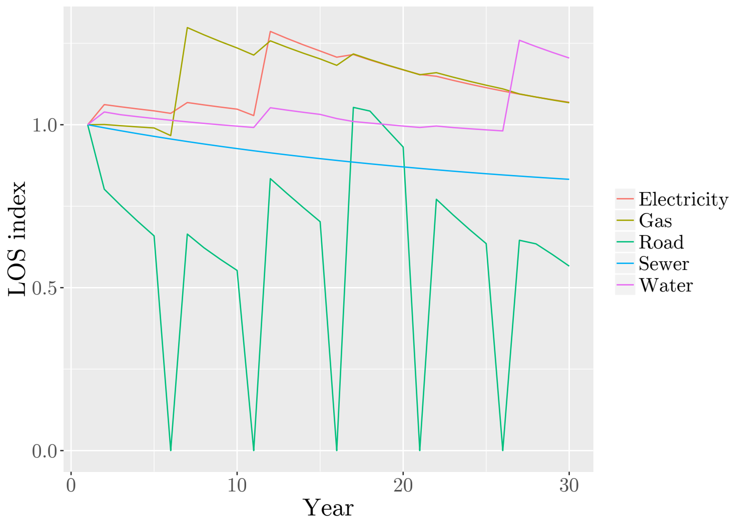



Figure 7.12.: Level of service index over time

From there the following things can be seen in Figure 7.12:

The level of service index for the electricity network slightly increases after the first interventions in year 1. In year 6 the second interventions are executed. It is important to notice that there is almost no drop in level of service on top of the normal loss in level of service due to deterioration. In year 7 the level of service is then increased due to the performed interventions. However, although the number of interventions is high (618 objects) in year 6, the increase in level of service is only small. Nevertheless, the redundancy is increased, as the drop in level of service due to the interventions in year 11 is also very small despite the high number of interventions (580 objects). Then from year 12 on, the level of service increases a lot. From there, as now a large number of objects is renewed (see section 7.2.1), the level of service curve follows more or less an exponential shape according to the chosen deterioration function.

The level of service index for the gas network is not largely affected by the intervention in year 1, as the line is almost horizontal. In year 6 there is a drop in level of service, that is attributed to the level of service loss during the intervention, before sharply increasing after the intervention, in year 7 due to interventions performed on many objects. From there, the level of service decreases again until year 11 where the next interventions are executed. Although the number of interventions in year 11 is also large, the increase in level of service is not that large as in year 6. This can be attributed to the fact that in year 11 the redundancies might be increased. The same schema follows for the remainder of the time.

The level of service index for the road network is the worst of all networks (as it is the only one that drops to zero), but demonstrates the effects of interactions between the networks. After year 1, where only 1 intervention on a road was executed, the level of service sharply decreases. This is due to interactions from other interventions. For example, if an intervention on a gas network object that lies underneath a road object is executed (but no intervention on the road object because the condition is not in a range where grouping is justified), the road condition is worsened due to the fact that the road is opened, the gas intervention executed, and the road closed again. Then, in year 6 (and in years 11, 16, 21, 26 as well) the level of service drops to zero. This is due to the fact that the interventions on the other networks plus the interventions on the road itself lead to a blockage of the road network (at least in the mathematical model - this is more thoroughly discussed in section 7.3). Then, the level of service increases again, as in the other networks. The last thing to notice in the level of service index graph is the two kinks at years 18 and 28. These are attributed again to weak points that are introduced in the road and thus increase the deterioration speed.

The level of service for the sewer network follows an exponential shape, as no interventions are executed, and the deterioration model is based on an exponential function. Additionally, as the sewer network is the deepest-buried network, no interactions affect the sewer network, and so there are also no kinks in the graph.

The level of service for the water network stays relatively stable, with small increases, decreases and kinks due to interventions and interactions, but increases largely after year 26 where the highest number of interventions is performed (43 objects).

### 7.2.5. Sensitivity analysis

Additionally to the calculation of the optimal intervention program, a sensitivity analysis was performed. The total number of assumed parameters/functions is 55 (see Tables 7.13 and 7.14). Three parameters were selected to investigate the effects on the optimal intervention program: 1) the grouping distance for objects of different networks was varied, 2) the intervention program was calculated without grouping, and 3) the intervention program was calculated without taking into account the level of service costs. The reasoning for the choice of these three parameters is as follows: For 1), the grouping distance is the fundamental value that determines the cluster formation, but has to be manually selected. Therefore this was chosen for a sensitivity analysis. For 2), the reason is to show that the methodology provides an advantage over no grouping, and for 3) the reason is to show that the consideration of the level of service on the networks does substantially change the intervention program.

For the grouping distance for objects of different networks, a comparison produces the graph shown in Figure 7.13.

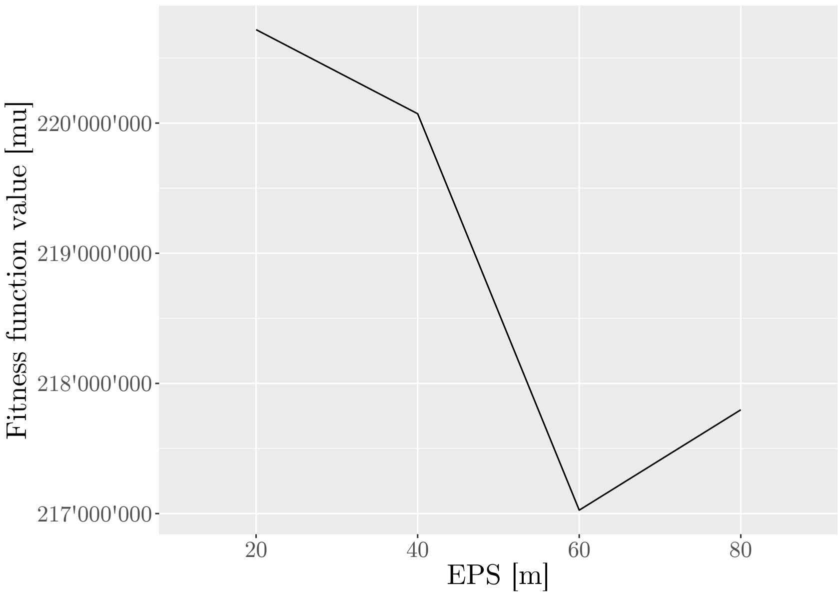



Figure 7.13.: Sensitivity analysis of grouping distance parameter $EPS$

It can be seen that the fitness function value decreases (i.e. is getting better) with increasing size of the grouping distance parameter $EPS$ (see list of abbreviations for a detailed description). This is to a certain extent expected, because as demonstrated during the analysis of the intervention program, there is a large number of interventions to be executed on the electricity network, that are done at the same time. By further increasing the distance, the number of clusters will decrease. At a distance of $80\,m$ however, the fitness gets worse again, as the large cluster size now causes too much disturbance in the level of service.

When looking at the intervention program in Table 7.17 on page 170, one can already see, that there are benefits that arise from grouping, because the actual intervention cost (i.e. the intervention cost, including clustering benefits) is significantly lower than the nominal intervention cost, that represents the intervention costs if the intervention would be executed on its own. This opens up the question how the intervention strategy (as a reminder: the algorithm optimises a (simple) strategy, taking into account the grouping possibilities, that combined with the actual network condition results in an intervention program) would change if there was no grouping. This has been done in Table 7.18. The table shows the strategy thresholds, when an intervention should be executed. It can be seen that the calculated level 1 thresholds for the electricity, gas and sewer network decrease, whereas for the road and water network, the levels increase. The level 2 thresholds (which only make sense if there is grouping) are not applicable.

Table 7.18.: Comparison of clustered and unclustered intervention program

| Grouping | Level 1 threshold | | | | | Fitness value | Intervention cost |
|---|---|---|---|---|---|---|---|
| | Electricity | Gas | Road | Sewer | Water | [smaller is better] | [mu] |
| Yes | 47 $y$ | 46 $y$ | 24 $y$ | 80 $y$ | 66 $y$ | 217 026 114 | 10 490 625.19 |
| No | 45 $y$ | 44 $y$ | 25 $y$ | 79 $y$ | 70 $y$ | 219 730 957 | 14 060 596.08 |

The first thing that can be noticed is, that the fitness value is smaller (i.e.) better with grouping, which is expectable when looking at the intervention program in Table 7.17 on page 170. It is therefore a good decision to group objects instead of executing interventions individually.

From a logical point of view, it should be expected that the thresholds change as two different scenarios can happen: 1) Objects that did benefit from grouping (i.e. that could be *added* to a cluster) cannot be added if there is no clustering. Therefore the level 1 threshold for networks with mainly level 2 interventions (i.e. those that are added to level 1 interventions) should see their threshold age decreasing, as now the non existing level 2 has to be replaced by a level 1 threshold. 2) Objects that initiated a cluster (level 1 objects), do not need to initiate the cluster any more. Therefore, networks with mainly level 1 interventions should see their threshold age increasing, as no other interventions on other networks have to be initiated as well.

For the electricity and gas network, scenario 1 dominates, i.e. the networks did benefit from being added to clusters (if grouping is performed) at an earlier age, and now have to be individually executed at this earlier age via a decreased level 1 threshold. For the sewer network, as within the investigated time period no interventions are executed, it is logical that the level 1 threshold stays the same apart from a rounding difference. For the road and water network, the level 1 threshold increases. This can be explained due to the fact that if an object acts as the "germination point" for a cluster, the grouping benefits can be taken advantage of, even if the condition state is not yet as bad. However, without grouping, there is no grouping benefit and as such, the timepoint for an intervention is only depending on the object condition.

Another comparison that could be made is the comparison between an intervention program with and without consideration of level of service (LOS). This is shown in Table 7.19. Again, the comparison has been made based on the strategy rather than the intervention program itself. What can be expected in general is, that the ages, at which an intervention is executed, rise. This is due to the fact that if the level of service is not accounted for, it is much more likely that objects are going to be let failing, as the impedance of the user is not accounted for.

Table 7.19.: Comparison of level of service consideration

| Network | Level 1 | | Level 2 | |
|---|---|---|---|---|
| | LOS | no LOS | LOS | no LOS |
| Electricity | 47 $y$ | 62 $y$ | 42 $y$ | 59 $y$ |
| Gas | 46 $y$ | 71 $y$ | 47 $y$ | 53 $y$ |
| Roads | 24 $y$ | 35 $y$ | 24 $y$ | 31 $y$ |
| Sewer | 80 $y$ | 89 $y$ | 79 $y$ | 92 $y$ |
| Water | 66 $y$ | 70 $y$ | 62 $y$ | 55 $y$ |

As expected, the level 1 and level 2 thresholds are increasing if there is no level of service consideration taken into account. This is due to the fact that, if no level of service is accounted for, the thresholds for intervention only are dependent on the grouping benefits and the limits for the condition. For example, an electric conductor should be replaced at an age of 62 instead of 47 years, if it cannot be combined with another level 1 intervention, otherwise at an age of 59 years instead of 42 years. This increase can be seen in all networks except for the level 2 threshold for the water network. Here, the level 2 threshold decreases, which can be explained by the fact that it might be possible to add these objects to existing clusters (and as such profit from clustering benefits) by reducing the level 2 threshold.

## 7.3. Example Discussion

In this section, the results of the example are discussed.

The strategy used in this example is due to calculational considerations rather simple. It was assumed, that all objects from one network age at the same speed, regardless of their material. This allowed in turn a faster calculation. Certainly, different ageing speeds should be used if this data is available. Nevertheless, this does not change the functionality of the example. Even if a more detailed strategy is used (possibly also on an object-per-object basis), the result of the strategy is still the same: namely a pair of thresholds for each object: the level 1 threshold and the level 2 threshold. A more refined strategy might change the actual numbers that are in the respective thresholds, but will not add a third threshold or any other number.

When looking at the bare result of the intervention program, it can be seen that the algorithm performs grouping, but also takes into account the continuity of the network, which could be seen in Figure 7.9 on page 172. Still, some objects are executed individually, as there are no other objects that could be combined into an intervention group. It is also noted that there is no direct possibility for a single object to calculate the "improvement in level of service". This is due to the dependency of the objects' role in the actual network configuration. For example, if an object only has a redundancy role (i.e. due to network configuration, there is no flow at the moment), no level of service can be increased by improving this objects' condition. Thus it is not possible to give a number that represents the "improvement in level of service" generated by this single object. However the total improvement in level of service for the network can be shown, and this is done in Figure 7.12 on page 178.

When looking at the fitness function (Figure 7.10), it can be seen that the optimisation value is constant for 50 generations, which triggered the stopping of the iteration routine. When applying genetic algorithms, there is always the question, if the real optimum or a local optimum has been found. In the field of evolutionary computing, this is an ongoing research topic. For example, Kosiński et al. (2010) define general criteria about the optimality and demonstrate the attainability of the true optimum, and Li et al. (2006) give numerical estimates for the needed generations and likelihood of the true optimum. Although there can be no absolute certainty, looking at the median plot in Figure 7.10 suggests due to the high variations that the population is sufficiently diverse and as such the likelihood of the solution being the optimum is high, though this would have to be confirmed by running additional iterations. Nevertheless, as Genetic Algorithms in infrastructure maintenance optimisation are widely used (e.g. Savic et al. (1995); Halhal et al. (1997); Miyamoto et al. (2000); Halfawy et al. (2008); Deshpande et al. (2010); Mathew and Isaac (2013)) and as such the general approach seems well accepted within literature. Even more, as shown in Table 7.18, the clustered intervention program performs better in fitness than the unclustered intervention program, and as such there is already an improvement, which is the main goal of the methodology.

The split of intervention cost versus level of service cost (Figure 7.11) shows that the intervention cost is not an indicator for a good or bad intervention program, as there is a huge influence in the network configuration itself that influences the total cost. For example, an intervention program with the same cost can cause totally different level of service costs, if the interventions are grouped wisely or poorly. The high percentage of level of service cost is mainly caused by the road network, as in this simplified example, no partial closures of roads are accounted for, and the travel time costs contribute much to the overall costs. Nevertheless, as the example area mainly consists of tertiary roads, the assumption of a full closure during intervention is valid for the small size of the roads.

When looking at the generated intervention program, it can be seen that the most number of objects, together with the least number of clusters occurs in year 6. This is due to the fact, that from a certain point on, the level of service is already impeded to a high degree and as such any split into more clusters will not decrease the effect on the level of service enough to outweigh the benefits of less grouping setup costs. In a more detailed model, this can be improved by adding additional constraints, such as minimal level of service provided, or maximal percentage of "out of service" objects. In this example, these constraints were not considered directly, but indirectly by assigning values to losses in level of service. Future work may increase the accuracy of those loss in level of service cost estimations, but the principle will stay the same.

When looking at the fitness function in Table 7.18, the difference seen in the fitness function seems very small. This is, however, misleading, as the value is not directly measurable in money, but also includes the cost to the public plus eventual penalties. A better comparison would be to compare the intervention costs directly. There, the difference is approximately 25%. However, what has to be noted is that the biggest part of the costs is due to disruptions in road traffic. This occurs during all interventions. Furthermore, the time of disruption is, as stated before, much bigger than the disruption time on the other networks. For example, the interruption during a pipe replacement is usually in a range of hours to days, but the worksite on the road remains for days to weeks. The main part of the level of service disruption is, therefore, due to the road network, and as such the road network generates the largest cost.

In the generated intervention program, it can be seen that there are no interventions on the sewer network. This might seem unusual at first, but as the sewage system has the oldest object from 1973, and the youngest from 1980, this gives (with an average lifetime of 80 years) an expected year of renewal of approx. 2053–2060 (i.e. outside of the 30-year period), given that due to the zoning plan no large growth and therefore replacement for capacity reason is expected. It is, however, completely expected that there will be corrective interventions due to an "unexpected" failure of certain pipes. This however, is outside of the scope of this methodology that is focused on preventive interventions.

When looking at the estimation of level of service plot, different shapes of level of service curves can be observed. The level of service provided itself is defined as $A_{out}$ (resp. $\int_0^t B_{out}$ ) shown in Eq. 5.19 generally, and in Equations 7.2, 7.4, 7.6, 7.8, and 7.10 for the example. In order to better see how the level of service from each of the networks change over time the level of service provided by each network was calibrated so that it has a value of 1 at year 0 and a value of 0 when it provided no service at all.

It can be seen that the level of service sometimes falls to zero. This is because it was assumed that there are no local detours around intervention sites, e.g. constructing a ramp up the sidewalk and bypass the traffic there, so when an intervention is executed traffic flow stops. This was done to avoid a multi-lane calculation, which adds to computational complexity. In reality, there would be local detours, that might use for example the hard shoulders of the road, or even a part of the sidewalk, and as such this calculation is on the pessimistic side. Still, the fact that the level of service drops that much is an indication for a need for more-detailed planning and in-depth modelling.

Also, it can be seen that all effects that were aimed to include can be found in the level of service plot, i.e. interactions between the networks and subsequent faster deterioration, the reduced level of service due to interventions, as well as location dependency of interventions (that can be seen by the fact that the number of objects with interventions does not linearly correlate with the increase in level of service, and thus their position in the network determines the amount of loss in level of service during the intervention). However, due to calculational complexity, the level of service was estimated with the simplification that there is no supply shortage, i.e. the producer can fulfil any demand plus losses. This simplification allows for faster calculation. When looking at intervention planning, it can be assumed that the intervention program is constructed long-term, and as such the needed supply can be estimated, and measures could be taken to ensure enough supply. Therefore, this assumption is seen as justified.

The clustering distance parameter $EPS$ of the $DBSCAN$ algorithm was chosen to be $60m$. As this choice was done arbitrarily, a sensitivity analysis was performed for this parameter. The evaluation showed, that for $60\,m$ there is a local optimum in the fitness function, with worse fitness values for both larger and smaller values. However, the sensitivity analysis was only performed for 3 other values (namely $20m$, $40m$, and $80m$.) It might be that there are intermediate values that provide better fitness. Nevertheless the logical examination of the parameter suggests that an optimum cannot lie at the boundary values (i.e. $0m$ or infinity), as for the former case no grouping would be performed (and for this case the sensitivity analysis shows a worse fitness value), and for the latter case, there would be only 1 cluster, incorporating all possible interventions in the respective year, which would effectively block all networks for all years, and not only in those years where a huge number of interventions is being executed.

If looking at the comparison between the intervention program with and without consideration of level of service, the obvious result is, that the level 1 and level 2 thresholds are increased, as there are no implications on the level of service if an intervention is done at a very late stage and thus affecting the condition state and as such as well the level of service. There is still grouping performed however, as with grouping, the intervention costs can still be reduced even without considering the level of service.

The function used to model the deterioration was chosen to be an exponential function, as it fulfils the requirement of being a monotonically decreasing function and additionally corresponds to a deterioration process that removes a constant percentage of "usability" per time unit. The function can, however, be replaced by any monotonically decreasing function, if such function is available for the corresponding networks. Nevertheless, it is true that both deterioration functions would give for each point in time a conductivity, a condition state and time-points for level 1 and level 2. Even if a probabilistic approach was used instead of these functions, to be able to make a decision, a single (expected) way of how the future develops has to be chosen

The 30-year period in the example was chosen to balance out 1) the computational demand and 2) the possibility to demonstrate long-term effects, that happen over the course of multiple years, e.g. the additional deterioration caused by neighbouring networks. A full lifetime consideration was deemed to long for the example, as with the limited data availability in some networks, it was deemed too difficult to produce reliable predictions, and therefore this was omitted. Nevertheless, the methodology shows that long-term effects can be accounted for, given that reliable information for all networks is available.

The sewage system was assumed to not also function as a stormwater drain. The methodology, however, can be adapted to account for stormwater networks as well, even more taking into account that the main function of a stormwater drain network is to prevent flooding in urban areas, and as such, the conductivity of the pipes (i.e. ensuring sufficient conductivity) is paramount. Of course, the conductivity-over-time-functions have to be adapted to the fact that conductivity changes in stormwater pipes are mostly caused by blockages (either gradual or sudden), but still the methodology is able to account for that, as the formulation basis in terms of conductivity remains.

The calculation time for this example was approximately 26 hours for each optimisation run, but with only using one CPU core and no GPU acceleration. The calculatory task is, however, parallelizable and due to the use of many matrices in the calculation also GPU-acceleration capable. Therefore, the example itself is able to be calculated in much less time, given that more CPU cores and/or GPU acceleration is available.

In summary, the example application demonstrates the applicability of the methodology to a real-world problem and produces results that are 1) within the usual ranges and 2) perform better than a calculated intervention program without grouping and 3) can cope with the combinatorial problem of an urban area. The effects shown in the discussion are all explainable and can (if the data availability permits) be reduced in their amount. Nevertheless the effects, for example the benefit of non grouping still exist even with a more detailed calculation and as such the methodology can be regarded as functioning and performing as expected.

# 8. Discussion and conclusion

The goal of this thesis was to present a methodology that is able to determine optimal intervention programs for urban infrastructure networks, taking into account deterioration and level of service on the infrastructure networks. Additionally, the interactions between the networks and a possibility to construct intervention programs for multiple infrastructure networks jointly, with grouping of interventions for multiple time frames should also be possible, while keeping the computational effort within reasonable amounts. As has been demonstrated in the example application, the methodology is able to determine optimal intervention programs for urban infrastructure networks.

The remaining chapter is divided in seven sections: Section 8.1 covers the general methodology setup, section 8.2 discusses the clustering component of the methodology, in section 8.3 a discussion of the interaction consideration is presented, section 8.4 discusses the consideration of level of service, section 8.5 discusses the fitness function, while in section 8.6, the computational effort is discussed. Finally, in section 8.8, a summary is given.

## 8.1. General methodology setup

The deterioration is accounted for by using a deterministic deterioration function that can be adjusted to the deterioration found on the respective networks, as long as the mathematical deterioration function is decreasing over time. This is reasonable, as deterioration does not improve the condition of an object over time. The use of a deterministic function for decision making can be justified by the fact, that even if a probabilistic approach were to be used, the final decision has to be based on one function, which for the most part would be the expected deterioration function, that is calculated using probabilistic methodologies. Furthermore, as the methodology is able to define the deterioration on object-level, specific local phenomena can be accounted for, and as the (deterministic) deterioration functions can be updated, the influence of newly available information can also be accounted for.

The level of service is accounted for by defining a service on the network, and then calculating the deviation (i.e. the loss in level of service) thereof. For this, an object-based approach is used that captures the flow of service on all networks.

The interactions between the networks are included in the methodology by defining a transmission process that transmits damage to the network from one object to other objects, according to a transmission function. This transmission function is also able to account for transmission hierarchy, i.e. interaction can be reciprocal, but does not have to be.

With both, the object based approach that simulates the network flow for each time step, it is possible to take into account the relative importance of the objects within the network, and also between networks, as it can be accounted for the damages one object of network A causes on other objects of network B.

The joint calculation of the intervention program is made possible by a consistent mathematical model for all networks.

The grouping of interventions is based on four different types of neighbourhoods: 1) the temporal neighbourhood, that takes care of the multiple time-frame combination, 2) the topological neighbourhood, that provides grouping for objects from the same network, 3) the distance neighbourhood, that is an alternative formulation of 2) that provides grouping for networks with vastly different object sizes, and 4) the Voronoi neighbourhood, that provides spatial grouping for objects from different networks.

The combination of all neighbourhoods gives a search space for adding interventions to "germination point" (i.e. level 1) interventions. By applying this germination point method, the calculation time, in conjunction with an iterative heuristic process, can be kept at an acceptable level. Thus it is deemed that the presented methodology is able to address both the scientific and practical goals that have been set in the introduction.

The remainder of this chapter will go through the advantages and disadvantages of the methodology and technical concept step by step and discuss the assumptions made and their implications. Then, a summary and a conclusion is given.

The methodology is based on an iterative process that starts with an initial suggestion (that could be the actual intervention program, or artificially created) in order to improve this intervention program in each iteration. This iteration concept is reflecting the actual practice of starting with an initial suggestion of an intervention program and then step-by-step trying to improve the it. Therefore, it is assumed that the methodology can easily be integrated into existing processes, as it functions as a "computational assistant" to the process. Additionally, the mathematical problem behind the task of creating an intervention program is a generalised weighted set problem with the objects being the elements that have to be assigned to certain sets, i.e. type of intervention, year, cluster. The sets then have different weights (which in this case is the total cost), and the goal is to minimise the sum of weights (which in this methodology is the total cost). With the mathematical problem being *NP-complete*, there is no fast algorithm for an exact solution[1], and thus a kind of heuristic is needed, which always uses iterations. Therefore, the choice of an iterative process is deemed correct.

The use of Genetic Algorithms always leaves the question of true optimality. However, the sheer size of the possible solutions makes it impossible to conduct an exhaustive search. These comparisons have though been done already in the past in the area of evolutionary computing (e.g.Li et al. (2006); Kosiński et al. (2010)) proving the ability of GA to provide reliable results when enough generations are run. It is a standard process in evolutionary computing to select the solutions (i.e., to decide when enough generations have been run) based on the stabilisation of results in the search space. Per mathematical definition GAs always find the optimal solution within a finite time (This is ensured by the random mutation: given enough time, at some point the chromosome will mutate to the optimal solution). As it is, however, impossible to directly identify the moment that the optimal solution is reached, it is necessary to evaluate the development of the fitness value in the search for the optimal solution. This is done by evaluating the stability of the solution. In other words, when many generations yield solutions where there is no change in the value of the fitness function it is assumed that an optimum is reached. This has been covered for example in (Li et al. (2006); Kosiński et al. (2010)), where certain indicators have been developed that give information about the qualities of the optimum, such as analysing the mean plot (which has been done in Fig. 7.10) and the development of improvement over generations. Therefore, and taking into consideration the fact

[1]unless $P$=$NP$, but this is still an unsolved problem in complexity theory

that Genetic Algorithms in infrastructure maintenance optimisation are widely used (e.g. Savic et al., 1995; Halhal et al., 1997; Miyamoto et al., 2000; Halfawy et al., 2008; Deshpande et al., 2010; Mathew and Isaac, 2013) it was deemed that the choice of Genetic Algorithms and the evaluation of the plot was appropriate.

The selection of the objects to be candidates for intervention is based on a distinction between so-called level 1 and level 2 objects. Level 1 objects were defined as objects that need an intervention on their own, i.e. where an intervention is beneficial without considering other objects, and level 2 objects are defined as objects where an intervention is only beneficial in conjunction with other objects. As the value of these objects is determined by the algorithm, there is no "manual choice" for this parameter. However, the "correct" calculation depends on the choice of what to include in the fitness function. If the fitness function is chosen poorly, the result is mathematically correct, but may lack important aspects. Summing up, the level 1 / level 2 concept is deemed good, however with the side note that care has to be taken when defining the fitness function, as the choice largely influences the quality of the values.

The methodology is at present focused on maintenance, as described in Chapter 3.1. However, it is expandable by adapting the timeline function (4.25b) (e.g. $\gamma_2$ can be made higher than $\gamma_0$ in order to represent a capacity increase for a specific object. Furthermore, it is possible to set $\gamma_0$ to 0, and only provide conductivity from time point $t_2$ on, which represents the fact that the object (in a providing-service-sense) only exists from time point $t_2$, which can emulate network expansion given that the location of the objects to be added is already known. It is, therefore, deemed that the methodology can be easily expanded into capacity change and network extension.

## 8.2. Clustering

The clustering component of the methodology uses dynamically calculated neighbourhoods, which rely on a suitable definition of closeness. The temporal closeness is based on a time range that has to be chosen manually. This time range acts as a maximal distance for that grouping is considered. This is deemed reasonable, as it is possible to antedate or postpone interventions to a certain extent. There is a range for objects in which an intervention can be performed, and as such applying a time range as neighbourhood provides grouping possibilities without endangering safety, if the latest time for an intervention is observed. To be on the safe side, in this methodology only antedating was considered, but an adaption for post-dating can be easily done. For the closeness within one network, the closeness definition of distance along the network and the number of crossed logical nodes is intuitive and straightforward. The Voronoi cell based closeness definition might be less intuitive, but using the geometric definition of Voronoi cells[2] is possible. However, there may be certain cases, where the automated spatial neighbourhood calculation could lead to unwanted results. It may be the case, that two objects should not be included in the same cluster even if they are in the same Voronoi cell as defined here, e.g. two pipes are within the same voronoi cell but separated by a railway track. To counteract this problem, dummy objects, which work as a "barrier" could be implemented.

The clustering is based on the *DBSCAN* algorithm (Ester et al., 1996), which uses two parameters as input. The first one, *minPts*, defines the minimal size (in terms of number of objects) of a cluster. This parameter is owed to the roots of this algorithm in data mining. For the methodology, the value is set to a value of 2, meaning that a cluster can be formed by two or more objects. This seems reasonable and straightforward. The second parameter, *EPS*, defines an area in which the algorithm looks for objects to add to the cluster. This is also straightforward, as for grouping outside of the same network, a certain spatial distance has to be set. The choice of the numeric value is, however not straightforward. Therefore, a sensitivity analysis (as was performed in the example application in Chapter 7) is recommended to verify the right choice for this parameter.

In the methodology, level 2 clusters, i.e. clusters only consisting of level 2 objects are removed. This is due to the fact that per definition, level 2 objects are only to be considered for intervention in combination with other objects. However, it might be the case, that there are enough level 2 objects with a (relatively) high cost to benefit ratio that the formation of a cluster may still be financially viable. However, as this has to be calculated on a case by case basis, this was considered to be too computationally demanding for this methodology. Therefore, level 2 clusters have been removed from the calculation generally. However, if desired, the evaluation of level 2 clusters can be added again in the future.

[2]Simplified: A Voronoi cell defines the region around an object, where no other object is closer

## 8.3. Interactions

The interactions are considered in the methodology during the creation of the object condition timeline. It is assumed, that there is only one level of iteration present. However, it might be the case that there are cascading effects, i.e. interactions that propagate through the networks. However, as the goal of this methodology is to calculate an optimal intervention program, it can be assumed, that before performing the interventions, the proposed intervention program is checked for cascading effects, and accordingly adjusted to prevent those. From that point of view it is reasonable to assume that there is only one single interaction step.

The transmission of interactions in the methodology is based on a single transmission matrix, that captures the interacting effects between the object, and is mainly dependent on the distance, but also on a hierarchy between the objects. This has been assumed due to simplification of calculation. It is, however, possible to manually determine and adjust the levels of interactions between all objects if it is deemed necessary and if the required data is available. Therefore, the concept of the transmission matrix seems suitable.

## 8.4. Calculation of loss in level of service

The calculation of loss in level of service in the methodology is based on the assumption that the loss in level of service is proportional to the service provided through the network, plus additional fixed costs. As has been shown in the literature review, there are many different ways of quantifying the service (and the loss thereof), depending on the reference frame. Many of the presented ways can, however, be broken down in a part proportional to the provided service, and a second "fixed" part. Nevertheless, there are certain aspects of service definitions that are dependent on other parameters, for example service definitions based on accident rate on roads or chemical parameters in the water network. By amending the service equations, this can be accounted for as well, though this has not been done in this thesis.

Additionally, the methodology does not take into account any "backup configurations". For example, if parts of the electricity network are out of service, mobile generators can be used to connect to the remaining unserved network parts where there would be no service, but also no intervention in order to provide electricity to the affected customers. The same can also be done with the gas network, or by installing bypass water pipes on the street for the water network. In this methodology, such backup configurations cannot be accounted for directly in the level of service formulation, but if the costs for losses in level of service are chosen accordingly (i.e. by capturing the costs for these backup configurations), they can be included in the generation of the optimal work program as well, though this has not been done in this thesis.

The assumption of the conductivity being represented by a smooth[3] decreasing function relies on the fact that ageing only leads to decrease of the network-specific flow. However, for the water network, this is not necessary true in all cases. If the chemical parameters of the water change (for example a shift in pH value), the water can start as limestone-depositing, but with a shift in pH value, the limestone can then be re-solved in the water, and thus effectively increase the inner diameter again, which could lead to a higher conductivity. However, if this level of detail is investigated, the actual roughness of the pipe inside, as well as other effects, also should be considered. This however exceeds the level of detail that is possible to be used with this methodology due to calculation power demand, and as such the methodology can be seen as a reasonable approximation, that can be expanded if substantially more calculation power is available.

In the methodology, the flow in the networks is calculated based on the conductivity. For all networks except the road network, this represents the physical facts (however, with different names for conductivity in each network). For the road network, this assumption basically requires a Wardrop-type equilibrium in the network, which is only an approximation. The real flow in the road network is hard to calculate, as it is dependent on the decisions of the drivers of the vehicles. Nevertheless, approximations for road traffic flow on the network are used due to their shown applicability and utility, so this approach is also followed in this methodology.

## 8.5. Fitness function

The fitness function in this methodology is based on the assumption that everything necessary to calculate the "best" intervention program can be expressed as costs.

[3] if neither interventions nor interactions are present

For the intervention costs themselves, this is straightforward. For the costs related to the level of service, this is not so straightforward. The right choice of level of service consideration strongly depends on the choice of the cost function of level of service. In this methodology, the level of service costs can be split into two parts: 1) fixed costs for operating the network, and 2) costs that are depending on the service provided. With the right calculation of the numbers for the costs, this can be used to capture most setups for service provision. However, if contracts for service for example contain penalties for limited service, this has to be considered via logical functions, that check for condition fulfilment. Additionally, it can happen that is deemed "financially beneficial" to terminate service to certain households. In reality, this would not be possible due to legal obligation to provide, for example, water service. In this case, the cost function has been chosen poorly, as the cost function should account for such cases as well. However, this is not always possible as these costs are hard to determine. A possibility to mitigate this problem is the introduction of penalties for violation of such conditions. This adds "virtual cost" to the real cost, as the fitness is expressed as cost, and such a violation would cost "artificial money". Nevertheless, this helps to find an optimum by balancing out the effort to find real costs for the restriction violations with the approximated penalty costs.

## 8.6. Computational effort

The computational effort for this methodology is, as expected from the mathematical problem behind the optimisation, rather high. Nevertheless, the methodology allows reduction of calculation time. For example, due to the use of genetic algorithms, the computational task is parallelizable, as within one generation all chromosomes are independent and thus can be evaluated by multiple CPU cores at the same time. Additionally, as a lot of matrix operations are performed during the level of service calculation, additional GPU acceleration can be used to speed up the calculation. Finally, a lot of functions in the algorithm can be memoised[4] as well. Additionally, there is the possibility of simplification in the calculation functions. This is of course coupled to a potential loss in accuracy. Nevertheless, the genetic algorithm setup allows a quick estimation of runtime per generation, and as such the calculation time can be estimated upfront, with then performing simplifications until an acceptable runtime is reached.

[4]memoization: a technique that trades computational time for memory demand

## 8.7. Practical implementation

The methodology has been demonstrated on a real-world-data based example. However, in order to be implemented in practice, further steps would have to be taken. The example is based on simplifications, which, although being used in practice, might not be applicable to certain network (areas). For example, the traffic was calculated using a Wardrop-type equilibrium. While this type of equilibrium is being successfully used in certain parts of traffic flow calculation, it is also well understood that certain traffic phenomena cannot be captured by it. This is conceptually also true for the other networks. It would, therefore, be necessary to check the network, where this methodology would be applied for situations, where the used simplifications are not sufficiently representing the dominating phenomena. If such areas in the network were identified, the simplified equations would have to be exchanged for equations that improve the accuracy. This however comes at an increased computational cost. Additionally, the level of service definition examples, which were given in 2.3, might be adapted to the level of service goals that were defined for that specific network, as these goals can be influenced by legal, regulatorial or contractual boundaries, which are specific to the location (i.e. country, state, city, etc.) of the network. It also would be necessary to adapt the deterioration, conductivity and transmission functions (including transmission hierarchy), to the data availability (i.e. if more detailed deterioration and conductivity functions are available, they can be used instead of generic functions). With that changes being taken into account, and with sufficient computational power available, the methodology can be applied to a real network.

The methodology at the moment only accounts for interactions between the networks themselves. It is possible, however, to extend the methodology to also account for third-party damages (i.e. interactions with objects that are not part of any of the networks investigated). This can be done by adapting the penalty function (Eq. 5.38) in order to impose higher penalties for objects that are in certain areas (that would for example be vulnerable to object failure). The amount of penalty imposed could be calculated using risk-based methods.

## 8.8. Summary

Summarising, the methodology presents a way to combine intervention planning over multiple networks with multiple time steps and with consideration of level of service. The methodology is able to construct intervention programs for multiple infrastructure networks jointly, by using a combined dynamic spatiotemporal neighbourhood approach. The methodology is set up in a modular way that allows the exchange of computational models (e.g. for flow calculation) in order to adapt the computation to the data availability (i.e. if a certain computational model requires unavailable data, it can be exchanged for another model, that only requires available data). The methodology is able to integrate in the actual intervention planning process, as due to the iterative process formulation, the methodology can be applied to improve the already performed manual iterations. An example application was performed on a small urban region in order to demonstrate the real-world applicability. The example shows that there is a benefit to be generated by executing interventions together. The results also demonstrate that the methodology is able to account for cluster setup costs and is able to determine if grouping is recommended in terms of these costs. The phenomena found during the example application can easily be explained by the available data. Therefore, the example application can be seen as successful, and thus the methodology is regarded as applicable for the real world, as well as addressing the aims set in the introduction.

# 9. Outlook

The methodology presented in this thesis contributes to providing infrastructure managers with a better way to generate optimal intervention programs for multiple networks with multiple time steps and with consideration of level of service. With this, a number of real world problems can be solved, as stated in the introduction and conclusion. However, for the sake of keeping the computational demand at an acceptable level, certain simplifications have been made, that are suggested by the relevant literature, as shown in the literature review. Nonetheless, with computational power availability steadily increasing, there are still improvements possible that can further foster the applicability of the presented methodology. Improvements can be foreseen in two directions: 1) validation improvements, that analyse the range of validity for the taken assumptions and 2) extension improvements, that address issues that have not been taken into account.

## 9.1. Validation improvements

For the validation improvements, future work can compare the traffic flow equations with advanced, though computationally intensive agent-based traffic models to check for certain situations where the Wardrop type-equilibrium is not accurate enough. This would allow to further strengthen the degree of trust in the quality of the estimation of traffic effects on the level of service.

Additionally, the flow simulation can also be compared with advanced simulation algorithms. This would allow, to account for certain phenomena where flow deviates from the flow calculated by the simplified models (which are, as shown in the literature review in Chapter 2, well rooted), in order to improve the accuracy of the calculated level of service. Additionally, a comparison searching for situations where the flow deviates from the flow calculated by the simplified models could improve knowledge about if and where these situations exist during normal operation or just in special situations.

As mentioned in the discussion section, the level of service is approximated by using the assumptions proposed in the mathematical formulation in chapter 5, which are backed by the literature presented in chapter 2. Nevertheless, these approximations could be tested in order to give more information about the range of validity, i.e. in which cases the approximations can be used to give information in the required accuracy, and in which cases an in-depth analysis is needed in order to have an appropriate accuracy. This would improve the range of validity, and thus demonstrate further the range of applicability for the methodology.

A comparative study with other methodologies to generate optimal intervention programs could also be of interest for future research to measure the benefit of grouping interventions taking into account the computational demand as well. Additionally, provided that the computational power is sufficient, the example could be extended to a larger urban area, for example the whole urban area of which the example is a section of.

For validation, it would also be nice to test the process on a "sensed" network, i.e. a network that is tightly monitored by various sensors in order to compare the simulated results with the measured values. In conjunction with artificial intelligence and learning algorithms, this would provide both validation and new insights due to the results expected from analysing the learning algorithm outcomes.

## 9.2. Extension improvements

In terms of extension of the presented methodology, it has been assumed that the different infrastructure networks do have the same owner. However, it might be that the infrastructure networks are owned by different entities, and such there is a need to justify the coordination between those entities. Here, a future extension of the methodology could include a cost-benefit analysis tool that 1) directly points out the benefits of grouping to the respective infrastructure managers, and 2) is also able to provide a way of modifying the grouping rules so that the infrastructure managers can test for themselves, in which way grouping is beneficial.

A second extension would be testing of potential simplifications in order to develop a cost-benefit chart of certain calculational models (with cost in this context being understood as calculational cost). This could help further reducing the calculation time with less loss in accuracy.

Another future extension could be the introduction of multi-attribute fitness, i.e. combining different goals into the fitness, such as reliability or a certain safety reserve. At the moment, these have to be included by assigning costs to these attributes, so that they can then be compared with the intervention costs. However, it might be easier in certain cases to state e.g. safety reserve goals directly, than calculating the according costs. Therefore, an extension could add the possibility of including multiple goals, however at the cost of a set of non-inferior results instead of a single optimum in some cases, depending on the type of goals.

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# A. Appendix

The appendix is, due to size, provided in digital form.