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Introduction

1.1 • Background

This thesis seeks to combine two different research topics; Multi-Objective Optimization and Complex Network Analysis.

Multi-Objective Optimization aims at finding a set of optimal, non-dominated solutions for optimization problems with multiple (actually, many) conflicting objectives. There is a wide range of applications of multi-objective optimization such as in science, engineering design, network analysis, chemical processes, delivery of products, economics and logistics, medical health and so forth. Since one often faces problems with a larger number of objective functions to be optimized simultaneously, the research topic has shifted to Many-Objective Optimization, which means optimization with (far) more than three objective functions.

Complex network analysis is a research field that deals with analyzing large networks. In this research line, there are some active research topics, such as controlling complex networks, finding communities in a network, and measuring the importance of nodes in networks. Due to the bigger amount of data and more difficult problems arising in complex network analysis, research in this field has increased significantly. To this end, more complex networks has given the challenge of finding better approaches in dealing with the problem to yield some adequate result of an analysis. One active research relating to this problem is known as multiplex network analysis. This is the study of networks that feature different layers of edges for the same set of nodes.

Furthermore, the research in this thesis try to combine many-objective optimization and complex network analysis. The idea is to attain a benefit for many-objective optimization by applying complex network analysis techniques and the other way around,i.e, to apply many-objective optimization for complex network analysis. Finally, both approaches are combined with an additional contribution to data mining, knowledge discovery and decision analysis.

1.2 • Research Goal and Contribution of this Thesis

The main goal of this research is to study how the fields of complex network analysis and many-objective optimization can benefit from each other.

The first part of this thesis is concerned with using a complex network analysis technique (community detection) for the purpose of many-objective optimization, specifically for visualizing and reducing complexity of many-objective optimization problems. The example of a facility location problem in a city is used in order to demonstrate the applicability and scalability of the approach. Moreover, we study many-objective optimization problems in genetic engineering and complex system design, when multiple traits should be changed to a desired value at the same time. In this study, depending on the structure and intensity of interaction among genes, a complexity transition from simple problems to very difficult problems can be observed. The NK-landscapes model is used as an abstraction of a system of interacting genes (or agents) and by controlling the number of epistatic genes and the radius of interaction the complexity of the problem can be controlled.

The second part deals with applying many-objective optimization for complex network analysis. This part includes the study of modularity- and centrality maximization for multiplex networks, and the combinatorial optimization problem of selecting subsets of nodes to be controlled/immunized when the goal is to prevent the spread of an epidemic throughout the network.

The data used in the experiments is real-world data related to international trade economic, European flight networks, US flight networks, datasets from the UCI network repository, and artificial networks made to resemble real data. In the study with multiplex networks, the network consist of many layers and each layer gives rise to an objective function. Analyzing them in one unity will give an integral depiction on how the network layers correspond with each other. Moreover, this method will help to detect commonalities between clusters and node centrality in the network layers and thereby help to group them in a meaningful manner. For this purpose, since the network consists of many layers, applying many-objective optimizations is the proper approach. Optimization for all layers of the network will be done simultaneously.

1.3 · Thesis Outline

This thesis consists of eight chapters. The main research result are discussed in Chapter 3,4,5,6 and 7 and divided into two main parts. Part I is composed of Chapter 3 and 4 and part II includes Chapter 5, 6 and 7. Their content is corresponds to the scientific publications that related from the research conducted by the author of this thesis. In the following a brief description of the outline is provided:

- Chapter 2 presents all theoretical preliminaries and definitions for the topics that will be discussed in the subsequent chapters. It includes the definition of multi- and many-objective optimization, network clustering and community detection, network centrality, multiplex networks, and correlation analysis.

- Chapter 3 discusses the use of complex network analysis techniques for reducing complexity in many objective optimizations. This approach is achieved by decomposing many objective functions into a set of independent lower dimensional subproblems, or by aggregating some objective functions into a single objective function. This work introduces a technique from social network analysis for decomposition and aggregation of a system of objective functions. The key idea is to interpret an objective function as a node (agent) in a social network, and a link between nodes to indicate relationships: Negatively weighted links stand for conflicting objectives, zero weighted links for independent objectives, and positively weighted links for objectives that support each other. Using well-known algorithms for community detection it can be shown that, given certain preconditions, it is possible to decompose a many-objective optimization problem into a set of lower dimensional multi-objective optimization problems. This makes it easier to solve the problem and interpret the resulting trade-off (hyper-)surfaces.
  Publication:
  Asep Maulana, Zhongzhou Jiang, Jing Liu, Thomas Bäck, and Michael TM Emmerich. "Reducing complexity in many objective optimization using community

detection." In Evolutionary Computation (CEC), 2015 IEEE Congress on, pp. 3140-3147. IEEE, 2015.

- Chapter 4 presents the empirical study of complexity transitions in interactive networks using community detection techniques. In this research, we investigate NK-landscape models. They are models of the interaction of genes or agents in a network resulting in levels of expression of different phenotypic traits that further cumulate to the overall fitness of the network. We study the phenotypic trait expression levels from the perspective of communities and community detection. The communities are based on the correlation between the phenotypic traits. A single trait illustrates an individual agent which strives to maximize its contributed value to the net value of a community. If high values of one trait occur simultaneously with high values of other traits it regards the traits as high correlated or as supporting each other, and if the value of two traits is uncorrelated, it views their relationship as being neutral, otherwise as conflicting. The work studies what happens to the system of traits when the NK-landscape undergoes a critical transition to a more complex model via the increment of the number of interacting genes and the change of the radius of gene interaction.
  Publication:
  Asep Maulana, André H. Deutz, Erik Schultes, and Michael TM Emmerich. "Community Detection in NK Landscapes-An Empirical Study of Complexity Transitions in Interactive Networks." In EVOLVE-A Bridge between Probability, Set Oriented Numerics, and Evolutionary Computation VI, pp. 163-176. Springer, Cham, 2018.

- Chapter 5 shows how to apply many-objective optimization for the analysis of multiplex networks. The work applies different ways for analyzing the community structure in multilayer networks, all relying upon data from many-objective optimization. The first study is a proof of concept that seeks to understand the meaning of the Pareto fronts between modularities of different layers by exact computations of Pareto fronts on three illustrative examples (highly correlated, uncorrelated, and conflicting), which represent important boundary cases. The second step is a study and experiment using trade networks for commodities, by generating data using many-objective optimization, bi-objective optimization (of any pair of layers), and single objective optimization (of any single layer). The

results are analyzed using three tools suggested here: Correlation heatmap, the community of objectives analysis, and the Pareto-front plot matrix. The result shows clearly that a grouping emerges in terms of complementarity and/or in terms of neutrality. As a result, a novel, powerful analysis method for clustering in multilayer networks is proposed. In order to tackle the combinatorial problem, the study and experiment applies state-of-the-art multi-objective optimization algorithms, i.e, the Non-dominated Sorting Genetic Algorithm II (NSGA-II), S-Metric Selection Evolutionary Multi-objective Optimization Algorithm (SMS-EMOA), and a single-objective genetic algorithm.
Publication:

Asep Maulana, Gemmetto, V., Garlaschelli, D., Yevesyeva, I., and Emmerich, M. (2016, December). Modularities maximization in multiplex network analysis using many-objective optimization. In Computational Intelligence (SSCI), 2016 IEEE Symposium Series on (pp. 1-8). IEEE.

Asep Maulana and Michael Emmerich. "Multi-Objective Optimization Approach for Multi-Layers Network Analysis". International conference in Multiple Criteria Decision Making (MCDM) 2017. Page 136, MCDM Society.

Asep Maulana, Gemmetto, V., Garlaschelli, D., Yevesyeva, I., and Emmerich, M. (2016, October). Computing Pareto Fronts of Modularities in Multiplex Economic Network Analysis In International Conference on ENTERprise Information System(CENTERIS), Porto, Portugal, October 2016.

- Chapter 6 presents another many-objective optimization for multiplex networks. Different to the previous chapter, the goal here is to apply it for centrality maximization. In particular, the focus is on the important case of eigenvector centrality. It starts by discussing eigenvector centrality in multiplex networks for the examples of Erdős Rényi random graphs and economic trade networks. Secondly, the non-dominated solutions of the entire network can be computed, the dominance rank for all solutions. In the example of the trade multiplex network, the dominance rank is a rough indicator of how important a node is in the global trade network across different commodities.
  Publication :

Asep Maulana, Michael T. M. Emmerich. "Towards many-objective optimization of eigenvector centrality in multiplex networks." Proc. of IEEE International Conference on Control Decision and Information Technology (CoDIT) April 2017: 729-734, IEEE.

- Chapter 7 presents studies of network immunization: The immunization of complex networks can be formulated as a subset selection problem, where the goal is to select a limited number of nodes to be immunized in order to effectively prevent or decelerate the spread of an epidemic. The drop of the largest eigenvalue (also referred to as 'eigen-drop') is a measure of the impact of an immunization strategy, because it is inversely related to the increase of the critical threshold. The critical threshold decides whether a virus resides in the network or evaporates. It was recently shown that the problem of selecting k out of n nodes from a network such that the eigenvalue drop is maximum belongs to the class of NP-hard problems. Heuristic algorithms have been suggested to solve these problems approximately, most importantly the Netshield algorithm, a greedy approach that approximates the eigenvalue drop by means of a submodular function, the *shield value*, and then maximizes the shield value by means of a greedy approximation algorithm. In this chapter, the topic is to develop and test a problem specific genetic algorithm and compare it to Netshield Plus – an improved variant of Netshield – and show that on six moderate size problems from literature their performance is competitive, and often better.
  Publication:
  Asep Maulana, Marios Kefalas and Michael T.M. Emmerich, "Immunization of Networks Using Genetic Algorithms and Multiobjective Metaheuristics.", Proceedings of IEEE Symposium Series of Computational Intelligence (SSCI) November 27, to December 1, 2017, Honolulu USA, Page 1-8, IEEE.

- Chapter 8 summarizes results of the thesis and provides ideas and promising directions and suggestion for the future work. During the time of the thesis the author also contributed algorithms and analysis techniques which are closely related to the main topic of the thesis, such as group decision making and multi-label classification. It is discussed, how these topics can be further explored and related to the thesis in the future work. These ideas and related works are partially published in the following research articles:

Zhao, J., Fernandes, V. B., Jiao, L., Yevseyeva, I., Maulana, A., Li, R., Emmerich, M. T. Multiobjective optimization of classifiers by means of 3D convex-hull-based evolutionary algorithms. Information Sciences, 367, 80-104, 2016.

Emmerich, Michael, André Deutz, Longmei Li, Asep Maulana, and Iryna Yevseyeva. "Maximizing Consensus in Portfolio Selection in Multicriteria Group Decision Making." Procedia Computer Science 100, 848-855, 2016.