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An Approach to Optical Network Design Using General Heuristic Optimization Framework

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Abstract

The article deals with the problem of optimization methods in the optical network design process, based on optimal traffic routing aimed at minimizing the utilized network resources for a given topology and traffic demands. An optimization framework ***Nyx*** has been developed with the focus on flexibility in solving optimization problems by implementing general heuristic search techniques. ***Nyx*** modular organization has been described, including coding types for solutions and a genetic algorithm as the optimization method. Optimal routing has been implemented to demonstrate the use of ***Nyx*** in the optical network design process. The optimal routing procedure has been applied to the Pan-European optical network with variations of routing procedures and the number of wavelengths. The analysis included a no-protection scenario, 1+1 protection and path restoration. The routing was performed using the shortest path routing and optimal routing, which minimizes the use of optical network resources, such as network multiplexers, amplifiers and fibers.

Keywords: General Heuristic Methods; Routing and Wavelength Assignment; optical network design

1. Introduction

One of the main issues of optical network design is the use of network resources so that each traffic demand can be supported at a minimal cost. The optimal solution includes the process of attributing physical paths to traffic demands. Additionally, in a no wavelength conversion environment, path selection is supplemented with a selection of wavelengths that will be attributed to each traffic demand. This problem will be referred to as optical traffic routing in this article. It belongs to the class of non-polynomial complex problems routing and wavelength assignment (RWA) problems [18] (for routing problems refer to pp. 61-97, for wavelength assignment problem to pp. 127-141) [1][14].

The optimal traffic routing has two main variations, one of which is static, assuming that the traffic demands are known in advance, i.e. before network dimensioning, and the other one dynamic, assuming that connection requests arrive after the network has been dimensioned. In this paper we will analyze the static variation.

Static optimal traffic routing is considered to be an NP-hard optimization problem, which is a special case of the integer multicommodity flow (MCF) problem with additional constraints (an overview of approaches to solving static optimal traffic routing can be found in [19]).

This kind of problem implies two possible solutions. The first one is to tailor a heuristic search technique through analysis of the problem, which requires a lot of time resources. The second possibility is to apply one of the general heuristic search techniques, which drastically reduces time to vigorously analyze the problem and its search space. Simulated annealing [8] and genetic algorithm [2] are some examples of these search techniques.

Two facts apply to modern heuristic search techniques [16]. They work with encoded solutions, not the solutions themselves, and they need only a fitness function to define their search. The term ‘general’ means that the algorithm itself contains no knowledge related to a specific problem. Their search for optimal solutions is based on guided random search, derived from natural processes.

The latter approach has motivated the development of the optimization framework which would enable problem solution with a small programming effort. We have developed such a tool, called ***Nyx***, which offers great flexibility in solving any kind of problem. The basic concept of the optimization kernel ***Nyx*** is the rapid development of applications for solving any kind of optimization problem for complex systems. The RWA problem will be modeled using ***Nyx*** with a detailed description of all steps.

The second section of the article introduces the modular organization of ***Nyx***, including the description of three module types, and the structure of optimization methods. The problem of optimal routing in optical networks is defined in the third section, with discussions on problem complexity, modeling of routing and wavelengths assignment, and construction of a fitness function. The modeled problem is applied to the Pan European Network test case described in the fourth section, along with the numerical results, with a focus on the placement efficiency of traffic demands in the network. The last section of the article contains final comments and conclusion.

2. Modular Organization of *Nyx*

The ***Nyx*** optimization kernel is composed of three main modules:

- *Problem module* (PM) – implementation of fitness (goal) function of a particular problem using a selected coding type and setting optimization module parameters,
- *Optimization module* (OM) – implementation of a general optimization procedure, or optimization function which calls the fitness function of a particular problem module,
- *User Interface Module* (UIM) – setting and reading of parameters of problem and optimization, control, management and display of the optimization state, showing details and decoding of a particular solution.

The coding type is the optimization problem representation suitable for various optimization methods. The user has to choose the appropriate coding type that will best describe the solution of a stated problem. After selecting the coding type, the user can choose various optimization methods. The ***Nyx*** optimization kernel implements three basic coding types:

- *Binary* – solution is coded as a binary stream,
- *Integer* – solution is coded as a nonnegative integer stream. A minimum (often 1) and maximum value is defined for each member of the code word,
- *Permutation integer* – solution is coded as a nonnegative integer stream. All numbers in the solution have to be different.

Functional relationships and communication between ***Nyx*** modules are shown in Figure 1.

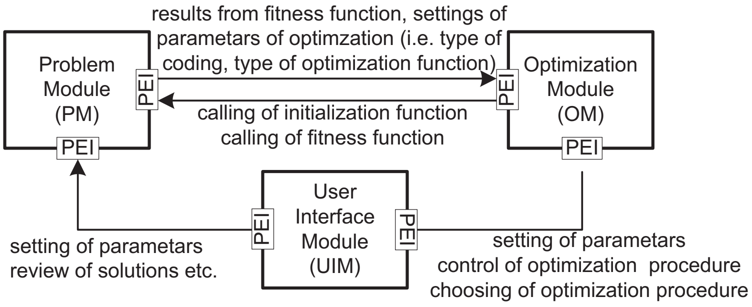


Figure 1. Basic ***Nyx*** modules functions and communication between modules

The optimization module communicates with problem modules using the fitness function. The fitness function retrieves a possible solution only in the coded form. The coded solution can be interpreted only by the problem module, and it has no meaning for the optimization module. Therefore, the optimization module connects the coded solution with its fitness function, and generates a next possible solution. The user has to define the coding type, by using some built-in codings, or tailoring a custom made coding suitable for a particular problem.

Modules communicate through Property Exchange Interfaces (PEI). PEI implement procedures for setting the values of parameters defined within modules.

2.1. Description of Modules

2.1.1. Problem Module (PM)

The problem module is a user defined module which contains knowledge on a problem subject intended for optimization. The main function of this module is to implement the fitness function for a specific problem. OM communicates with PM by calling the fitness function. The fitness function takes a possible solution in the coded form as the only parameter, connecting the coded solution to its fitness function. Using this information PM generates next possible solution. The user has to define the solution coding type. Some of the built-in codings can be used (e.g. binary, stream of charts and stream of numbers), or the user has to build their own coding type suitable for the analyzed problem.

Nyx contains a catalog of implemented problems recording how the ***Nyx*** optimization kernel was implemented as a set of optimization modules and user defined problems. Each new implemented problem has to be registered in this catalog.

2.1.2. Optimization Module (OM)

The optimization module (OM) contains the implementation of various general optimization methods. The term ‘general’ means that the method is independent of the problem type. Each method is defined using some coding type (type of representation of solutions), and uses particular methods. After creating a problem module, and choosing a coding type, user registers a PM. After that the user gets a set of optimization methods which can solve the created problem. An appropriate set of methods is offered to the user. This is possible due to registration of optimization methods in the catalog with the coding type as the search key. This concept is illustrated in Figure 2.

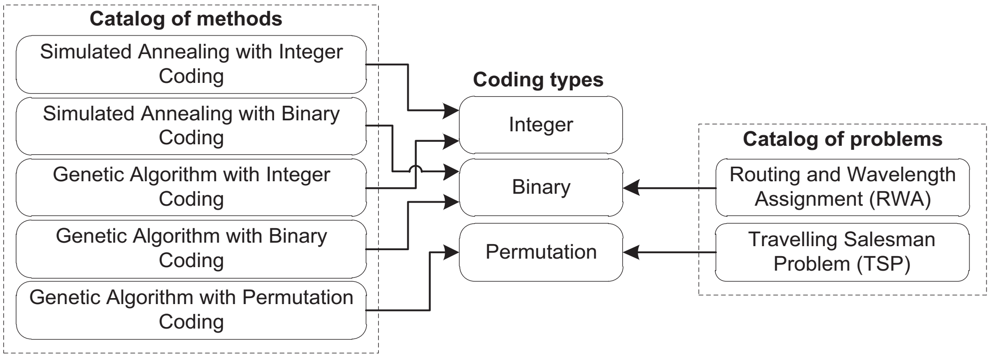


Figure 2. Relationship between problems and methods

Figure 2 shows that the *TSP* problem uses permutation coding and that this problem can only be solved by a genetic algorithm with permutation coding. On the other side, the *RWA* problem can be solved by two optimization methods: simulated annealing with binary coding and a genetic algorithm with binary coding. All methods inside the optimization kernel must be registered in the catalog of methods, similar to problem modules.

2.1.3. User interface module (UIM)

PM and OM parameters can be set and read through the UIM module. UIM retrieves a dynamic list of parameters through PEI, which enables search by parameter names. After finding a parameter, UIM calls the appropriate method in PEI to access that parameter.

2.2. Optimization Methods

The genetic algorithm (GA) is the optimization method based on the biological evolution process. This is a heuristic method implying that the quality of the produced solution depends of many parameters. GA works with coded solutions, each representing one chromosome composed of genes. Following the evolution process, GA method implements three operators with defined parameters:

- *crossover* – crossover of chromosomes (type of crossover, probability and number of crossover points),
- *mutation* – mutation of chromosomes (mutation probability), and
- *selection* – selects solutions for next generation (selection technique and size of population).

A genetic algorithm starts with the creation of an initial set of solutions and sequential application of described operators until some criteria are satisfied.

Enumeration is another method implemented in the ***Nyx*** kernel. This method checks all possible solutions and finds a global optimum. It is thus unusable for a problem with a large solution set and it is usually used for checking the difference between the optimal solution and (sub)optimal solutions offered by heuristic methods.

Before the creation of a user problem module, a choice of suitable optimization methods and the coding type from the ***Nyx*** kernel has to be made. There are two possible approaches:

1. User can use the existing coding in the kernel;
2. User can define their own coding type.

3. Optimal Traffic Routing in Optical Network

The optimal traffic routing defined within this paper minimizes the utilized network resources, with the traffic characteristics defined in advance and the network resources (number of available wavelengths) restricted per each link. This problem is often denoted as the Max-RWA problem. The authors in [14] give the ILP formulation for the Max-RWA, using the LP relaxation to obtain an upper bound on the traffic that can be routed and using this bound as a reference metric to evaluate a shortest-path RWA heuristic algorithm. The same problem is examined in [17], where the authors prove that the upper bound can be computed exactly by solving a significantly simplified LP that considers only one wavelength. In [9] the authors provide two ILP formulations for the Max-RWA problem that are based on multicommodity flow (MCF) formulations. To obtain results for large networks they describe two algorithms that are based on the relaxed linear formulations combined with proper rounding techniques.

Alternatively, the same problem can be defined as the problem of minimizing the number of wavelengths to serve a given set of connections. This is often denoted as the Min-RWA problem [1]. The referenced work gives an ILP formulation and decomposes the problem into the routing and the wavelength assignment subproblems, which are solved sequentially. The Max-RWA problem discussed in this paper is also often solved sequentially, mostly in order to make the problem more computationally feasible [3]. Various efficient heuristics have been lately developed for both routing and wavelength assignment that can be combined to produce solutions for the joint RWA problem [10], [23]. However, such decomposition suffers from the drawback that the optimal solution of the (joint) RWA problem may not be included in the solutions provided by the decomposed algorithms.

One of possible approaches to the routing problem is to route traffic demands using the shortest path routing, after which the selected optimization procedure assigns a wavelength to each wavelength path. The drawback of this solution is the limitation of the possible solution space. Namely, some network links can turn out to be underused, and some overloaded, making the solution suboptimal in terms of minimization of the required number of fibers. The idea is to use a heuristic method (e.g. genetic algorithm, simulated annealing, etc.) to search numerous network configurations regarding routing, and to assign wavelengths for each one. Each solution is evaluated considering required network characteristics, as depicted in Figure 3.

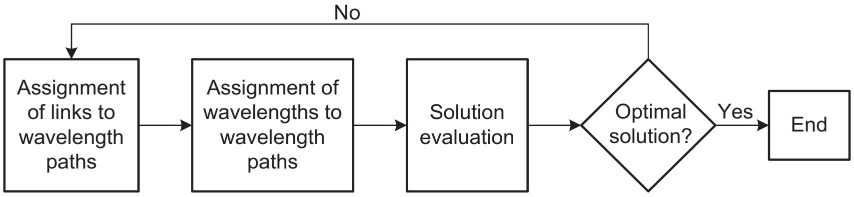


Figure 3. Procedure for Finding Optimal Solution

This part describes in detail the solution for optimal routing and wavelength assignment. These two subproblems are mutually dependent, and will be jointly solved in this approach.

3.1. Problem Formulation, Assumptions and Complexity

The problem is defined as the selection of optimal routing in the optical network. It is assumed that traffic demands are given between node pairs (as a required number of wavelengths) and network topology. Each required wavelength will be served by one wavelength path if a demand is unidirectional, or by two wavelength paths in the case of bidirectional demand. The number of wavelength paths will be larger if some resilience mechanism is used.

For each wavelength path a tuple has to be selected, including:

- Set of nodes and links that it will transverse, and
- Wavelengths that will be assigned to that communication.

The number of possible combinations of nodes and links that can be assigned to a certain demand is equal to the number of all possible paths between the selected pair of communicating nodes. We can use this conclusion to calculate the number of configurations in the entire network which depends on the network connectivity and the used resilience mechanism. The total number of possible configurations for the network without protection is equal to

$$N = \prod_{i=0}^{i=N-1} \prod_{j=i+1}^{j=N} np_{ij}^{w(i,j)}, \tag{1}$$

where np_{ij} denotes the number of possible paths between the pair of nodes i and j, while $w(i,j)$ denotes the number of demands expressed as number of required wavelength channels. It is evident that N depends on the network topology since network connectivity defines the values of the elements within the product, as well as on required wavelength channels that define the exponents. In case of photonic protection each wavelength channel has a primary and a spare path. The number of possible network configurations is calculated using the upper equation, where np_{ij} represents the number of possible pairs of primary and spare paths between nodes i and j.

In order to calculate the number of primary and spare paths between two nodes it is necessary to determine the relation between primary and spare path. It is clear that the failure of the primary path must not influence the spare path. Therefore, the spare path has to be selected so that it does not have common physical elements with the primary path. This requirement can be simplified into a requirement which states that primary and spare paths do not have common links, assuming that link failure probability is much greater than node failure probability.

Table 1 depicts the dependence of the number of possible configurations N for network with and without protection on the number of nodes with the assumption that each pair of nodes uses two wavelength channels for communication.

It is evident from Table 1 that number of possible network configurations increases rapidly with the increase of the number of nodes. The problem arises when one of these configurations has to be selected so that the network performances are optimal. The number of network configurations can be drastically reduced if we take into account characteristics and limitations of basic optical components, such as optical amplifiers, wavelength converters and multiplexers/demultiplexers. For example, only those paths that do not exceed selected length or selected number of nodes can be examined. Even with this reduction, the number of possible solutions remains too high for the enumeration methods to be used, forcing the use of heuristic methods. Optimal routing, besides the selection of the path for each wavelength channel, hence includes the problem of realization of these wavelength channels by using wavelengths.

Number of nodes	**no protection**		**with protection**		**Node pairs**
	Number of paths (np_{ij})	**Number of configurations (N)**	**Number of paths (np_{ij})**	**Number of configurations (N)**	
3	2	$(2^3)^2 \approx 10^2$	1	$(1^3)^2 \approx 1$	3
4	5	$(5^6)^2 \approx 10^8$	10	$(10^6)^2 \approx 10^{12}$	6
5	16	$(16^{10})^2 \approx 10^{24}$	84	$(84^{10})^2 \approx 10^{38}$	10
6	65	$(65^{15})^2 \approx 10^{54}$	1100	$(1100^{15})^2 \approx 10^{91}$	15

Table 1. Dependence of number of possible network configurations on number of nodes

For each wavelength channel it is necessary to assure optical fibers that will propagate the optical signal from the source to the destination node. A wavelength channel can use one or more wavelengths depending on whether a network uses wavelength converters or not. Wavelength path that uses several wavelengths is denoted as a virtual wavelength path. The main problem of assigning wavelengths to wavelength paths is the requirement that two wavelength channels in the same fiber must have different wavelengths. One of the ways to achieve this is to use wavelength converters, which can reduce the total required number of wavelengths. The number of possible wavelength assignments in the optical network without wavelength conversion is equal to

$$N = \left(N_\lambda\right)^w, \tag{2}$$

where w denotes the total number of wavelength paths, and N_λ the maximum number of wavelengths per optical fiber.

In case that the wavelength assignment procedure assigns more than N_λ channels to one link, more links have to be added to that cable. It is clear that each network configuration in terms of the number of required wavelengths defines the number of required fibers, multiplexers and demultiplexers. The implementation of the described problem in ***Nyx*** will be described in next section. It is assumed that the network does not employ wavelength converters and that it has symmetrical traffic demands.

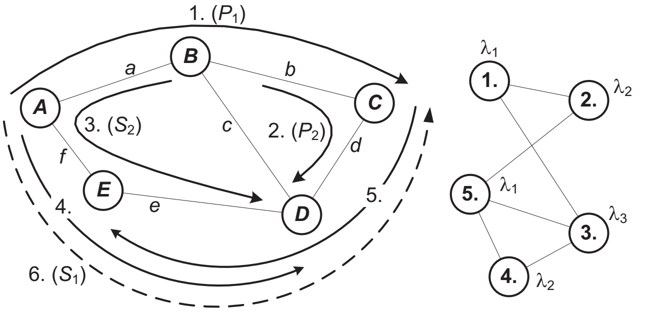
3.2. Optimal Wavelength Assignment

The goal of the optimal assignment of wavelengths to wavelength paths is to minimize the number of used wavelengths. This approach assures a minimum number of used fibers, which minimizes network cost. The wavelength assignment procedure depends on:

- Temporal and physical relationship between wavelength channels, and
- Maximum number of wavelengths per optical fiber.

The relationship domain between wavelength paths in the physical domain can be analyzed by comparing sets of physical network elements used by those wavelength paths. Two wavelength paths which do not share any physical elements can be denoted as independent paths in the physical domain. The same wavelength can be attributed to independent paths. Temporal relationship between two wavelength paths implies the possibility of their existence (usage) at the same point of time. Wavelength paths which cannot exist (be used) at the same time can be denoted as (time) disjoint. Wavelength paths' disjointness will depend on the resilience mechanism used in the network. Figure 4 illustrates the difference between independent and disjoint wavelength channels, with the assumed path restoration and 1+1 protection [22], which will be further analyzed in this paper.

1+1 protection assumes that each primary communication channel has a dedicated protection communication channel. Path restoration, on the other hand, allows that the protection communication channel is shared in its physical segments among several primary communication channels, with the condition that those primary channels cannot fail at the same point in time. There are several variations of analysis scenarios. The most common are 1:1 protection, a modification of 1+1 protection, which allows the dedicated spare path to be used by lower priority traffic, until the working path fails. This scenario, which reduces the high capacity demands of 1+1 scenario, can be implemented in the ***Nyx*** tool in the same way as the 1+1 scenario. The reason for that is the fact that lower-priority traffic can be put on each spare path, assuming that 1+1 communication does not utilize both primary and spare communication path at the same time, which has not been observed in this paper. Another modification is the 1:*N* protection scenario, assuming that one spare path is used by *N* primary paths. This is basically the simplification of the path restoration scenario, assuming that there is one fixed spare path shared among *N* independent primary paths [15].



Routing

Assignment of Wavelengths

Wav. path pair	1+1 prot.		Path rest.	
	Dis.	**Ind.**	**Dis.**	**Ind.**
P_1, S_1	×	√	√	√
P_1, P_2	×	×	×	×
P_1, S_2	×	×	×	×
P_2, S_1	×	√	×	√
P_2, S_2	×	√	√	√
S_1, S_2	×	×	×	×

Figure 4. Routing and Assignment of Wavelengths to Wavelength Paths

The following analysis relates 1+1 protection and path restoration scenarios with the conditions of independence and disjointness.

For the 1+1 protection scenario none of the wavelength path pairs contain disjoint elements, as primary and their corresponding spare paths are used at the same time. Paths P_1 and S_1 are independent as they do not share any physical elements, while paths P_1 and P_2 share link *b*. The restoration mechanism assumes the use of the spare wavelength path only in the case of primary path failure. Each primary and associated spare path must therefore be independent. The test of physical independence is the same as the test of the 1+1 protection case. For the path restoration scenario it is important to test if two spare paths are disjoint as well, because in that case they can share some physical elements. This test is based on the analysis of the independence of their primary paths and the assumption that a failure at a point in time cannot affect two independent primary paths, which implies independence of their spare paths. Primary and spare paths are disjoint if only the failure of the primary path activates the use of the spare path.

It is necessary to analyze disjointedness and independence of wavelength paths in order to assign wavelengths. We will use a perfect node scenario, assuming that link failures have a dominant influence on communication availability. In that case the independence of communication paths is influenced only by common links. This is a consequence of the field measured reliability data for optical components and optical cables, which shows that the optical cables and optical transponders (lasers and modulators) are the components with lowest availability in the optical network. Sources like IEC TR 62380 (French telecommunications standard, formerly RDF 2000/UTE C 80-810) [6], MIL-HDBK-217 (US Department of Defense standard for the reliability prediction of electronic components), excerpts of which can be found in [12], or GJB/Z 299B (Chinese standard for the reliability prediction of electronic components), excerpts of which can be found in [11], state unavailability 100-300 fit/km (1 failure per 10^9 hours) for optical cable, 2000-5000 fit for external modulator, and 1000 -2000 for integrated laser modulator.

Assuming that communication paths are link independent, it can be concluded that they do not share the same transponder. The other optical components shared in the common node have significantly higher availability than the two mentioned components which are not shared.

It is necessary to assign different wavelengths to the primary and associated protection wavelength paths if they are independent but not disjoint. The same applies to two spare wavelength paths. Wavelengths are assigned after determining pairs of wavelength paths which must have a different wavelength. The optimization goal is to minimize the number of assigned wavelengths. The problem can be solved as a graph coloring problem with additional assumptions, or by using linear programming.

Graph coloring can be described as assigning colors to nodes in the graph so that two neighboring nodes do not have the same color. This problem can be solved by using the Largest First algorithm [4]. In the Largest First algorithm nodes in the graph $V(G) = \{v_1, v_2, \dots, v_n\}$ are sorted so that $\deg(v_i) \leq \deg(v_{i+1})$ for each $0 < i < n$, where n denotes total number of nodes, and $\deg(v_i)$ number of neighbors of each node in the graph (node degree). $V_1(G)$ denotes a set of colored nodes in the graph. Figure 5 depicts the phases of the graph coloring algorithm.

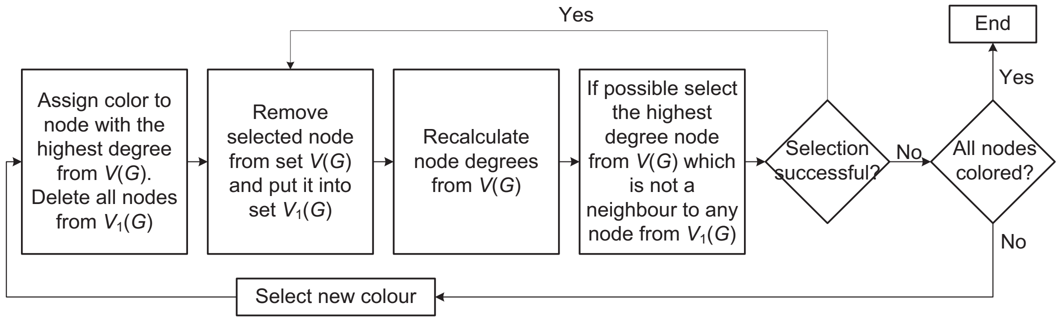


Figure 5. Graph Coloring Algorithm (Largest First)

The described algorithm can be applied to the assignment of wavelengths to wavelength paths, so that each wavelength path is represented as a node in the graph. It is also necessary to define which nodes are neighbors. Two neighbor nodes must not be of the same color. The color can be replaced by a wavelength, while two nodes are neighbors if they represent wavelength paths which are dependent and not disjoint.

Figure 4 also depicts the application of the described algorithm on the example of a simple network with denoted wavelength paths 1-5. The first step is to assign wavelength 1 to a node with the highest number of neighbors, being wavelength path 5. This is followed by the selection of node 1 (a highest degree node which is not a neighbor of node 5), which is assigned the same wavelength. After that it is not possible to find a node which is not a neighbor of node 1 or node 5 when wavelength 2 is selected. The algorithm assigns wavelength 2 to nodes 4 and 2, and wavelength 3 to node 3.

3.3. Modeling of Optimal Routing Problem in *Nyx* Optimization Kernel

The optimization kernel ***Nyx*** has heuristic methods which can be used to solve the described problem. Besides heuristic methods, ***Nyx*** has a user interface and a procedure for the optimization problem definition. After modeling of the optimization problem it is possible to run an optimization process by using any of the implemented heuristic methods of the optimization kernel. In next section the following phases in the definition of the problem module are described:

- Definition of problem module parameters,
- Creation of the initialization method,
- Creation of the fitness function, and
- Definition of methods for result representation.

The definition of the problem module parameters assumes the detection of all the key parameters that influence optimization and can be used to modify the problem. Important parameters for the optimal routing problem are a maximum number of wavelengths per fiber and the used protection mechanism. The purpose of the initialization method is the realization of the pre-optimization procedure, which loads various data needed for problem definition. For example, the connectivity matrix of the WDM network nodes has to be loaded before the optimization process starts. The fitness function assures a return value for optimization methods. It receives a possible coded solution from the optimization module, decodes it and calculates the solution quality based on the defined characteristics. For the optimal routing problem a measure of solution quality can be the total length of the installed optical fiber or their mean usage.

The last phase of the problem module modeling is the definition of methods for presentation of results obtained by the optimization process.

Following assumptions have been used to model an optimal routing problem:

- Each wavelength path has one assigned wavelength (no wavelength conversion);
- Symmetrical traffic demands between node pairs.

3.3.1. Problem Module Parameters

First step in the modeling of the optimal routing problem is the definition of parameters that can modify the module behavior:

- Maximum path length in the network,
- Maximum number of nodes that a wavelength path can transgress,
- Protection type,
- Optimization type (defines fitness function), and
- Number of paths to be analyzed.

Basic parameters which directly influence the optimization problem are optimization type and protection type. Optimization type defines what is to be optimized, i.e. directly influences the return value of the fitness function. It is possible to change the optimization goal by changing the return value of the fitness function.

Three optimization alternatives are assumed regarding the network cost, maximum fiber length, and link usage. The parameter protection type determines the type of protection used in the network. Three scenarios are analyzed in the network: no protection, 1+1 protection and path restoration.

The defined parameters limit the set of possible solutions to those which have a practical usage. This includes a maximum number of nodes that a wavelength path can transgress, maximum path length in the network and number of paths to be analyzed. The maximum number of nodes which a wavelength path can transgress is determined by signal degradation in intermediate nodes. The maximum path length in the network limits the maximum length of a wavelength path between a pair of nodes. The number of paths to be analyzed defines the maximum number of shortest paths between two nodes. By setting this parameter to 1 the routing and wavelength assignment problem is reduced to optimal wavelength assignment problem.

3.3.2. Solution Coding Procedure

The solution has to be presented in the coded form in order to enable the functioning of the optimization method for a given problem. The appropriate coding for the optimal routing problem can be selected if we analyze the wavelength path structure. Each wavelength path can be described as an array of nodes. We can attribute an integer to each node and hence describe a wavelength path as an array of integers. The paths are stored in this form within the path catalogue of the problem module. Each traffic demand can be realized using one or more wavelength paths, depending on the requested capacity. It is assumed that all wavelength paths that serve the same demand use the same physical paths. Hence it is more convenient to code each wavelength path as a number which corresponds to the position of the physical path in the catalogue of paths, while each physical path is coded as an array of integers. Figure 6 depicts the coding of paths in the network example given on the left. Assuming that this numeration starts from 0, and focusing on communication of a node pair (2, 3), index 0 would be attributed to path *e*, index 1 to path *b–c*, while path *b–a–d* would be attributed index 2. The described procedure has to be applied to every node pair and each wavelength path.

Figure 6 assumes that traffic demands for each node pair are equal to one wavelength channel, except pair (0, 3) which requires two wavelength channels. It is also assumed that the physical paths used by wavelength paths are given.

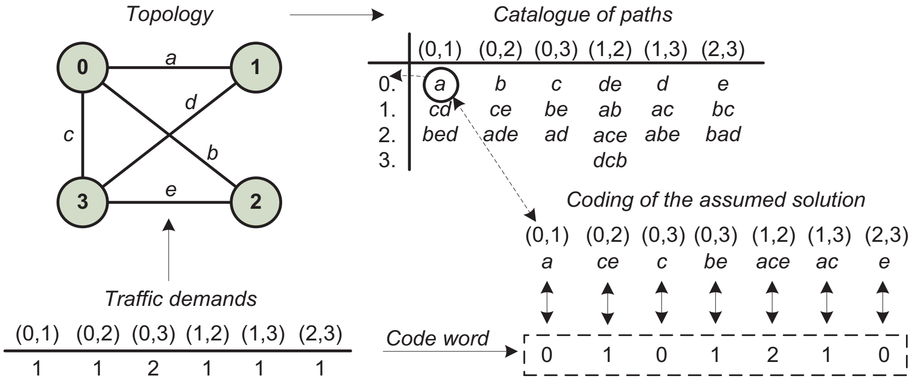


Figure 6. Coding of network paths

The fact that each traffic demand can have several wavelength channels implies that the coded solution can have greater length than the number of traffic demands. The path assigned to each wavelength channel is searched for in the catalogue of paths and then coded using the index (position in the column). For example, for path *a* the column (0, 1) has to be searched, while for the path *b–e* column (0, 3) has to be searched.

The coding is different for the protection case, as each wavelength channel assumes the use of the primary and the protection wavelength path. The catalogue of paths contains all possible pairs of primary and protection paths (Table 2) for the node pair where a wavelength path exists. A combination of positions of primary and protection paths is assigned to the traffic demand or wavelength paths that serve traffic demand. Table 2 depicts possible combinations of primary and protection paths, as well as one of the possible solutions for optimal routing.

The described examples imply that integer coding can be used in cases with and without protection. Maximum values that can be assigned to wavelength channels during coding do not have to be the same, so that the coding where maximum value of each item depends on the item position in the coded word has to be used. Such coding is implemented within the integer coding in the optimization kernel ***Nyx***.

	(0,1)		(0,2)		(0,3)		(0,3)		(1,2)		(1,3)		(2,3)	
	P	*S*	*P*	*S*	*P*	*S*	*P*	*S*	*P*	*S*	*P*	*S*	*P*	*S*
0.	*cd*	*a*	*ce*	*b*	*c*	*ad*	*c*	*ad*	*de*	*ab*	*ac*	*d*	*e*	*bc*
Coding	0		0		1		4		1		0		3	
1.	*a*	*cd*	*b*	*ade*	*c*	*be*	*e*	*be*	*ab*	*de*	*d*	*abe*	*e*	*bad*
2.	*a*	*bed*	*b*	*ce*	*be*	*ad*	*be*	*ad*			*d*	*ac*	*bc*	*e*
3.	*bed*	*a*	*ade*	*b*	*be*	*c*	*be*	*c*			*abe*	*d*	*bad*	*e*
4.					*ad*	*be*	*ad*	*be*						
5.					*ad*	*c*	*ad*	*c*						

Table 2. Combinations of primary and protection paths with solution codings

3.3.3. Definition of Fitness Function

The fitness function is part of the problem module. The fitness function represents an interface towards optimization methods which works with coded solutions. It receives a coded solution as an argument and returns a positive value which represents solution quality. Its execution is comprised of three phases, as depicted in Figure 7.

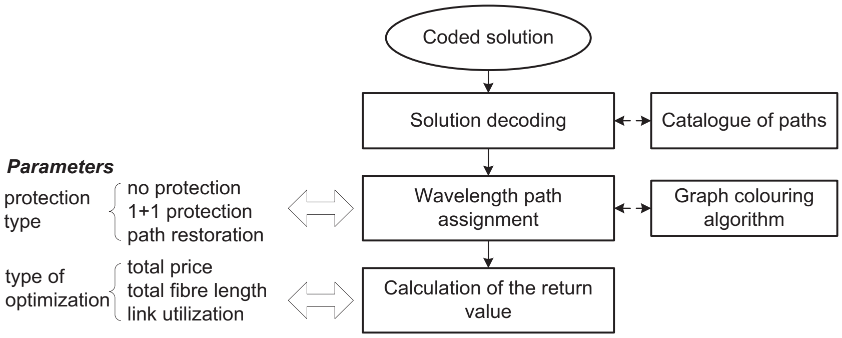


Figure 7. Phases of fitness function execution

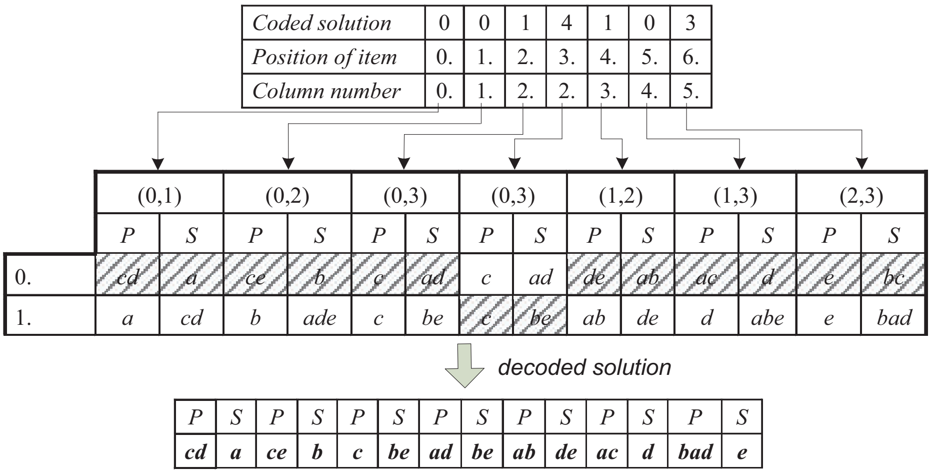
The following paragraphs illustrate all the mentioned execution phases and influences of problem module parameters (introduced and explained in 2.1.1) on each of them. The network defined in Figure 10 will be used with the assumption of path restoration as the used protection mechanism.

3.3.3.1 Decoding

The process of solution decoding is the reverse of solution coding described in 3.3.2. The goal is to get pairs of primary and protection paths for each node pair using the integer coded word. Solution decoding for each integer value requires the following information:

- which node pair it belongs to, and
- which pair of primary and protection path it represents.

It is important to emphasize that the code word itself does not hold any information that could be used to detect the relation between the part of the solution and the node pair. This is because the length of the code word does not have to be equal to the number of traffic demands in the network. On the other hand, as all coded solutions are of the same length, during initialization it is possible to make an array by copying the positions of items in the coded solution into the pair of nodes related to that traffic demand, as depicted in Figure 8.



Coded solution	0	0	1	4	1	0	3
Position of item	0.	1.	2.	3.	4.	5.	6.
Column number	0.	1.	2.	2.	3.	4.	5.

	(0,1)		(0,2)		(0,3)		(0,3)		(1,2)		(1,3)		(2,3)	
	P	*S*	*P*	*S*	*P*	*S*	*P*	*S*	*P*	*S*	*P*	*S*	*P*	*S*
0.	*cd*	*a*	*ce*	*b*	*c*	*ad*	*c*	*ad*	*de*	*ab*	*ac*	*d*	*e*	*bc*
1.	*a*	*cd*	*b*	*ade*	*c*	*be*	*c*	*be*	*ab*	*de*	*d*	*abe*	*e*	*bad*

P	*S*	*P*	*S*	*P*	*S*	*P*	*S*	*P*	*S*	*P*	*S*	*P*	*S*
cd	***a***	***ce***	***b***	***c***	***be***	***ad***	***be***	***ab***	***de***	***ac***	***d***	***bad***	***e***

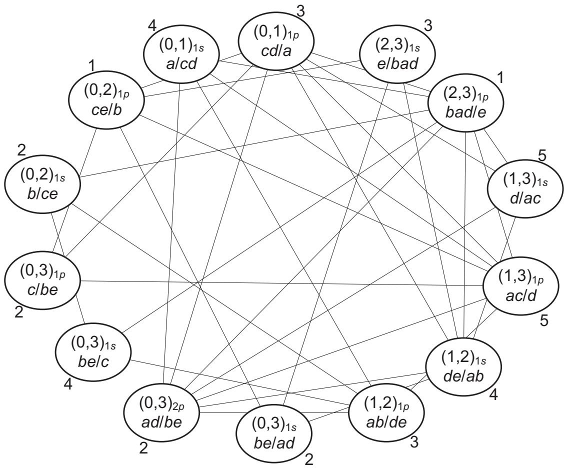
Figure 8. Solution decoding procedure

After determining the column of the catalogue of paths for each item in the coded solution, the pair of primary and spare path is retrieved from the position determined by the value of the item itself.

3.3.3.2 Wavelength Assignment

The goal of this phase is to assign wavelengths to primary and protection paths obtained from the decoding phase. The graph coloring algorithm described in 3.2 is used. The algorithm is implemented within the problem module for the optimal routing and works with objects of any type. The input of the algorithm is a list of objects (nodes of a graph), while the output is the list of assigned colors. Each node in the graph represents one wavelength path, previously explained in Section 3.2. The neighborhood function has to be defined for proper functioning of the algorithm. The neighborhood function takes two objects from the input list as input values and decides whether they are neighbors or not. Based on the result, links in the graph are created. This actually corresponds to determining whether two wavelength paths are independent or disjoint. In the optimal routing problem the input to the algorithm is the decoded solution, i.e., a list of primary and spare paths, while the output is the list containing wavelengths assigned to wavelength paths. Whether two paths can have the same wavelength is determined by the return value of the neighborhood function. This information also depends on the used protection mechanism. Figure 9 depicts the described procedure for one of the decoded solutions.

The figure illustrates that any two connected nodes have different assigned wavelengths, which is the goal of the graph coloring algorithm, as the existence of a node denotes spatial and temporal relationship of two wavelength paths. Protection (spare) paths $(0, 2)_{1s}$ and $(0, 3)_{2s}$ are dependent as they share link *b*, but are also disjoint as their assigned primary paths are independent. Therefore the same wavelength can be assigned. In case of 1+1 protection the same paths are not disjoint, and therefore require different wavelengths. After assigning wavelengths to wavelength paths, real wavelengths that are going to be used for signal multiplexing and demultiplexing have to be determined. This procedure is influenced by a maximum possible number of wavelengths per fiber. All wavelengths obtained from the graph coloring algorithm whose values exceed a maximum possible number of wavelengths in the system have to be mapped to additional optical fibers.



$(0,1)_{1p}$ $(0,1)_{1s}$ *cd* *a* 0	$(0,2)_{1p}$ $(0,2)_{1s}$ *ce* *b* 0
$(0,3)_{1p}$ $(0,3)_{1s}$ *c* *be* 1	$(0,3)_{2p}$ $(0,3)_{2s}$ *ad* *be* 4 …
$(1,2)_{1p}$ $(1,2)_{1s}$ *ab* *de* … 1	$(1,3)_{1p}$ $(1,3)_{1s}$ *ac* *d* 0
$(2,3)_{1p}$ $(2,3)_{1s}$ *bad* *e* 3	

Figure 9. Wavelength assignment to wavelength paths

Table 3 depicts the attributed real wavelengths to wavelength paths for the described solution from Figure 6. In this example we have assumed a maximum of four wavelengths per fiber.

Link	**Attributed wavelength paths**				**Number of**		
					wl. paths	**wl. channels**	**fibers**
a	$(2,3)_{1p}$	$(0,3)_{2p}$	$(1,2)_{1p}$	$(0,1)_{1s}$ $(1,3)_{1p}$	5	5	2
b	$(2,3)_{1p}$	$(0,3)_{1s}$ $(0,2)_{1s}$	$(1,2)_{1p}$	$(0,3)_{1x}$	5	4	1
c	$(0,2)_{1p}$	$(0,3)_{1p}$	$(0,1)_{1p}$	$(1,3)_{1p}$	4	4	1
d	$(2,3)_{1p}$	$(0,3)_{1s}$	$(0,1)_{1p}$	$(1,2)_{1s}$ $(1,3)_{1s}$	5	5	2
e	$(0,2)_{1p}$	$(0,3)_{2s}$	$(2,3)_{1s}$	$(0,3)_{1s}$ $(1,2)_{1s}$	5	4	1

Table 3. Wavelength paths attributed to network links

In order to determine the number of required fibers for each link, the number of required wavelength channels for each link has to be calculated. The number of wavelength channels is calculated by counting wavelength paths that use the same link. The following requirements are valid for each link:

- All primary paths must have different wavelengths;
- Primary and any protection wavelength path assigned to the same link can have the same wavelength in case that the primary wavelength path is disjoint with the wavelength path using that protection path;
- Two protection wavelength paths can have the same wavelength if they are disjoint.

These requirements are a consequence of the graph coloring algorithm. For each primary path that transgresses a link one wavelength (channel) will be needed. The protection channel will be needed only if there is no primary path with the same assigned wavelength. One wavelength channel is needed for all protection paths with the same assigned wavelength (disjoint paths). This is followed by the calculation of the number of necessary fibers. This number is calculated as the first integer larger than the result obtained from the division of the number of channels and the maximum number of wavelengths per fiber (given in Table 3).

It is clear from the table that in case of path restoration, the number of required wavelength channels on a link does not have to be equal to the number of wavelength paths that transgress that link (disjoint paths).

3.3.3.3 Fitness function value

The last step in the creation of the fitness function is the calculation of the fitness function value based on the decoded solution. As mentioned before, the return value of the fitness function depends on the optimization type parameter that determines the type of optimization. Three distinct optimizations are possible regarding the total fiber length, link utilization, and network cost.

Total fiber length (*TFL*) is calculated using data on the distance between nodes and the number of installed fibers per link:

$$TFL = \sum_{k=1}^{E} F(k) l_k, \tag{3}$$

where E denotes the total number of links in the network, $F(k)$ number of fibers per link k, and l_k the length of link k.

Link utilization factor (*UF*) of link k is defined as the ratio between the used wavelength channels on the link and the maximum possible number of channels on the link:

$$UF(k) = \frac{w(k)}{F(k) N_\lambda}, \tag{4}$$

where $w(k)$ denotes the number of used channels on link k, and N_λ the maximum number of wavelength per fiber. The mean value of all link utilizations is used as a measure of the quality of utilization in the network:

$$UF = \frac{1}{E} \sum_{k=1}^{E} UF(k). \tag{5}$$

The network cost depends on the assumed network architecture and used optical components, and can be classified as switching the related network cost and transmission related network cost. In the analyzed example we assumed that each node of the WDM network contains the following components:

- WDM multiplexers and demultiplexers,
- Emitters and transceivers (optical interfaces),
- Space switches, and
- Optical amplifiers.

The cost of commutation is equal to the total cost of all optical components contained in network nodes. The cost of transmission includes the total length of the installed optical fibers and used optical amplifiers. The total cost is hence equal to

$$C = C_{MUX} + C_{DMUX} + C_{F\_INF} + C_{AMP} + C_{IO} + C_{OXC}, \tag{6}$$

where C_{MUX} and C_{DMUX} denote multiplexer and demultiplexer costs, C_{F_INF} costs of optical fiber infrastructure, C_{AMP} cost of optical amplifiers, C_{IO} cost of optical interfaces, and C_{OXC} cost of optical space switches.

The cost of optical fiber infrastructure, C_{F_INF}, is composed of two components – the cost of optical fibers C_{FIB} and the cost of laying the optical infrastructure C_{INF} (includes cost of concession, construction works, etc.):

$$C_{F\_INF} = C_{FIB} + C_{INF}, \tag{7}$$

Both of these components are related to fiber length.

The higher return value of the fitness function should correspond to a better solution. In case of the total fiber length optimization the return value is the inverse of the calculated total fiber length for a given solution. In case of network cost optimization network cost does not have to contain transmitters and receivers, as their cost is determined only by traffic demands (in terms of the number of required wavelength channels), and not a particular network configuration. Table 4 depicts possible return values of the fitness function.

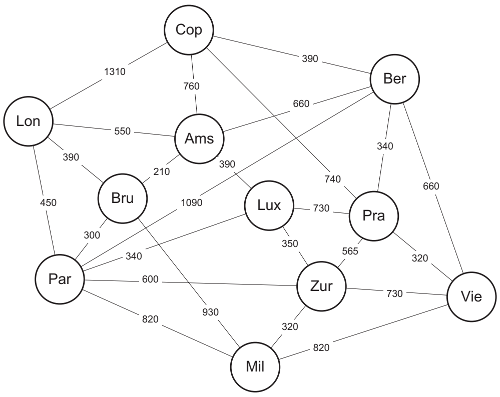
Optimization type	**Return value**
Total fiber length (*TFL*)	1/*TFL*
Utilization factor (*UF*)	*UF*
Cost	$1/(C_{MUX} + C_{DMUX} + C_{F\_INF} + C_{AMP})$

Table 4. Return values of the fitness function

4. Pan European Network Test Case

In previous sections a short overview of the ***Nyx*** optimization kernel was given, illustrated by optimal routing problem modeling. The described solution will be applied on the routing and wavelength assignment problem regarding link usage and total optical fiber length for the Pan-European optical network used in the Cost 239, Cost 266 [7] and Cost 291 projects [21]. The required communication capacity between nodes is determined using the population–distance model with the extrapolation of traffic for year 2009 [7].

The network is comprised of 11 nodes and 26 physical connections, as depicted in Figure 10.



	Par	Mil	Zur	Pra	Vie	Ber	Ams	Lux	Bru	Lon	Cop
Par	0	21	20	10	10	59	20	10	20	30	10
Mil	21	0	20	10	10	36	10	10	10	10	10
Zur	20	20	0	10	10	30	10	10	10	10	10
Pra	10	10	10	0	14	20	10	10	10	10	10
Vie	10	10	10	14	0	48	10	10	10	10	10
Ber	59	36	30	20	48	0	22	10	20	20	10
Ams	20	10	10	10	10	22	0	10	10	20	10
Lux	10	10	10	10	10	10	10	0	10	10	10
Bru	20	10	10	10	10	20	10	10	0	10	10
Lon	97	16	11	15	15	51	34	10	10	0	10
Cop	10	10	10	10	10	10	10	10	10	10	0

Number of wavelength channels @ 40 Gbps

Figure 10. Analyzed network topology with traffic demands and distances between nodes

Every physical connection requires an installed optical cable. The optimization process yields a required number of optical fibers per each cable. The figure defines traffic demands in terms of the required number of wavelength channels between any pair of nodes, under the assumption of 40Gbps channel capacity, as well as distances between nodes in kilometers.

Due to its complexity the optimization is conducted using the genetic algorithm with integer coding. Table 5 gives basic parameters of the optimization and problem module.

The chromosome length corresponds to the number of wavelength paths to be established (1780 in this example).

Crossover probability determines the frequency of the crossover operation. If there is no crossover, a child is exact copy of parents. Otherwise, a child is made from parts of parents' chromosomes. If crossover probability is 100%, then all children are made by crossover. If it is 0%, an entire new generation is made from exact copies of chromosomes from the parent population.

Mutation probability determines the frequency of chromosome mutation. If there is no mutation, a chromosome is not additionally changed after crossover (or copy). Otherwise, a part of chromosome is changed. If mutation probability is 1, the whole chromosome is changed, if it is 0, there is no change. Mutation prevents the genetic algorithm from falling into a local extreme. However, balance is needed because the genetic algorithm would turn into random search if mutation occurred too often.

In this approach crossover operators involve a higher number of crossover points, due to benefits exhibited in [3].

Population size determines how many chromosomes there are in one generation of population. If there are too few chromosomes, there is a possibility that genetic algorithm may not explore enough of the solution space to consistently find good solutions. On the other hand, if there are too many chromosomes, the genetic algorithm slows down. Population size has been determined experimentally in this case.

Elitism is the process of selecting the better individuals, or selecting an individual with a bias towards the better ones. Elitism will help the general algorithm to converge more quickly.

Stop generation determines the maximum number of generations, after which the genetic algorithm will be stopped. Stop generation is determined experimentally for this case by monitoring convergence of the algorithm for the parameter values as defined in the table.

	Parameter	**Value**
Optimization module	Crossover probability	0.6
	Mutation probability	0.05–0.1
	Number of crossover points	Depends on chromosome length (4–15 in this example)
	Population size	1000
	Elitism (on/off)	On
	Stop generation	10000
Problem module	Number of wavelengths	40, 80, 128, 192
	Distance between optical amplifiers [km]	100
	Optimization type	0
	Protection type	no protection, 1+1 protection, path restoration
	Maximum number of nodes on the path	6
	Maximum path length [km]	2500
	Limitation of the number of possible pairs of primary and protection paths	6

Table 5. Parameterization of the genetic algorithm for optimal routing problem

Parameters related to optical networks include the number of wavelengths (range 40-192 wavelengths per fiber has been used according to current commercial implementations [5]), while the distance between amplifiers has been set to 100 km. It has been assumed that the maximum path length is 2500 km due to the degradation of the optical signal in the fiber.

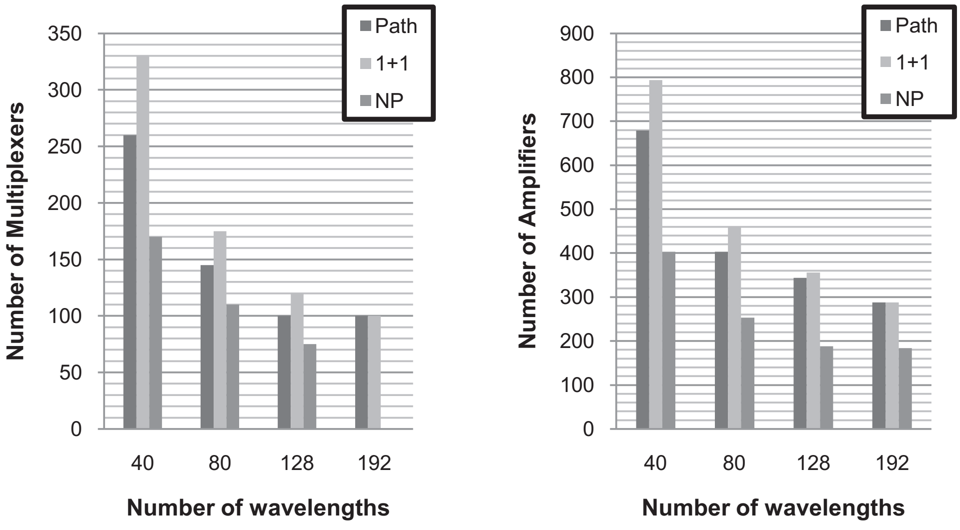
Limitation of the number of possible pairs of primary and protection paths imposes the constraint on the number of paths for each pair of nodes in the path catalogue. This means that 6 pairs of primary and spare paths are examined at maximum. This is appropriate for this network size and network connectivity. Pairs of primary and spare paths are sorted by the sum of the primary and spare path lengths. The value of this parameter is very important as for larger values of the number of paths to be analyzed a genetic algorithm does not provide as good results as for lower values, considering the same stop generation value. This is mainly due to the increase of the solution space, which cannot be properly examined, and leads to sub-optimal solution. With the increase of the number of nodes and network connectivity, the number of paths to be examined should be increased, as well as the stop generation of the algorithm.

The other parameter that possibly limits the number of paths in the catalogue is the limitation of the number of nodes in the path. This parameter introduces sensitivity to physical impairments that are introduced in network nodes.

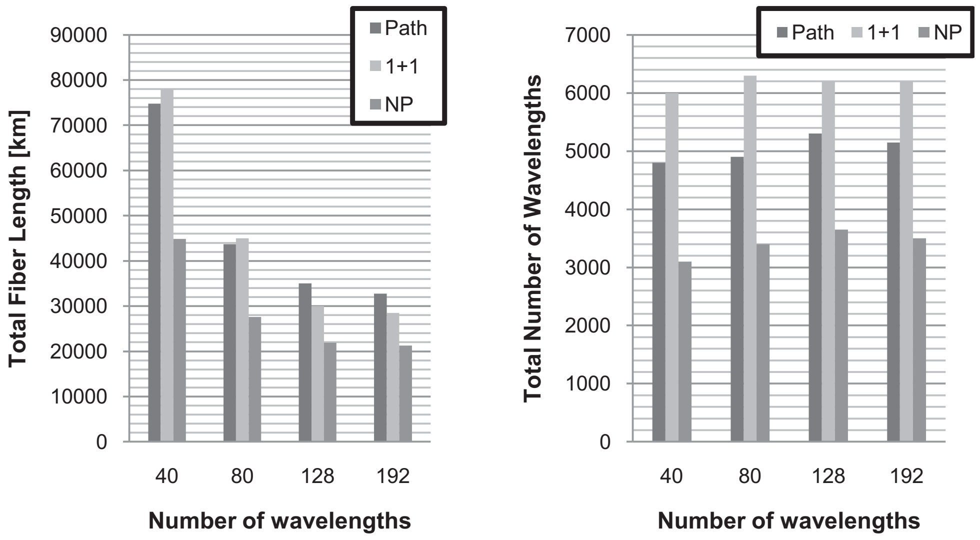
It is important to emphasize that the optical cross connect (OXC) is used only in the path restoration mechanism. The dependence of the number of required components on the number of wavelengths N_λ and the protection mechanism in the optimal routing case is shown in Figure 11.

The number of optical components decreases regardless of the protection mechanism with the increase of the number of wavelengths per fiber. Having fixed the wavelength, most resources are needed for the 1+1 protection followed by the path restoration and no-protection cases. This is caused by the number of required channels, which is the largest in case of 1+1 protection and the smallest in the no-protection case.

The path restoration mechanism implies a smaller number of required components than in the case of 1+1 protection. This is caused by the disjointness of wavelength paths, which requires a smaller number of wavelength channels. On the other hand, the number of optical cross connects increases. The total cost savings on the total fiber length reduction is greater than the higher cost of optical cross connects. For $N_\lambda = 192$ there is a difference in the number of required optical components (excluding the number of cross connects) between the restoration and 1+1 protection mechanisms. The increase in the number of required wavelength channels per demand further increases these differences.



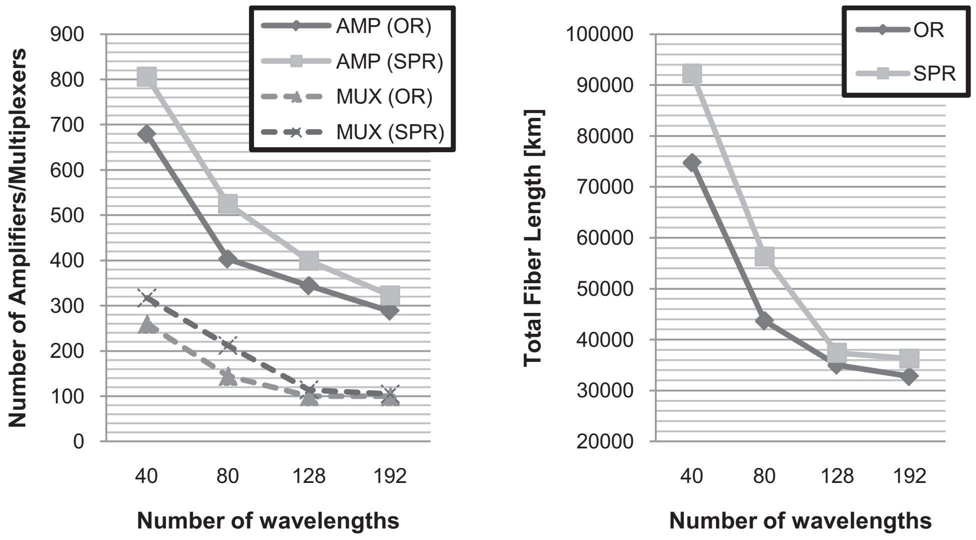
a Number of multiplexers *b* Number of optical amplifiers



c Total fiber length *d* Total number of wavelengths

Figure 11. Dependence of network design parameters on the number of wavelengths and protection type

Figure 12*a*, *b* shows the comparison of required resources in case of optimal routing (OR) and the shortest path routing (SPR). These results are related to the restoration mechanism.



a Comparison of optimal routing and shortest path for number of multiplexers/optical amplifiers

b Comparison of optimal routing and shortest path for total fiber length

Figure 12. Influence of network routing on network design

It is evident from the figures that the number of required components in case of optimal routing is 15-25% smaller than in the shortest path routing case. The increase in the number of wavelengths reduces differences in the number of components, but increases the costs of multiplexers and demultiplexers. These differences are much smaller for the $N_\lambda=192$ case. The increase in the number of wavelength channels per demand increases these differences.

5. Conclusion

General heuristic search techniques have become an attractive approach to optical network design process due to their applicability to a wide range of non-polynomial complex problems. The optimization framework ***Nyx*** utilizes the two key advantages of these techniques: working with encoded solutions, and the limitation of problem specific issues only to the fitness function of the optimization procedure. In the paper the ***Nyx*** modular organization has been described, with a specific emphasis on the coding types as the communication means between the problem module and the optimization module.

One example of optical network design has been implemented in the ***Nyx*** framework to illustrate the use of binary coding in combination with the genetic algorithm implemented in the optimization module. The implemented problem was denoted as optimal traffic routing with network cost minimization as the optimization goal. The analyzed object was the Pan-European optical network without wavelength conversion, and with fixed traffic demands. Therefore, the optimal routing can be classified as a routing and wavelength assignment problem.

The analysis included a no-protection scenario, 1+1 protection and path restoration, with variations of the number of wavelengths. The results have been compared to the case where the shortest path routing with the graph coloring procedure has been applied. The analysis included a number of utilized wavelengths, network multiplexers, amplifiers and fibers.

The results show that with the increase of the number of wavelengths per fiber, the number of optical components is reduced regardless of the protection mechanism. If the number of wavelengths is fixed, most resources are needed for the 1+1 protection followed by the path restoration and no-protection cases. The total fiber length is smaller for the path restoration mechanism than in the case of 1+1 protection, which is caused by the disjointness of wavelength paths and smaller number of required wavelength channels. On the other hand, the number of optical cross connects increases. The total cost savings on the total fiber length reduction is greater than the higher cost of optical cross connects. The number of required components in the case of optimal routing is 15-25% smaller than in the shortest path routing case.

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