Multi-period Planning of WDM-Networks: Comparison of Incremental and EoL Approaches

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***Abstract*— In this paper, we present a complete planning procedure for WDM-networks. We designed a detailed topology and cost model for actual network architectures. Network planning is done with mathematical optimization. Moreover, we describe three different multi-period planning approaches, which are proved in two near realistic case studies. We consider multi-period aspects of uncertainty, capital return, reduction of component cost over time and new technologies.**

I. Introduction

Backbone networks are operated and constantly upgraded over longer periods of time. As these networks involve large cost investments, appropriate planning of the network elements, deployed initially and in the course of the operation, is necessary.

For transparent WDM networks [1], [2], we present a planning procedure in this paper. We model network elements representing the main cost contributors. These comprise not only system elements such as (de-)multiplexers, switches, reach-dependent transponders, and transmission systems, but also topology elements such as ducts and nodes. Besides deciding on how many of these elements are deployed, the planning includes solving the routing and wavelength assignment (RWA) problem [1], [2]. We use mathematical optimization to obtain reference values and to create a basis for developing heuristics.

We investigate three principal procedures for planning WDM networks operated over multiple periods of time. Firstly, we consider the End-of-Life (EoL) approach where, before the network is built, we plan the final composition of the network for a given forecasted demand. In the intermediate stages, new connection demand is satisfied by provisioning according to the EoL plan. If the EoL plan does not contain an arriving demand, an intermediate planning for that demand is done. Secondly, we consider the incremental approach where the network is upgraded in each time period. At each stage the previously build network remains unchanged and new connection demand is satisfied by existing free resources and by adding network elements. Thirdly, we consider a hybrid approach where planning includes knowledge of several future time periods. This approach presents a compromise between EoL and incremental planning. In this paper we evaluate these approaches under multi-period aspects of uncertainty, capital return, and reduction of component cost over time.

The paper is organized as follows. Section II formulates the mathematical model. Section III details the three multi-period planning approaches. Section IV presents results for two case studies comparing the approaches. Section V draws several conclusions and Section VI provides an outlook.

II. Modeling

A. Notations

A network is modeled by an undirected graph. We use following notations:

$V = \{v_1, \dots, v_n\}$	Set of nodes. They represent add/drop-multiplexers or crossconnects dependent on the nodal degree.
$E = \{e_1, \dots, e_m\}$	Set of edges. Each edge describes a fiber link.
$G = (V, E)$	An undirected graph. It represents the topology of a network.
$\mathcal{G}$	Set of all undirected graphs.
$P = \{p_1, \dots, p_u\}$	Set of nodepairs. $P := \{p = \{v, v'\} : v, v' \in V, v \neq v'\}$.
$d = (d_i)_{i=1}^{u}$	Vector of bidirectional traffic. $d \in \mathbb{N}_0^u$. d_i states the demand for nodepair p_i, $\forall i \in \{1, \dots, u\}$.
$\lambda \in \mathbb{N}$	Number of System wavelengths.
$R = \{r_1, \dots, r_s\}$	Set of all loopless paths.
$A = (a_{ij})_{\substack{i=1,\dots,u \\ j=1,\dots,s}}$	Matrix for paths and nodepairs. $a_{ij} = 1$, if nodepair p_i is connected by route r_j; $a_{ij} = 0$, otherwise.

As we use the transparent lightpath routing, we assign both a route *and* a wavelength to each demanded connection. We define a variable vector Y

$Y = (y_{ij})_{\substack{i=1,\dots,s \\ j=1,\dots,\lambda}}$	where $y_{ij} \in \mathbb{N}_0$ is the number of provided connections with path r_i and wavelength j

and the auxiliary variable vector $x := Y \cdot 1_\lambda$, where $1_\lambda := (1, \dots, 1)^T \in \mathbb{N}^\lambda$.

B. Objective Function

It is our aim to minimize the cost of network upgrading, i.e., the cost of supplying capacity. We model the cost function:

$$C(Y,G) := \sum_{e_j \in E} (C_F(Y,e_j) + C_M(Y,e_j)) + \sum_{v_k \in V} C_N(Y,v_k) + C_T(Y,G).$$

Now, we detail the elements fiber system, multiplexer, node and transponder costs:

Fiber system: The number of fibers per edge is determined by the maximum of connections of all wavelengths. We multiply the number of fibers and the cost per fiber c_f

$$C_F(Y,e_j) := \max \left\{ \sum_{\substack{i \in \{1,\dots,s\}: \\ e_j \in r_i}} y_{i1}, \dots, \sum_{\substack{i \in \{1,\dots,s\}: \\ e_j \in r_i}} y_{i\lambda} \right\} \cdot c_f(e_j),$$

where c_f is considered in Section II-C.

Furthermore we model the cost function for multiplexers of the second stage:

$$C_M : (Y,e_j) := c_{mux2} \cdot \left\lceil \frac{\sum_{\substack{i \in \{1,\dots,s\}: \\ e_j \in r_i}} x_i}{gr} \right\rceil,$$

where $gr \in \mathbb{N}$ is the granularity of multiplexer of second stage. c_{mux2} is explained in Section II-C. The calculation of multiplexers of second stage is a simplification, but it is necessary because of computing complexity.

Node costs: We include the above calculation of the number of fibers within the node costs. The outcome of all in-fibers per node is the node degree.

$$C_N(Y,v_k) := c_n \left(\sum_{\substack{j \in \{1,\dots,m\}: \\ v_k \in e_j}} \max \left\{ \sum_{\substack{i \in \{1,\dots,s\}: \\ e_j \in r_i}} y_{i1}, \dots, \sum_{\substack{i \in \{1,\dots,s\}: \\ e_j \in r_i}} y_{i\lambda} \right\} \right)$$

The function c_n calculates the node costs depending on the node degree.

Transponder costs: We split up the transponder costs due to the transponder reach. We calculate the number of transponders of each type k. Each number is multiplied by the cost c_k for a transponder of the k-type.

$$C_T(Y,G) := \sum_k c_k \cdot \sum_{\substack{r_j \in R \\ r_j \in k}} \sum_{\substack{i=1 \\ a_{ij}=1}}^{u} x_i$$

where $r_j \in k$ means that length of route j requires a transponder of type k.

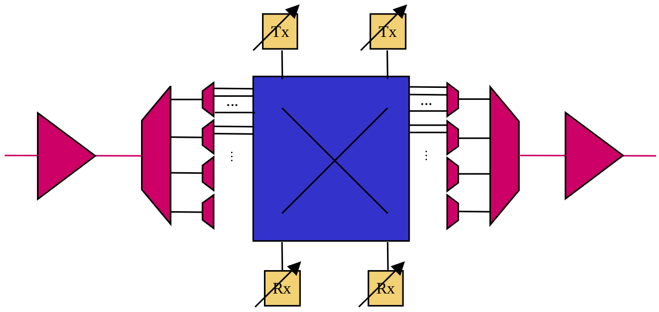

Fig. 1. Wavelength Selective node architecture with two-stage multiplexer (see [4], p. 34 and [2], p. 149)

C. Cost Model

Within this analysis we consider a WDM-network with wavelength selective node architecture (see Fig. 1). We use two-stage band multiplexers. Multiplexers of the second stage are only put in if related wavelengths are used. We divide the network in three parts:

- Fiber costs: We consider all costs, depending on the fiber link. They are amps, dispersion compensating fiber, multiplexer of the first and second stage.
- Node costs: Here we can include cost of switches.
- Transponder costs: We distinguish transponder cost dependent on the required transponder type. There are differences due to the reach.

We analyze the component cost in detail. All data supposed to be bidirectional.

1) Fiber System: We define the parameters

c_{mux1}	Cost of a multiplexer of first stage.
c_{mux2}	Cost of a multiplexer of second stage.
c_{amp}	Cost of an optical line amplifier. We use S km span.
c_{dcf}	Cost of dispersion compensating fiber.

Hence, we specify the fiber cost c_f:

$$c_f(e_j) := 2 \cdot c_{mux1} + c_{amp} \cdot \left(\left\lceil \frac{l(e_j)}{S} \right\rceil + 1 \right) + c_{dcf} \cdot \left\lfloor \frac{l(e_j)}{S} \right\rfloor,$$

where $l(e_j)$ represents the physical length of edge e_j. Cost of the multiplexer of the second stage are used in the cost function directly, see above.

2) Nodes: Here we can use a cost function c_n, depending on the node degree.

3) Transponder cost: We assign costs values c_k to each transponder type k due to their reach.

D. Optimization problem

In the previous section we extracted all necessary data for the planning. The solution of the problem is calculated by mathematical optimization. We formulate the objective:

$$\min! C(Y,G) \text{ considering } Ax \geq d.$$

Above model is implemented in AMPL. The AMPL CPLEX system finds the optimal solution by use of the Branch-and-Cut algorithm.

E. Alternative model for Max-function

Above, we calculate the number of fibers per edge with a maximum-function. But this function is not linear. As we want to get a linear problem, we have to enforce a linear objective for the implementation. We replace the function by an auxiliary variable and include additional inequalities. For detailed description of procedure see [1].

III. Multi-period Planning

Due to their high costs and long operating time optical networks have to be planned carefully. Two general approaches exist to cope with planning uncertainties:

1) Incremental planning: Purely incremental network planning considers in each period just the current demand: The network extension is optimized for the per-period requests, i.e., existing connections are not changed. This surely will give us the cheapest possible network extension per period. But this can come at the expense of possible suboptimalities (routes and wavelengths) over the full operation time and therefore mean increased total costs.

2) End-of-Life network planning: We estimate the demand matrix at the end-of-life of the network and optimize the network extension for these demands. The resulting plan for routing and wavelength assignment of each connection is then used at the time the connection demands arrive. This planning approach guarantees an optimal network extension over time.

In this section we first describe the details and elaborate the influence of these uncertainties. Then we introduce mathematical descriptions of the three planning approaches mentioned above. In the next section we use two scenarios for comparing the planning approaches and vary influence factors like interest rates and price degression.

A. Issues in Multi-Period Planning

EoL planning yields to cost-optimized networks. Thus, why do we considering the incremental planning?

But in reality some factors in the network planning process strongly influence the cost balance of the planning procedures.

1) Demand Deviations: The future demand is an estimate and therefore always affected by uncertainty. If the real demand differs from the forecast, the EoL planning has to diverge from the calculated EoL plan. Therefore EoL planning can no longer guarantee an cost-optimal network extension. Incremental planning is not impaired since it does not rely on forecast. Thus, the costs for network extensions in EoL planning may exceed the costs of the incremental procedure, if the real demand differs from the forecast.

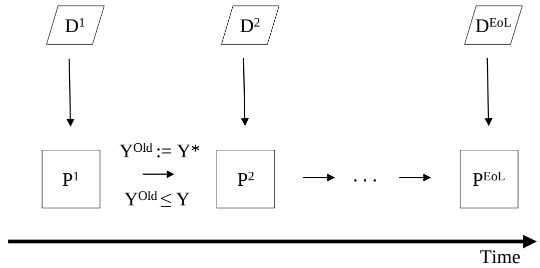

Fig. 2. Incremental Planning

2) Capital Return: Capital return is a main factor within the multi-period planning. Comparing costs is realistic after discounting only. Thus, instead of declaring total costs as $\sum_{i=1}^{n} c_i$, where c_i are costs in period i, we consider the *cash value*

$$\sum_{i=1}^{n} \frac{1}{(1+p)^i} \cdot c_i.$$

resulting from multiplying the costs of the single periods with the *load reduction factor*. The interest rate p should match the rate of return of an investment with similar risk as the load reduction factor has to be adapted to the planning uncertainty.

After discounting we may assume a cost advantage of incremental planning: We do not adhere to an EoL plan. Therefore the investments in the first periods will be reduced. This overcompensates the higher investments in later periods toward end-of-life since the latter are discounted more heavily in the cash value computation above. But interests vary and it is advisable to compare both planning procedures under different interest rates.

3) Learning Curve: Reduction of Component Costs: Usually, component prices decrease over time. An equal cost reduction of all components can also be modelled by discounting. Due to the low initial costs within the incremental planning, the learning curve is a plus for the incremental approach.

4) Technology Development: Technological progress will not only affect component prices but also allow extended element features, e.g. increasing the maximum number of wavelengths in a system. This in turn would impact both routing and wavelength assignment and reduce the value of an EoL plan whereas the incremental planning procedure can react more flexibly.

Considering these factors it becomes clear that EoL planning cannot guarantee optimality as all aspects above would lead to cost disadvantages of the EoL approach - the exact value depends, e.g., on network topology, network components, and the planning horizon. An incremental planning with forecast is a combination of both incremental planning and EoL approach. The idea is – as with the EoL approach

– to integrate future development in the planning. Now the horizon does reach not until end-of-life but any point between present and EoL. In that way we consider future aspects without losing flexibility. Concerning total investment cost we are likely to achieve an improvement compared with the incremental planning, but generally not the cost optimality of the EoL approach. On the other hand, if the demand differs from forecast, indeed, costs are more stable. Here we probably will not reach the top values of incremental planning but a significant cost reduction compared with the EoL approach.

B. Mathematical Formulation of Planning Approaches

The following subsections describe the different planning approaches in more detail.

1) Incremental Planning: At any time, we have to consider the existing network. Therefore we fix the network structure and regard these as foundation for the network upgrade.

We define:

$Y^{Old} = \left(y_{ij}^{Old}\right)_{\substack{i=1,\dots,s \\ j=1,\dots,\lambda}}$ Number of connections with path r_i and wavelength j.

Matrix Y^{Old} determines existing connections.

Within a *Greenfield-Planning*, i.e., planning without existing structures, we set $Y^{Old} := 0$. If there are already connections of previous periods in the network (Y^*) we set $Y^{Old} := Y^*$. Moreover we have to adapt the cost function C. We minimize

$$C(Y,G) - C(Y^{Old},G). \quad (1)$$

As $C(Y^{Old},G)$ is usually known from the previous period we can save calculation time.

In the optimization process we consider the existing routing and wavelength assignment by the inequality

$$Y^{Old} \quad \leq \quad Y. \quad (2)$$

We point out that the network extension is done concerning all – previous and current – demands. But inequality (2) fixes existing connections. Due to the adjustment of the objective function (1) we consider costs for the network upgrade only. The incremental planning procedure is diagrammed in Figure 2. D^i and P^i represent demand and optimization problem at point i, respectively.

2) End-of-Life Planning: To consider the EoL plan in the further planning process we define:

$Y^{EoL} = \left(y_{ij}^{EoL}\right)_{\substack{i=1,\dots,s \\ j=1,\dots,\lambda}}$ Number of connections with path r_i and wavelength j.

We save the optimal routing and wavelength assignment for the end-of-life in a matrix Y^{EoL}. As we have to follow the plan in all periods, we integrate the inequality $Y^{EoL} \geq Y$ in the optimization problem. In each period we use the results of the incremental planning section to regard former periods. The EoL procedure is shown in figure 3.

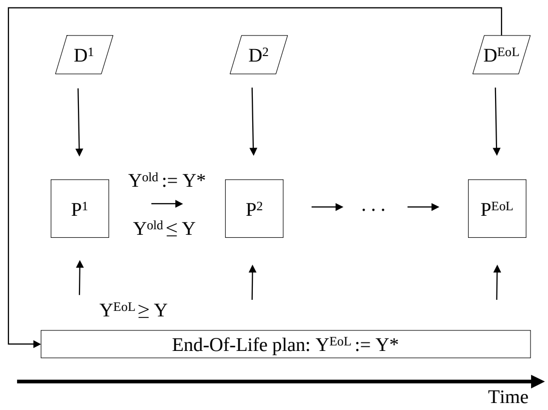

Fig. 3. End-of-Life Planning

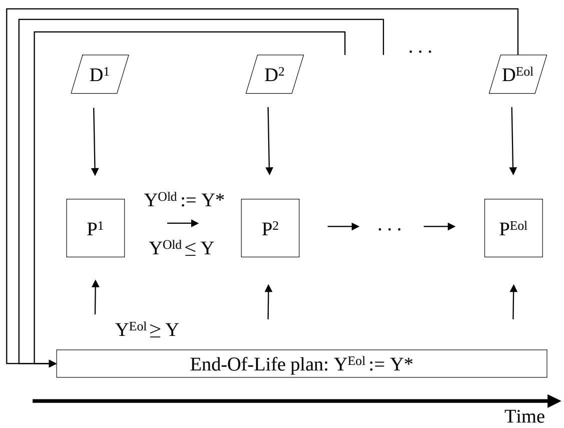

Fig. 4. Incremental planning with forecast

In case we have to deviate from our plan because of a wrong forecast, we switch to the incremental planning procedure for all affected node pairs.

C. Incremental planning with forecast

Incremental planning with forecast (Figure 4) is a combination of the two other basic planning types. In particular cases we can vary the forecast horizon dependent on the value of uncertainty. High uncertainty can lead to a short forecast horizon. More predictable demand can yield a long-term planning technique with wide horizon.

IV. RESULTS

To compare the total costs of the three planning approaches we model two case studies: In case study 1 we model a scenario where the real demand fits the forecast whereas in case study 2 the real demand differs from the forecast. We discuss the total costs of the alternative approaches in each study.

We use a Germany network topology (see Fig. 5). The maximum number of wavelengths per fiber is 40. We can have a maximum of four multiplexers of second stage with

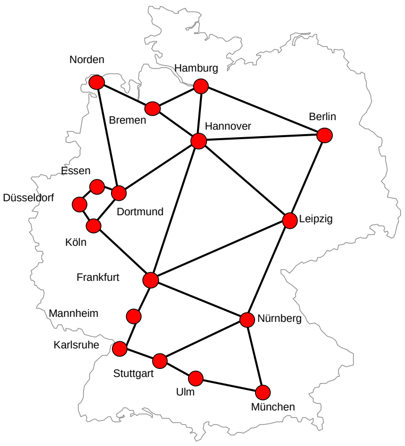

Fig. 5. Germany network, see [3]

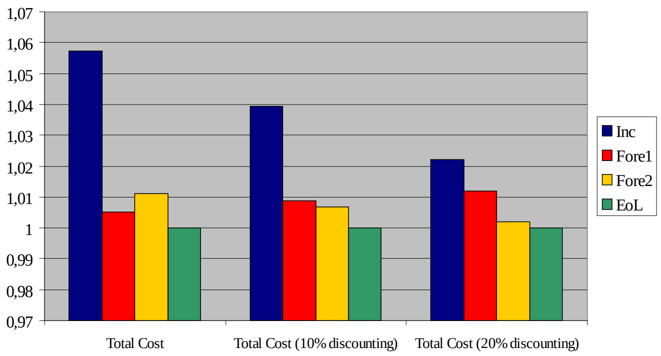

Fig. 6. Total Investment Cost: Case Study 1

granularity of 10 each. The routing is limited to the three shortest paths. Other parameters are as we introduced in the previous sections. We assign transparent and unprotected lightpaths (no regeneration).

We use the above costmodel with costs for fiber systems and transponders. As we assume fixed connections node costs are not considered. We distinguish three transponder types of 750, 1500 and 3000 km reach. Cost values come from an the European project NOBEL.

A. Case Study 1: Demand Matches Forecast

The demand matrix is taken from [3]. We use a planning horizon of four periods with demand doubling in each period. The considered approaches are EoL planning (EoL), incremental planning (Inc), incremental planning with a forecast horizon of one (Fore1) and two periods (Fore2).

Figure 6 shows total cost over time in the form of the not discounted sum and two discounting rates of 10% and 20%. In the not discounted case (left part of Figure 6) we see a significant difference between incremental planning and the approaches that use forecasts. There is additional charge of nearly six percent. Moreover, we emphasize that approach Fore1 has a important cost advantage compared to

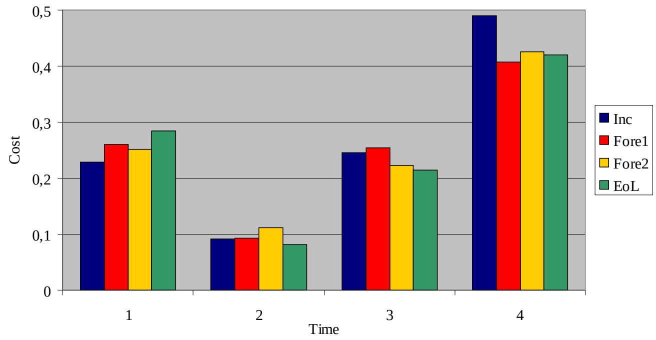

Fig. 7. Extension Costs per Period: Case Study 1

the incremental planning - it is worthwhile to integrate future aspects.

If we consider capital return and cost reduction by discounting (middle and right part of 6) we obtain a cost difference of 5 % (10% discounting) and 2% (20%) between the Eol approach and incremental planning: Incremental planning is nearly as cheap as the EoL-approach. The reasons for this change of relations in the case of discounting can be found in figure 7: Incremental planning shows particularly low initial cost that also provide an excellent sales argument! If we include the flexibility of the incremental planning, e.g. the possibility of adaption to new technologies, this method further becomes point of interest.

B. Case study 2: Demand Differs From Forecast

To analyze to which extent deviating forecasts influence the performance of each approach, we first have to modify the demand matrix. In the EoL approach we assume a fully-meshed demand forecast for the end-of-life, i.e., an identical number of demands between every nodepair. The real demand the differs strongly: There are only connections between an arbitrary node and the hub Frankfurt – a starlike demand with Frankfurt in the center. In this case EoL planning will not produce an optimal network as the EoL plan has to be abandoned.

Comment: In the case of incremental planning with one period forecast we consider the full-meshed demand only in the first period. As full-meshing is not visible then, we consider only starlike forecasts in the further periods. In this way learning effects are included. Already without discounting (left side of figure 8) the total investment costs of all planning approaches are nearly identical. Advantages of the EoL approach vanish due to a wrong EoL plan.

After discounting (middle and right side of figure 8)we obtain significant cost advantages for the incremental planning. We have a cost difference of two (10% discounting) and five percent (20%). This is due to the low initial cost as we can see in figure 9. Initial cost in the EoL approach are nearly twice as much as high in incremental planning. The reasons are the

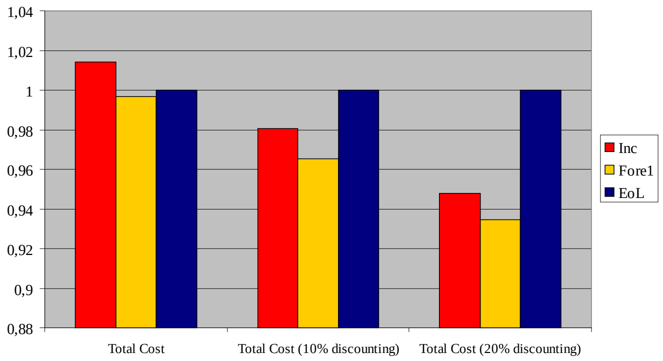

Fig. 8. Total Investment Cost: Case Study 2

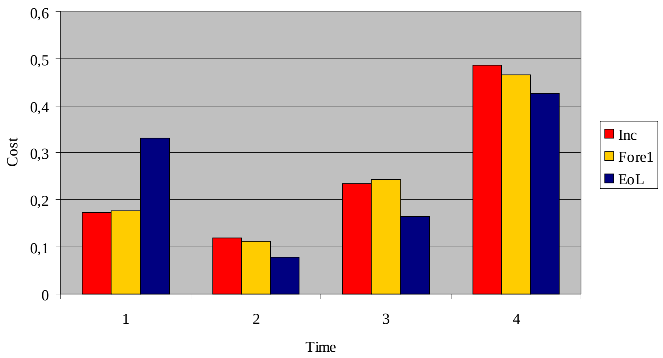

Fig. 9. Extension Costs per Period: Case Study 2

stepwise optimization within the incremental process as well as the incorrect planning of the EoL approach.

The incremental planning with forecast is the cheapest alternative. Including the learning effects eliminates the bad planning of the first period.

V. Conclusion

The EoL planning appears to be inflexible, especially since it is only optimal if the forecasted demand occurs. But if the real demand differs from forecast EoL planning can yield to expensive incorrect planning. Moreover we get high initial investment cost.

The incremental planning with forecast is an interesting alternative approach. We reach nearly optimal cost values in case study 1. Modelling a learning effect we get a very good cost balance in case study 2. But without the learning effect costs would rise over the costs in EoL planning.

The incremental approach seems to be the best option. It is the most expensive alternative, if forecast fits the real demand. But the additional charge decreases as the load reduction factor increases. Moreover, the incremental planning offers highest reliability as no forecast is considered. The main plus comes up if the real demand differs from the forecast. Then we yield cost advantages compared to the EoL approach. In addition a network planned incrementally is a good offer as initial cost are low. Higher investment is necessary not until later periods – after winning the customer. Until then the provider finances the extensions with his first profits.

We have to mark that these studies are simplifications of reality.

The use of networks is surely longer than four periods. But we expect cost advantages of the incremental planning as the planning horizon grows. Then the uncertainty of approaches with forecast increases. Therefore we can use a higher load reduction factor. The resulting reduced total cost argue for the incremental planning due to low initial cost.

In reality we would use not only the three shortest paths for routing. More options mean cost advantage in each optimization. We calculate only one network optimization in the EoL approach but one per period in incremental planning. On this account we get another cost advantage for the incremental planning.

VI. Outlook

We suggest some aspects for future research.

- Weighting of forecast with probabilities: The idea is to weight forecast with occurrence probabilities. They could influence, e.g. within the incremental planning with forecast, the width of the forecast horizon (see paragraph III-C).
- Network elements. Research can be widened to other network elements. In particular we think of regenerators, Broadcast & Select nodes.
- Wavelength dependent reach. Up to now the we included the lowest reach of all wavelengths. We also could consider the effects of wavelength dependent reach on the network planning.
- Planning approaches with re-routing. Considered planning approaches could be compared with a network planning, which calculates a new routing and wavelength assignment in each period. This could be done with all or just a part (protected) connections. As expensive networks components would be necessary, the economic efficiency is quite interesting.

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