



OPTIMALIZATION PHASE USING GRAPH MODELLING FOR RELIABLE BUILDING COMPLEXES

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ABSTRACT

During the planning phase of modern, complex, block-structured, large-area located, but still landscape-harmonized health-care buildings, the key is the optimal positioning of the blocks and functions, simultaneously ensuring the most-effective backup-paths for any transportation route failure in the buildings in order to speed up system operation, reduce maintenance costs and especially to improve patient safety and satisfaction. The importance of improving reliability and boundary conditions of the modelling in modern complex health-care building-systems are emphasized.

A cost efficient pre-phase solution of mathematical, graph modelling is presented, with introducing link doubling to linearize a two segment, non-linear capacity-cost function. The developed and detailed mathematical graph model can be used as part of the architectural planning workflow. This model allows distinguishing the sharable part from the free part of capacity on a link in case of simultaneously routing multiple protection paths. Link doubling allows finding optimal routing of shared protection paths for failure cases. Two algorithms are proposed for routing of the guaranteed bandwidth pipes with shared protection which provides reliable building structures through thrifty additional resources. It is assumed that a single working path can be protected by one or multiple protection paths, which are partially or fully disjoint from the working one. This approach allows better capacity sharing among protection paths.

The main aim of the recommendations is to achieve a reliable, fully operational building even if a failure, a reconditioning or emergency situation happens.

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KEY WORDS: graph optimization; reliable health-care buildings; optimal-positioning.

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1. LOCATING THE PROBLEM

The first phase of the design workflow in the present architectural planning practice is to prepare sketches and versions. There are many alternatives raised in this section, which requires full openness. Though there are no legal obligations at this point, this stage of the design has the greatest responsibility. Current practice does not extend to assess the needs of the buildings, prepare a functional plan, a model of the buildings with necessary functions and relationships between them and finally verify the plan according to such important criteria as reliability of the buildings.

Nayma Khan [1] showed how spatial layouts effect patient-flow and will affect operational efficiency. Researches were performed by Michalek, Choudhary, Papalambros [2] on how the floorplan-layout affects the behavior of the patient-flows and what factors should be taken into consideration to have a cost efficient building. But none of them are dealing with failures in the buildings. Though, importance of this area is as critical. The health-care buildings should be able to serve all the patients in all areas without interruption in a failure case as well.

In order to progress further in this critical domain we need to have a clear interpretation of the term reliability. *Reliability* is when a building system could operate as a normal operation even if a failure occurs or planned works/renovations are taking place. Both mono-block buildings and complex, multi-block building systems should be checked if they operate properly in emergency case, or in damaged case caused by fire by natural disasters.

In modern social buildings it is not enough to satisfy the customers in normal operation without any unplanned failure in the building, like elevator malfunction, or without any planned restoration work on a part of the building but as well we need to take in consideration that the quality of the services provided during these critical periods plays also an increasingly important role. Service disruption is no longer tolerated by patients, business or industry. For this reason one of the requested properties of such buildings is the survivability of services. If any part of the building is affected by a failure, it still should provide services to customers as though nothing happened. The requested level of fault tolerance and availability can be expressed using the QoR (Quality of Resilience) framework that reflects the need of the customers and possibilities of the operator.

To successfull develop high performance and substantially more energy-efficient facilities than current best practice, integrated desing is essential as it is highlighted in [3]. On behalf of cost-effectiveness some kind of functional plan should be made considering the different functions and their connections. This could be done as a pre-step before making the architectural design. For analyzing modern complex block-structured buildings modeling have to be used.

Investigations were done on the effect of using the proposed functional pre-planning phase with modelling the complex buildings and examine the reliability and survivability of buildings.

During the research, a generally applicable mathematical model was introduced which was achieved by interconnecting and further developing the different methodological elements related to optimization. Several researches have been performed modelling the structures using graph theory [4], [5], and several metaheuristic algorithms are utilized [6], [7], [8], [9] for optimal design of structures, however, none of these are about the

architectural design of a reliable building. A *mathematical graph model* can be applied to any area where the normal operation requires the definition, design and implementation of working paths and their protection, backup paths. Such areas are the road networks, engineering systems, data-transferring systems and the area covered by this article: roads in complex healthcare building systems.

The patient-flow should be able to reach all targets in these buildings. The patient-flow could be represented as guaranteed bandwidth pipes. *Two algorithms* are proposed for routing of the guaranteed bandwidth pipes (patient-flow) with shared protection which provides reliable building structures through thrifty additional resources. It is assumed that a single working path can be protected by one or multiple protection paths, which are partially or fully disjoint from the working one. This allows better capacity re-use (i.e., better capacity sharing among protection paths). Furthermore, the resources of a working path affected by a failure can be re-used by the protection paths. The main feature of the proposed protection rearrangement framework is that since the protection paths do not carry any traffic until a failure they can be adaptively rerouted (rearranged). This steady re-optimization of protection paths leads to higher throughput with lower usage of resources.

The target is to highlight how important it is – especially in the healthcare systems – to have a complex building but still robust system as a physical background of the services for the less possible additional costs. This is made possible by using the proposed zero phase: pre-planning phase using protection in the building.

The maintenance of the buildings can ensure survivability using various methods - the building operator should decide which one to use. The modelling methodology will be discussed in Section 2, Section 3 discusses the alternatives of the resilience techniques, in Section 4 the spare capacity allocation method is presented, Section 5 presents the reference method used while the two proposed methods are presented in Section 6. Section 7 presents and evaluates the obtained numerical results.

2. MODELLING METHODOLOGY

2.1 Modeling of a building-complex, functions, blocks and buildings

The question is how to spare the investments and model the building-complex before making any resource-intensive architectural plans. This problem can be formulated mathematically using graph theory [10] and network flow theory. Due to the problem's complexity, heuristics are applied with the aim of being close to the global optimum. These heuristics include decompositions [4], approximations and modeling tricks.

When modelling a complex healthcare system containing multiple individual building units, hierarchical model is used. This means that first the separate buildings and the connections between them are modelled as the highest level of the hierarchy of the graph, then decomposition is used in which the individual buildings are modelled as domains, then the departments or the floors of the buildings are presented as subdomains of the firstly prepared graph model.

This hierarchical graph topology [11] is the cross-compliance for building-complexes and their connecting pathways. The functions, the blocks or departments, the buildings and their

functional connections, e.g. transportation are the nodes, sub-domains, domains and the links between them, respectively. The problem formulation could be aggregated with merging the proper functions in proper blocks; in practice these are the departments. In graph theory this means to merge the proper nodes in proper sub-domains.

This will result a new model where from this point the nodes will represent the departments. To define one building from the departments, the cognate sub-domains should be merged in an overall domain. This time the nodes of the graph model will represent one building and the links, the pathways across the buildings as shown in Figure 1.

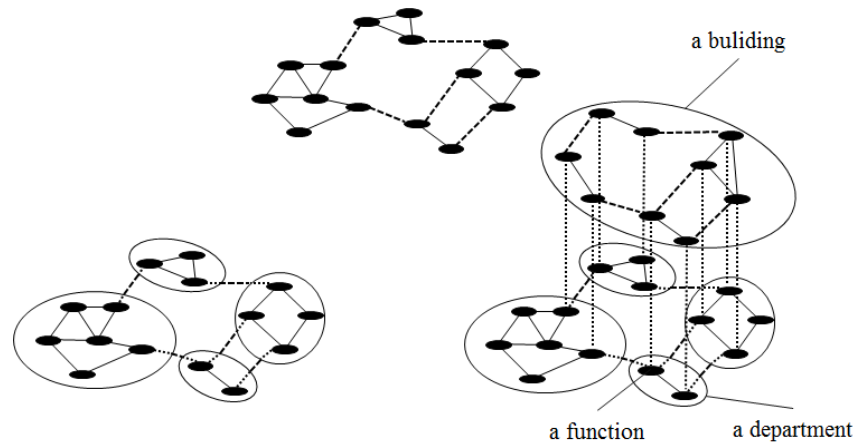


Figure 1. Hierarchical representation of the functions, blocks and buildings achieved

With this approach it is possible to prepare a hierarchical model from the building-complex [12]. An exam should be made separately on each aggregation level to check if the graphs are at least doubly connected, so in a single failure case all services, all parts of the buildings are still available.

2.2 Graph definition

Here the problem is formulated followed by the classification of the potential protection methods, mathematical methods will be proposed for solving it and finally the results to be achieved will be presented.

1. Given a building as a graph N with rooms as nodes $v \in V$, pathways as links $e(v_1, v_2) \in E$, the throughput of the pathways as link capacities C_l and the real costs of the pathways according to the throughput units as costs of the capacity units $\Omega_l : N = (V, E, C, \Omega)$.

2. All patients defined as a traffic pattern T are to be satisfied, where b_o stands for the necessary space for the patient (people who use wheelchairs do not need the same space as walking peer) as bandwidth of traffic demand o between source s_o , and destination d_o nodes that has arrived at time τ'_o , and lasts until τ''_o , $T(o : o(s_o, d_o, b_o, \tau'_o, \tau''_o))$.

3. The primary path, so called working path should be the shortest path with available capacity b_o through links e_p , $P'(o) = (e'_1, e'_2 \dots e'_{p'})$.

4. In case of link protection another ‘shortest’ path is sought for each link e' of the working path $P'(o)$, that may fail, $P'_{e'}(o) = (e'_1, e'_2 \dots e'_{|P'_{e'}|})$. To make it understandable, some definitions will be interpreted in the next section.

3. RESILIENCE TECHNICS

A health-care building system should be able to react as fast as possible to any single or multiple failures. A failure, which causes a service disruption, is no longer tolerated by health-care. A failure could be when an elevator goes wrong or a footway cannot be used. A common example for a more serious failure is when a reflector goes out in an operating room. For these failure cases there should always be a backup like another elevator with enough resources or an another operating room. For this reason one of the most requested properties is the survivability of services.

The failures can be single or multiple but since the problem could be aggregated to higher level, here the focus is on single failures only. These failures can affect only a room, more rooms or they could be on passageways. In modelling, these are the node(s) or link failures respectively. Only single link failure is discussed in this article. When a failure occurs patients or visitors could not to be served properly. Financial loss as well as prestige or reputation loss, especially any human loss and treatment delay have to be minimized.

Resilience is a predefined method how a building could operate smoothly, even in a failure in a transport path. Figure 2 shows a primary/working path between nodes s and d , consisting of links e_1 , e_2 and e_3 . Note, that if e_1 fails, the path can be protected by the dashed line and e_3 . If e_3 fails, the path can be protected by e_1 and the dotted line, while if e_2 fails both protection paths are suitable. Note, that the ‘dashed’ path protects both e_1 and e_2 , and the dotted line protects both, e_2 and e_3 .

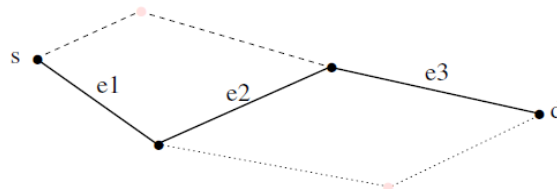


Figure 2. Illustration of a working path with partially disjoint shared protection paths

Two main resilience techniques have to be differentiated: *restoration* vs. *protection*. In case of restoration there are no predefined backup paths but the replacement is dealt when the failure occurs, while using protection it is considered that there always have to be enough spare resources between the functions and the blocks to any link failures. Though restoration uses significantly less resources, it reacts much slower and sometimes it does not even find a restoration path that is not allowed in such buildings.

There are several classifications in accordance with various criteria for the different protection and restoration techniques.

Dedicated vs. Shared Protection When using Dedicated Protection (DP), each working path has a standby path with exclusively dedicated resources. The advantage of DP is its simplicity, but it is wasting resources. For Shared Protection (SP) working trials share resources allocated for protection. The advantage of SP is its ability to protect the network against any single failure with only moderate resource usage.

A differentiation could be done regarding the part of the path to be protected. (1) *path protection*: the entire working path is protected by one completely disjoint backup path [10] often referred to as end-to-end protection; (2) *link protection*: all the traffic from the failed link is re-routed between the ends of that link; (3) *sub-network protection*: the network is clustered into protection domains (sub-networks) that define the ends of protection segments (4) *segment protection* [13] when only certain parts of a path are protected and not the whole working path or a network link. These protecting parts (segments) should of course cover the whole working path. These protecting paths should be at least partially disjoint from the working path. The segments of a path to be protected can be not predefined, but determined when the protection path is being sought.

The protection is referred to as *static* when, for each nodepair a working and one or more protection paths are assigned and no changes take effect. When these paths are reconfigured from time to time then we refer to it as *dynamic restoration/protection*. When protection paths are steadily changed whenever a new route request arrives to instantly adapt to changing traffic and network conditions we call it *adaptive protection*. The last one is the slowest and it needs the most processing, but it does not allocate resources in advance.

According to the definitions of the protection types, the protection algorithms that will be presented in this article:

- are shared;
- operate on segments (sub-networks) that can be a single or multiple links long and are determined when the protection paths are sought;
- use partially disjoint paths;
- guarantee survival of failures.

4. SPARE CAPACITY ALLOCATION

4.1 How to share capacity when allocating it for protection

The problem is how to optimally choose one working and one or more protection paths for a demand.

Let us look at an example to illuminate why the modeling methodology is essential. In the example, there are three-three functional areas connected with three-three paths: L1, L2 and L3. There are three teams of doctors with 5, 4 and 3 people respectively. To be sure that all the teams will reach their destinations, backup-paths should be defined for all single-failures cases of the transportation pathways Figure 3 shows the graph representation of the three-three functions: nodes A, B and D and nodes A', B' and D' and the three teams of doctors: traffic demands to be transmitted from nodes A, B and D to nodes A', B' and D'. Their traffic demands are 5, 4 and 3 units respectively. Each demand has a working path (solid lines) and restoration path (dashed lines) as shown in Figure 2 links are considered to

be failed: L1, L2 and L3.

Let us consider the case where all node-pairs are using paths denoted by solid lines as their working paths. If link L1 fails then the backup path of AA' (over link L2) should take over 5 units of traffic. But if L3 fails, then BB' and DD' will have to use their backup paths at the same time and for that reason L2 must ensure enough capacity for accommodating both simultaneously (i.e. 7 units of capacity for restoration purposes). In this case, link L2 has to have a capacity of 7 units to have a reliable graph. This is enough capacity for full restoration under the assumption that only one link can fail at a time. Therefore 7 units of capacity are enough instead of the 12 that would be needed if more links (i.e. L1 and L3) were to fail simultaneously. For example in practice, there should be an L2 elevator that could serve 7 people at the same time.

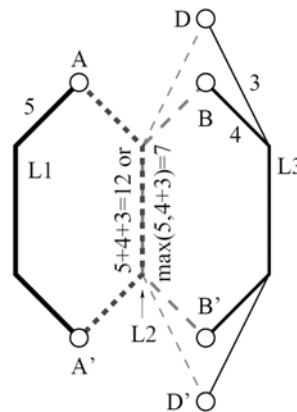


Figure 3. Sharing the spare capacity: 12 or 7 units

4.2 Cost calculation

The goal is to be able to specify how much a previously reserved protection path will cost in case of a possible failure, e.g. an elevator malfunction. Let us see the possibilities: another elevator could be used with the total amount of capacity to serve its' own demands and additionally the demands of the malfunctioning elevator; or a stairway could be used instead. Generally, the cost of the elevator would be much higher than the cost of the stairway. But in case the malfunctioning elevator is planned to be between the rehabilitation and the disabled department than there have to be an additional elevator for the failure case. So the cost of this additional elevator will be reduced.

In case the backup elevator or stairway could be used in another failure case as well, the capacity demand of that failure should also be considered.

The algorithm for determining the amount of capacity to be allocated for backup paths in a thrifty way is based on this idea how the total capacity C_e of each link e could be divided into three parts Figure 4:

- C'_e allocated to working paths;
- C''_e allocated for (shared) protection (i.e. spare capacity);
- $C_e - C'_e - C''_e$ the free, unallocated and unused capacity.

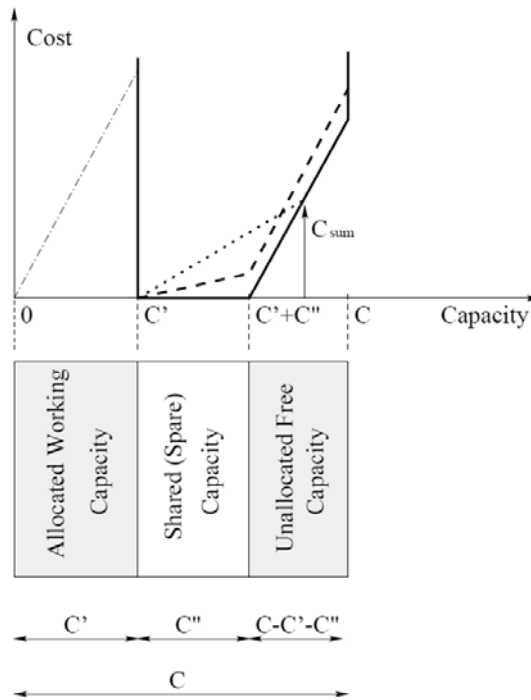


Figure 4. Three capacity cost models for protection paths

This way ‘shortest’ path means the path that requires the lowest resource allocation in sense of the capacity-cost functions, so the lowest resource allocation from the $C-C'-C''$ capacities (i.e. the lowest increment of C'' capacities).

For routing the protection path for demand o that has bandwidth b_o only that amount of capacity have to be reserved on each link that exceeds the capacity that is sharable by the considered demand over the considered link. The sum of these costs for all the links along a path will be minimal. This is the only metric to be used while routing. These paths $P_e''(o)$ are referred to as partially disjoint, shared protection paths for path $P_e'(o)$.

In case of dotted line, an alternative would be to make a single segment linear approximation of the two segments, however, the result would be sub-optimal.

In Figure 4 three capacity models are shown. In case of the *solid line*, the costs for capacity C'' and $C-C'-C''$ are zero and the original cost of the link respectively. In this case the shareable capacity is for free, till the unallocated free capacity is for the original cost. Cost for the shareable capacity as well with *dashed lines* should be assumed to avoid loops in the paths. But the problem is the same with both solutions: they result a non-linear cost function, both of them contains two separate linear sections. In case of *dotted line*, an alternative would be to make a single segment linear approximation of the two segments, however, the result would be suboptimal.

5. THE REFERENCE METHOD: SHARED PATH PROTECTION (SPP)

As the reference the well-known Shared Path Protection was used, where after routing the working path, an end-to-end disjoint protection path that requires the lowest cost in the sense of the capacity cost function is searched. Note, that to avoid loops and over lengthy paths the sharable capacity was not for free, but its unit capacity cost only a fraction of the cost of a unit of free capacity to be allocated. The same principle was used for all the evaluations in this paper: the cost ratio was 1:10.

A brief description is given of the Shared Path Protection algorithm. The algorithm works as follows:

- Step 1: For the new demand o_{new} :
 - Find the shortest working path.
 - Delete (hide) temporarily all the links of the working path.
- Step 2: For all links l' of the working path:
 - For all links l'' of potential protection paths:
 - Compute capacity $c_{l',l''}$ required on link l'' when link l' fails (Figs. 3 and 1).
- Step 3: Find the largest value $c_{l'}$ of $c_{l',l''}$ for all l' found so far.
- Step 4: Calculate the cost increment required for routing the protection path of bandwidth requirement b_o of demand o_{new} according to Fig. 2 based on $c_{l'}$ along all the links l'' in the network.
 - Step 5: Based on the cost increments obtained find the shortest protection path.
 - Step 6: Store the new paths, de-allocate resources for terminated connections, update the capacity allocations.
 - Step 7: If more new demands arrive go to Step 1.

In particular, Shared Path Protection (SPP) is a really fast and easy way of shared protection, without the capability of rerouting (rearranging) the previously allocated protection paths. But in meanwhile it is wasting the resources.

6. PROPOSED METHODS FOR SOLVING THE PROBLEM

In the previous section the reference method was presented. Now the idea of LD will be introduced followed by the the MILP formulation of Protection Re-arrangement and the two proposed methods, namely Shared Path Protection with Link Doubling (SPP-LD) and Partially Disjoint Shared Path protection with Link Doubling (PDSP-LD).

6.1 Link doubling

A modeling methodology referred as Link Doubling (LD) was presented in [14] that allows solving Minimum-Cost Multi-Commodity Flow (MCMCF) [12] problems is proposed. In Section Chapter 0Case 1 it was explained why LD is needed, now it is explained how it works.

Here Link Doubling (LD) is introduced. LD is not an algorithm in itself but a modeling-

trick however it is the basis of several proposed algorithms that allows distinguishing the sharable part of the link capacity from the free capacity. This could be used as well when multiple protection paths are rerouted simultaneously. LD allows finding optimal routing of shared protection paths for the case of link failures. Remember, that if two demands have a common link l' in their working paths, then they may not share capacity on link l' (Figure 3).

In LD a modeling trick is used to be able to represent the two-segment cost function as shown in Figure 4 by solid line, or rather by the dashed line, to avoid unnecessarily long paths. Since the two-segment capacity-cost function is a non-linear one it could not be used neither in an MILP (Integer Linear Program) formulation, nor by the Dijkstra's algorithm. Therefore, linearization is needed.

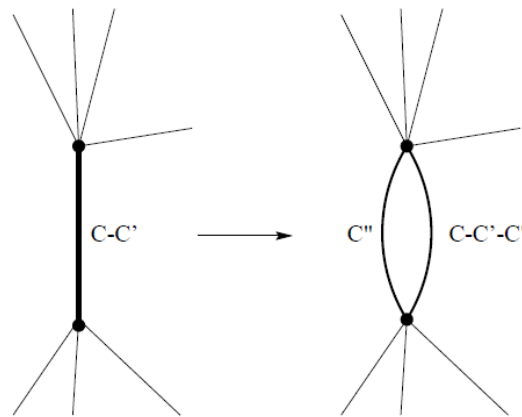


Figure 5. Illustration of the link doubling

The idea here is to use two parallel links (as shown in Figure 5) that both have linear capacity cost functions and represent the two segments of the cost function shown in Figure 4. The link representing the shared spare capacity will have capacity C'' and the other link, which represents the free capacity $C - C' - C''$.

The drawback is, that the number of links doubles in the worst case and therefore the runtime becomes longer, while the advantage is to have optimal result.

For routing multiple shared protection paths a Mixed Integer Linear Programming (MILP) formulation is needed. Using LD the problem will be linear and feasible.

6.2 MILP formulation

In this section the MILP formulation of the problem of routing multiple shared protection paths simultaneously is presented. The protection rearrangement means as we assume a failure, first the considered protection paths are removed from the graph, all the free and sharable capacities are recalculated and then all the removed and the new protection paths are routed simultaneously as follows.

Objective:

$$\min \sum_{o \in T_e} \left\{ \sum_{l \in E^{free}} x_l^o \omega_l + \sum_{l \in E^{sh}} x_l^o \gamma_l \right\}$$

where E^{sh} is the set of all added (doubled) edges, with capacity C'' , representing the shareable part and E^{free} with capacity $C - C' - C''$ being the set of edges that represent the remaining free capacity of all edges. Now $E' = E^{sh} \cup E^{free}$. Note that E' is the extended set of edges in contrast to E . Note that the capacity used for working paths is not represented in this graph. If there is no shareable or no free capacity along a link, then the corresponding link can be left out from the LD-graph the graph obtained by LD.

Here, γ_l represents the cost of a capacity unit for the shareable spare capacity on link l . It can take values $0 \leq \gamma_l \leq \omega_l$. If it is 0, then too long paths may appear. If it is equal to ω_l then shareable capacity is not preferred to free at all. Extensive simulations were shown that the best results can be achieved by setting $\gamma_l / \omega_l \approx 0.1, \forall l \in E$. Note, that here x_l^o is not a binary indicator variable, but it represents the amount of flow of demand o over link l . T_e is the set of those demands o for which the shared protection paths are routed simultaneously. This set typically depends on an edge e , which is within the working path of the demand that has been routed just before the protection path rearrangement is started. The composition and meaning of the set T_e will be discussed in more details in a next study discussing algorithms SPP-LD and PDSP-LD.

Subject to:

$$\sum_{o \in T_e} x_l^o \leq C_l - C'_l - C''_l \text{ for all links } l \in E^{free},$$

$$\sum_{o \in T_e} x_l^o \leq C''_l \text{ for all links } l \in E^{sh},$$

$$\sum_{j \in V, j \neq i} x_{ij}^o - \sum_{k \in V, k \neq i} x_{ki}^o = \begin{cases} 0, & \text{if } i \neq s_o \wedge i \neq d_o, \\ b_o, & \text{if } i = s_o, \\ -b_o, & \text{if } i = d_o, \end{cases}$$

for all nodes $i \in V$ and demands $o \in T_e$,

$$0 \leq x_l^o \leq b_o \text{ for all links } l \in E \text{ and demands } o \in T_e,$$

$$\sum_{k \in V, k \neq i} x_{ki}^o = b_o \cdot z_i^o \text{ for all nodes } i \in V \text{ and demands } o \in T_e,$$

$$z_i^o \in \{0,1\} \text{ for all nodes } i \in V \text{ and demands } o \in T_e.$$

where z_i^o is an auxiliary binary variable 0. Its role is to avoid flow branching, while it allows flow splitting between the pairs of parallel edges of an adjacent pair of nodes. Equations 0 and 0 are the capacity constraints for free and sharable capacities, respectively. Equation 0 is the well-known flow conservation constraint.

6.3 SPP-LD: Shared Path Protection with Link Doubling

Both SPP-LD and PDSP-LD use the MILP formulation of Link Doubling. The set T_e is the main difference between the SPP-LD and PDSP-LD. The basic idea of SPP-LD is that after

routing the working path of demand o we do not route its protection path only, but also the protection paths of all demands affected by routing the working path of demand o , all simultaneously. The requirement is that there is a single end-to-end protection path for each demand o that is disjoint with the working path of that demand only, i.e., a protection path may use any link except those used by its corresponding working path. Protection paths can share resources except if they have a common link in their working paths.

However, routing all these demands simultaneously, and considering all constraints on disjointness of working and protection paths appeared to be extremely complex and not feasible in reasonable time.

Therefore, an approximation of the above problem was used. The problem was decomposed in two ways. First to use the method separated on each domains and on each level of the hierarchy. And second by relaxing the “all simultaneously” constraint algorithmically, i.e., the links of the working path are considered one-by-one.

The algorithm works as follows:

- Step 1: For the new demand:
 - Find the shortest working path.
- Step 2: For the links e of the working path:
 - Delete temporarily link e .
 - De-allocate the protection paths of all the demands o that use e as a part of their working paths.
 - Set T_e to contain the new demand o_{new} and all the demands that used e as a part of their working paths.
 - Execute the MILP with added path diversity constraints.
- Step 3: If more links e go to Step 2.
 - Based on the knowledge of all working and protection paths currently present in the network calculate the capacity allocated for shared protection over all links.
- Step 4: If more new demands go to Step 1.

The path diversity constraint has not yet been discussed. It means, that a link e is either used by the working path of demand o or by its protection path or by non of them, but never by both of them. To avoid introducing new variables or by making real (continuous) variables binary (discrete) the simplest way was to simply leave out some of the variables that further decreased the complexity: If the working path of demand o uses link l then variable x_l^o is completely left out from the MILP formulation for edges representing both, the sharable and the free part of the link capacities. Note, this holds for the new demand o_{new} as well to have its protection completely diverse.

If a working path has more than one link in common with the working path of the new demand it can happen that it will have more than one protection paths. In that case any of them can be chosen. For simplicity reasons the latter found one is chosen. Then the capacities allocated for shared protection are calculated accordingly.

6.4 PDSP-LD: Partially Disjoint Shared Protection with Link Doubling

The difference between SPP-LD and PDSP-LD is that while SPP-LD requires end-to-end

disjoint protection paths, PDSP-LD will allow so-called partially disjoint paths as well. It means that protection paths will be allowed to have common parts with the working one. However, to be able to protect the working path in case of failure of any of its links more than one protection paths must be defined to cover all the failure cases.

As the numerical results show this leads to even better capacity sharing that results in better resource utilization, while the complexity (and running time) of the algorithm is about the same as of SPP-LD.

The algorithm differs only in the last item of Step 2, i.e. MILP is executed without forcing path diversity, i.e., since link e is deleted all the protection paths will exclude it. In this case a protection scenario for each link of a protection path is defined. Note that it can happen that a path will be protected in the same way in the case of failure of its different links.

7. NUMERICAL RESULTS

Simulations were used to compare the performance of the three algorithms SPP, SPP-LD and PDSP-LD on three models that consisted of 16, 22 and 30 nodes respectively. Table 1 shows the characteristics of the three models and the characteristics of the patient-flow offered to these buildings.

Table 1: Building-models used for simulation

Models of the buildings	16 functions	22 functions	30 functions
Number of the modelled functions	16	22	30
Density	0,59	0,49	0,47
Number of demands	646	709	1320
Number of arrival demand at one time	3,23	3,545	5,28
Time unit	200	200	250
Average holding time	15,55	25,06	19,89

To investigate different blocking ranges we have scaled the link capacities, not the traffic. Note that increasing uniformly the capacities of every link is analogous to decreasing bandwidth of traffic offered to the network. We have investigated roughly the 0% to 90% blocking range. The number of demands which were routed was large enough to make the influence on the initial transient negligible.

Fig. 5 shows the blocking ratios of demands of the three algorithms on three networks. The blocking drops as the capacities of all the links were scaled up. SPP-LD had typically slightly better performance than SPP. PDSP-LD had always the best performance except for the 30-node network in the 50-60 % blocking range. The enlarged figures within the figures show the range of practical interest.

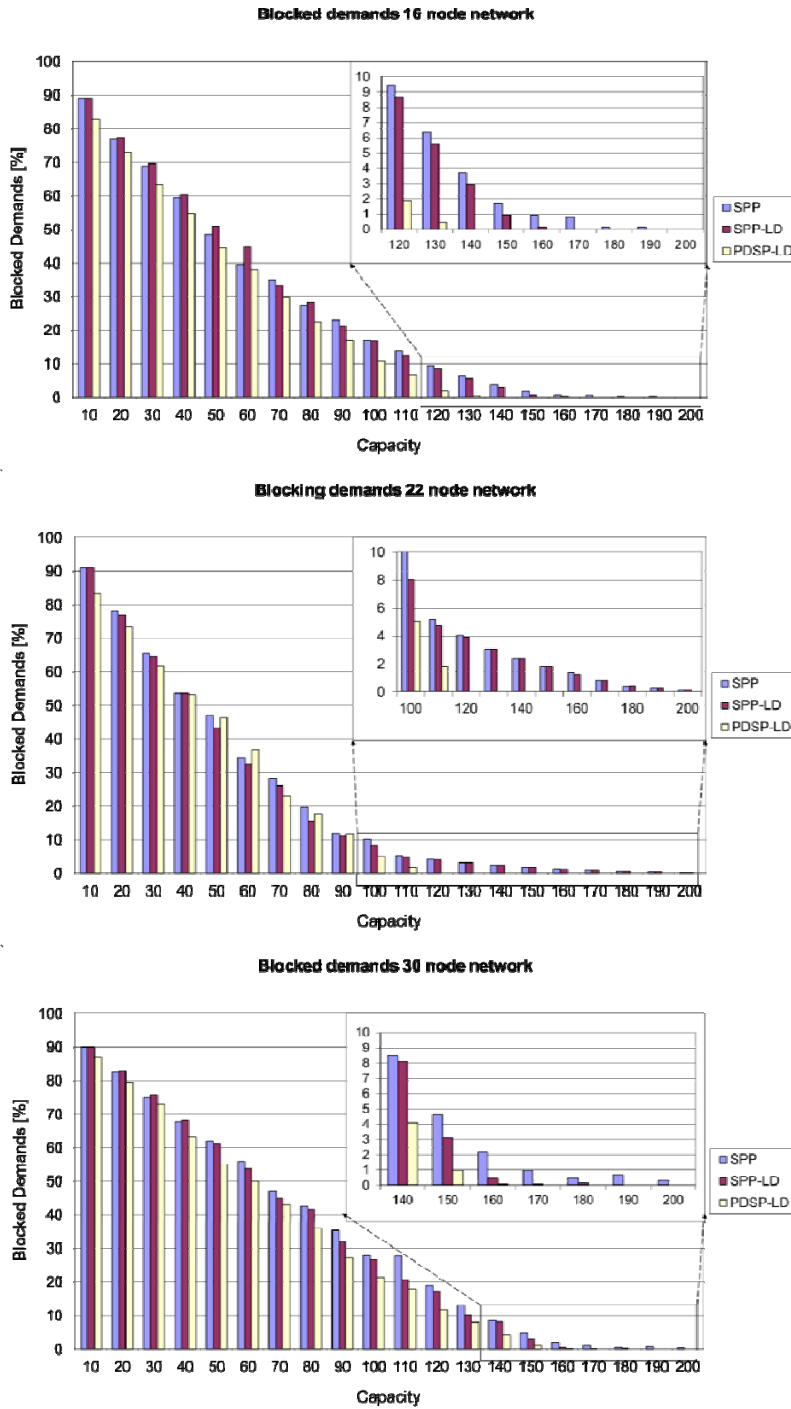


Figure 6. The blocking ratio in the buildings as the graph capacity increases (16, 22, 30 node graph model)

Figure 6 shows how the server capability changes in relation with the capacity of the buildings, and shows how much of the demands could not be served in a building with the given capabilities. Generally the SPP-LD algorithm has slightly better results than the SPP method (in some cases SPP performed better), but PDSP-LD results a significant improvement compared to the two other methods in all cases.

Our original target was to investigate the throughput of the buildings.

Using the SPP algorithm on the 16 functions model at least 200 units of capacity is needed to be able to serve the patient-flow defined for the test, while using SPP-LD this amount is only 170 units, with PDSP-LD it is only 140 units. This means that SPP-LD needs 15% less, PSDP-LD 30% less capacity than SPP method to achieve requirement of the reliable building.

Investigating from the other point of view, the up-scaling of the capacity equals the down-scaling of the demands. So the same building is said to be reliable with 15% more patient in case of SPP-LD and 30% more patient in case of PDSP-LD.

On the 22 functions model the results are the followings: the SPP and the SPP-LD performs similarly while PDSP-LD causes a 40% improvement. For the 30 functions model SPP-LD was able to serve 10% more patient and PDSP-LD to serve 20% more patient than the SPP algorithm meanwhile the building was operating without blocking patients. Table 2 shows the results of all three models.

Table 2: The maximum throughput of the buildings using the reference and the proposed algorithms

	SPP	SPP-LD	PDSP-LD
16 functions	100%	85%	70%
22 functions	100%	100%	60%
30 functions	100%	90%	80%

Figure 7 shows the average graph utilization for the complete building when the blocking was less than 1% for all the methods. Simulations showed that PDSP-LD allocates significantly less capacity in the buildings than SPP or SPP-LD. However, PDSP-LD uses slightly more resources for the working paths. In this respect SPP and SPP-LD allocated similar amount of capacity for the working paths and slightly less capacity for the protection paths.

Figure 8 shows the average running time of SPP on a logarithmic scale. The running time of SPP was much lower than the methods using protection rearrangement calculated with MILP.

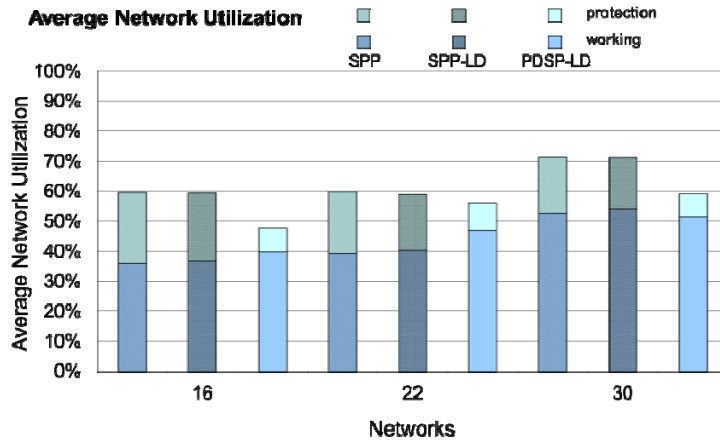


Figure 7. The average utilization of the buildings by working and protection paths for the three methods and for the three models

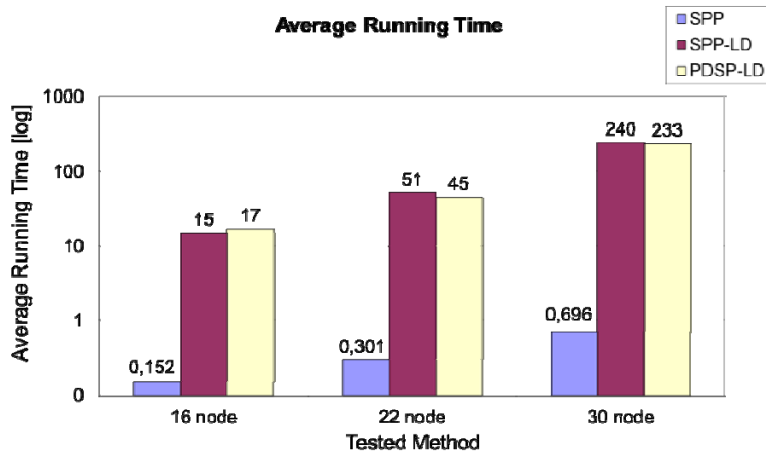


Figure 8. The running time average expressed in seconds on a logarithmic scale for the three methods for three buildings.

8. CONCLUSION

In this paper the importance of improving reliability and boundary conditions of the modeling in modern complex health-care building-systems was emphasized.

A cost efficient pre-phase solution of the mathematical modeling was presented, with introducing LD in order to linearize the two-segment capacity-cost functions to be used.

The mathematical model that was developed and detailed can be used as a part of the architectural planning workflow. The speciality of the model is the way how it represents the buildings' functions and the relationships between them. When modelling a complex healthcare building system containing multiple individual building units, hierarchical model

was used.

The shown method is to be used on the presented LD model to check whether a building complex is reliable or not in failure cases. One reference (SPP) and two proposed (SPP-LD and PDSP-LD) algorithms were introduced. The main goal is to enable the planning of reliable buildings with as few additional capacities (additional pathways, elevators, wider corridors, etc.) as possible.

The proposed optimization which is formulated as an integer linear programming problem is used iteratively on the separated parts of the hierarchical multi-domain graph model. The individual results of the subtasks are aggregated and do provide a result for the complete building: the whole complex building is reliable.

REFERENCES

1. Khan Nayma. Analyzing patient flow: Reviewing literature to understand the contribution of space syntax to improve operational efficiency in healthcare settings, *8th International Space Syntax Symposium, Santiago de Chile, Chile*, 3-6 January 2012, pp. 699-705.
2. Jeremy M, Ruchi C, Papalambros P. Architectural layout design optimisation, *Eng Optim* 2002; **34**(5): 461-84.
3. Guide to the design and construction of high performance hospitals, Homepage of BetterBricks, powerful energy ideas by NEEA, 2010.
http://www.betterbricks.com/graphics/assets/documents/DC_Healthcare_Broch0208_final.pdf, (last visited 25 June 2013).
4. Kaveh A, Salimbahrami B. Eigensolution of symmetric frames using graph factorization, *Commun Numer Meth En* 2004; **20**(12): 889-910.
5. Kaveh A. *Optimal Analysis of Structures by Concepts of Symmetry and Regularity*, Springer Verlag, GmbH, Wien-New York, 2013.
6. Kaveh A, Mahdavi VR. Colliding bodies optimization: A novel meta-heuristic method, *Comput Struct* 2014; **139**: 18-27.
7. Anikó Csébfalvi: ANGEL: *A Simplified Hybrid Metaheuristic for Structural Optimization, and Colony Optimization*, Rijeka: InTech Open Access Publisher, 2013, 107-27.
8. Anikó Csébfalvi: A new theoretical approach for robust truss optimization with uncertain load directions, *Mech Based Des Struc* 2014; **42**(4): 3-9.
9. Kaveh A. *Advances in Metaheuristic Algorithms for Optimal Design of Structures*, Springer Verlag, Switzerland, 2014.
10. Suurballe JW. Disjoint paths in a network, *Networks* 1974; **4**: 125-45.
11. Cinkler T, Meskó D, Viola G. A hierarchical and a non-hierarchical European multi-domain reference network: Routing and protection, *12th International Telecommunication Network Strategy and Planning*, New Delhi, India, November 6-9, 2006, pp. 101-5.
12. Ravindra KA, Magnanti TL, Orlin JB. *Network Flows: Theory, Algorithms and Applications*, Prentice Hall, 1993, pp. 108-13, pp. 649-95.

13. Ho PH, Mouftah HT. A framework for service-guaranteed shared protection in WDM mesh networks, *IEEE Commun Mag* 2002; **40**(2): 97-103.
14. Meskó D, Csébfalvi A. Modeling method in the architectural planning of reliable complex health-care systems, *Pollack Periodica* 2013; **8**(3): 35-46.