Austro2003: High Tech Forest Operations for Mountainous Terrain, October 5-9, 2003, Schlaegl - Austria

HARVEST LAYOUT PLANNING FOR HIGH-ALTITUDE PROTECTION FORESTS

Hans Rudolf Heinimann* and Karl Stampfer**
*Forest Engineering Group
Swiss Federal Institute of Technology ETH
CH-8092 Zurich, Switzerland
**Institute of Forest and Mountain Risk Engineering
University of Natural Resources and Applied Life Sciences
Peter-Jordan-Strasse 70/2, A-1190 Vienna, Austria
heinimann@fowi.ethz.ch; karl.stampfer@boku.ac.at

Keywords: harvest layout planning; protection forests, concurrent layout design, clustered stand structure, harvest swath pattern.

Abstract*:* *An increasing share in the forest area of the European Alps has to provide protection services to prevent natural hazards, such as avalanches, rock falls, erosion, and floods. Protection forests require special treatment to maximize sustained mechanical stability. Although there is a significant knowledge of growth characteristics and silvicultural regimes for high-altitude protection forests, there is a lack of knowledge of how to suit harvest layout to silvicultural layout.*
The paper aims to (1) outline the growth and management characteristics of high-altitude protection forests, (2) to provide an approach for harvest layout planning for cable-based systems under those conditions, (3) to discuss some typical harvest swaths geometry patterns for protection forest tending. Silvicultural interventions mainly consist of laying out about two regeneration slits per hectare, which have a size of about 0.05 hectares. The harvest engineer aims to concurrently suit the regeneration slit layout to the cable corridor layout for a whole area. This task is very demanding, and has still to be done manually. Defining harvests swaths geometry is the next step in layout planning. It has to define the spatial order of tree felling relating to cable road directions and to harvest system layout. Layout planning is the crucial step to minimize damages to residual trees, and to maximize economic efficiency of operations.

1. Introduction

The European Alps are a densely populated mountainous area in which interaction between natural hazards and human activities has been shaping the development of settlements and infrastructure. In many areas, forests have been providing protection against avalanches, rock fall, erosion, and floods. The Swiss national forest inventory estimated the share of forests, which provide direct protection services to about 15 to 20 percent of the total forest area of the central part of the Alps (Brassel and Brändli, 1999). Management of protection forests has been aiming at controlling protection services in order to maximize sustained mechanical resistance of stands to external strain. A majority of protection forests is located in high-altitudes. A stand life cycle of up to 300 years and special regeneration ecology are specific characteristics of those high-altitude forest ecosystems, which require special silvicultural treatment. Although there is a significant knowledge of their growth behavior and of corresponding silvicultural regimes (Mayer and Ott, 1991; Wasser and Frehner, 1996; Ott et al., 1997; Strobel, 1997), there is a lack of knowledge of how to suit harvest layout to silvicultural layout design.

The present paper aims (1) to outline the growth and management characteristics of high-altitude Norway Spruce forests, (2) to provide a harvest layout planning approach for cable-based systems and for those conditions, and (3) to discuss some typical harvest swath patterns for protection forest tending. The study followed a concurrent engineering philosophy (Chryssolouris, 1992), aiming to simultaneously suit silvicultural design to harvest layout design. It focused on Central European high-altitude forest ecosystems that are dominated by Norway Spruce. Additionally, it considered state-of-the-art practices for cable-based harvesting systems (Heinimann et al,. 2001). The paper first presents management regime characteristics for high-altitude forests, and then develops a framework for harvest layout planning.

2. Management regime for high-altitude protection forests

Management of protection forests differs from management for timber production. It aims at continually maintaining ecosystem stability on a high level. Stability is the ability of a system to persist and to remain qualitatively unchanged in response either to a disturbance or to fluctuations of the system caused by a disturbance (Heylighen, online; Heylighen, online). This understanding of stability combines the concepts of traditional stability and Holling's concept of resilience (Holling, 1973). Resilience is the ability of a system to make a smooth transition to a new stable state in response to changes in external conditions (Holling, 1973). The wider the range of external fluctuations in which the system can obtain a stable state, the greater is the resiliency of the system.

Based on this understanding, a forest ecosystem is a self-maintaining biological structure, which has the capability, to continuously regenerate and renew itself. Assuming that a protection forest is an engineering structure that consists of a structural system (stand structure, stand texture), and of structural members (trees), leads to the following tending objectives:

- Maintain mechanical resistance of a stand to external actions (snow, storms, rock fall) continuously on a high level (Structural System Function),
- Improve mechanical resistance of single trees against mechanical actions (Structural Member Function),
- Safeguard and foster adaptive capacity of the system, particularly regeneration and renewal capability of a stand (Resilience Function).

Science-based tending of protection forests is based on three components: (1) A thorough understanding of growth characteristics, (2) a vision how resistant stand structures should look like, and (3) a model how natural stands self-regenerate.

2.1. Growth characteristics

Growth of high-altitude Norway Spruce forests follow a characteristic growth curve (figure 1). It consists of three typical phases, (1) regeneration safeguarding, (2) major growth, and (3) regeneration. Typical figures for stand development are (Ott et al., 1997):

- A maximum reachable stand age of 250 to 300 years,
- A age of the regeneration at which it towers above snow cover of 50 to 80 years.

Growth characteristics let derive the following guidelines for a tending regime:

- Regeneration, which consists of the "regeneration-starting" and the "regeneration safeguarding" phases, have a share of about 40 to 50% in the total stand life-cycle. Therefore, regeneration is a continual task of a tending regime (Ott et al., 1997).
- The possibility to influence the shape of tree trunks and tree crowns by thinning measures is limited to the first half of the "main growth" phase (figure 1), corresponding to about 10% of the total stand life-cycle.

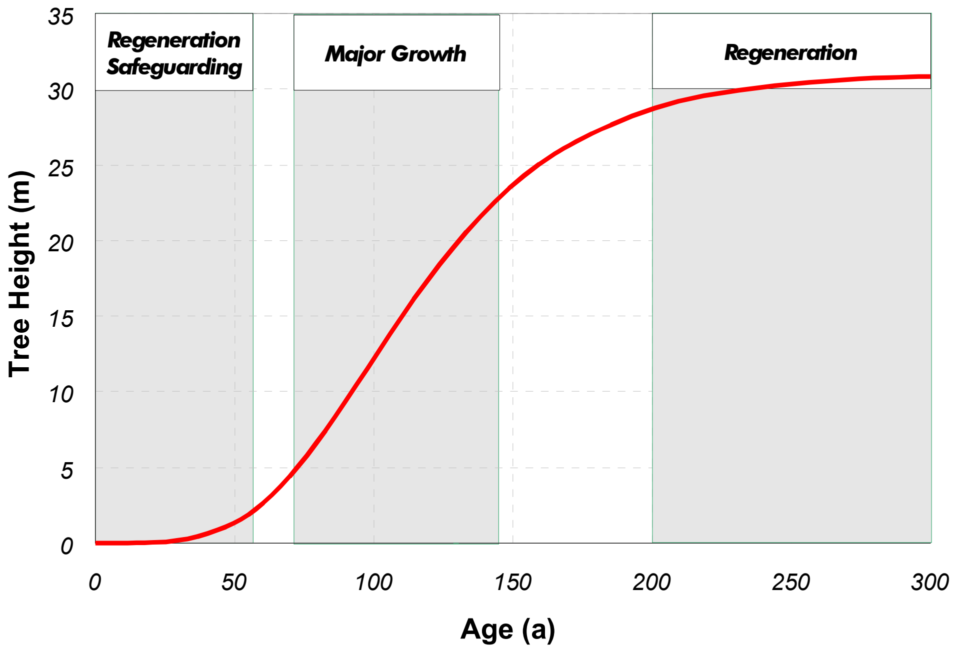


Figure 1: Height growth model for high-altitude Norway Spruce forests,
following (Strobel, 1997), modified.

2.2. Resistant stand structures

A model of how resistant stand structures should look like is the second component of a scientifically based protection forest tending regime. Forests in which Norway Spruce dominates are typical for many protection forests, which require specific silvicultural treatment (Mayer and Ott, 1991; Ott et al., 1997). In the European Alps, forest cover changes with increasing altitude. High-elevation forests near the timberline have a resolved crown surface with a clustered, lump-patterned distribution of trees. This discontinuous, lumpy template in space and time is called "Rotten-Struktur" (German), which could be translated into "clustered" or "lumped" stand structure. A cluster cell is a small group of trees, which are arranged densely, have high height variability and a collective outer branch surface that almost reaches the ground surface (Mayer and Ott, 1991). This type of lumped stand structure emerges in high-altitudes in which snow cover has a dominating influence on regeneration. Figure 2 illustrates a lump-patterned cell model for subalpine Norway Spruce stands, being based on the following assumptions (Ott et al., 1997):

- Growth characteristics follow the model of figure 1,
- A single cluster cell has a diameter of about 12m,
- The space between the branch surfaces two neighboring cluster cells is at least 2m,
- Cluster cells are all of the same size and are arranged hexagonally, corresponding to a triangular arrangement of cluster centers at 14m distance,
- There has to be a balance of inflowing cluster cells at the beginning of the stand life-cycle and of out flowing cluster cells at the end of the stand life-cycle. This leads to the requirement, that the share of a specific stand development phase has to be proportional to the time that is needed to grow through it.

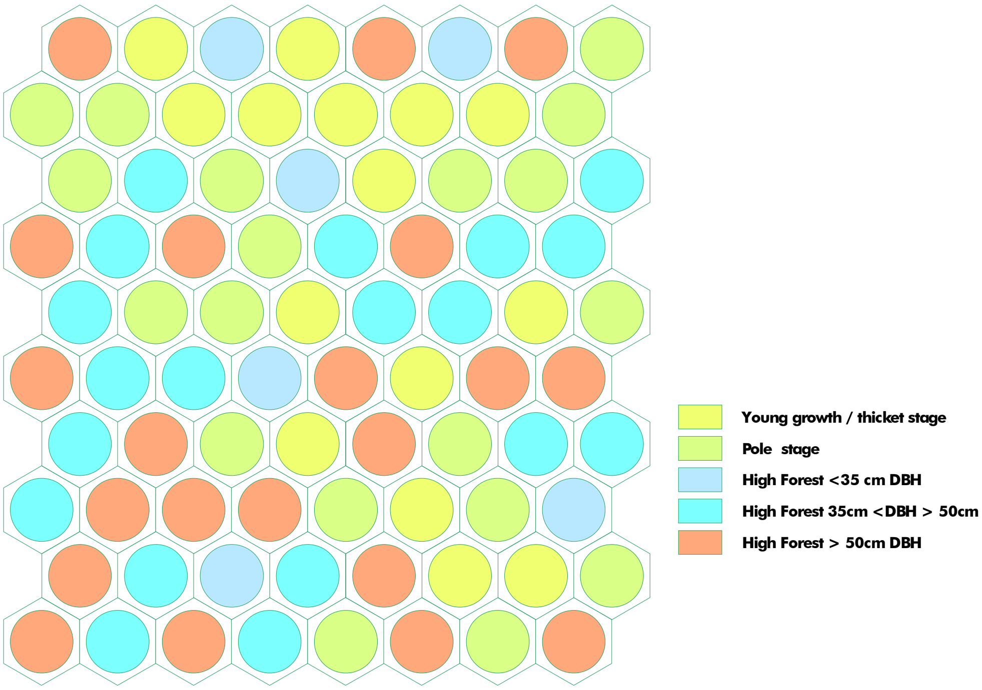


Figure 1: Lump-pattern cell model for high-altitude Norway Spruce stands.
„Honeycomb-structures“ are fault-resistant. They embody a high stability; disturbance of single cells alters systems characteristics only insignificantly.

Figure 2 illustrates a “honeycomb-model” for a model stand structure, which is. fault-tolerant and can continuously maintain protective resistance to natural hazards. Failure of single cells does not affect structural resistance. Different life-cycle phases are present side by side, and the spatial honeycomb structure forms the goal that silviculture tries to achieve.

2.3. Regeneration Slits

A model how natural stands self-regenerate is a third component of a scientifically-based protection forest tending regime. A clustered stand structure is the starting point of the considerations. Regeneration initiates when single cluster cells (figure 2) collapse or are artificially removed. This creates well-aimed openings into the crown surface (Ott et al., 1997). Those enable seedlings to settle due to the incident of light and heat that trigger regeneration. However, in some cases, especially on northwards exposed slopes, the amount of heat falling on the ground is too little. In those cases, slim slits, which are oriented towards the morning or the afternoon sun create openings into the crown surface that increase the amount of heat falling on the ground (figure 3). Figure 3 illustrates the layout of a “regeneration slit” that is typical for northern exposed slopes in higher elevations of the Alps.

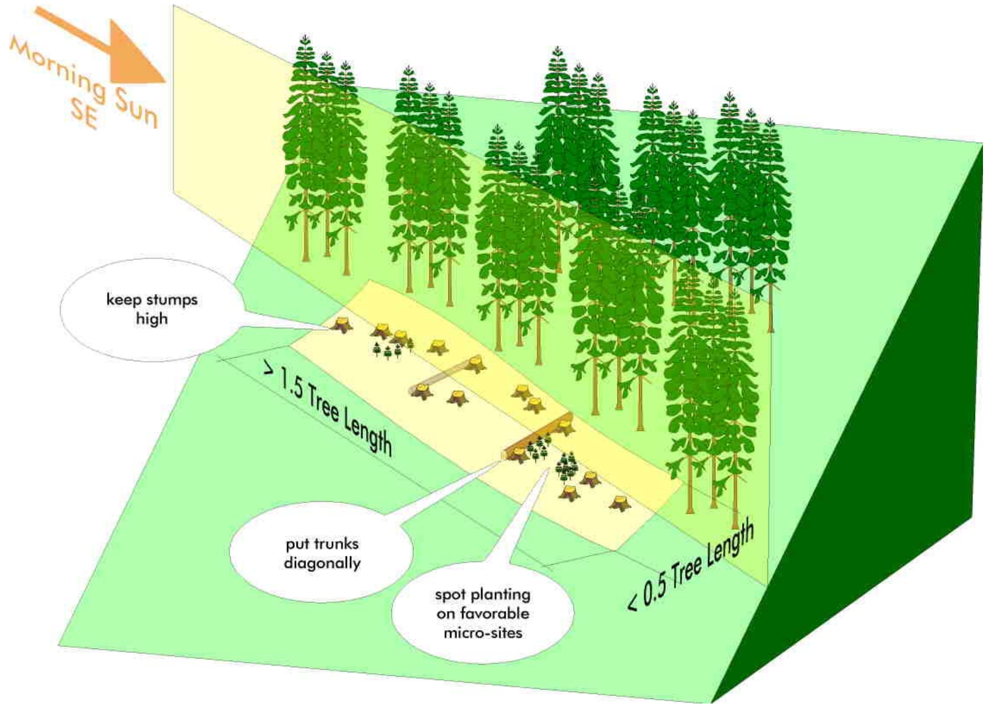


Figure 2: Regeneration slit model (Ott 1989). Layout, which is typical for subalpine Norway Spruce stands on northern exposed slopes of the Alps to initiate natural regeneration.

2.4. Silvicultural regime

Stand age is often the guiding variable to control silvicultural interventions. In high-altitude forests, age is difficult to estimate, why tree height is a more practical guiding variable. Figure 4 shows a silvicultural regime for protection forests that reverses the axis of figure 1.

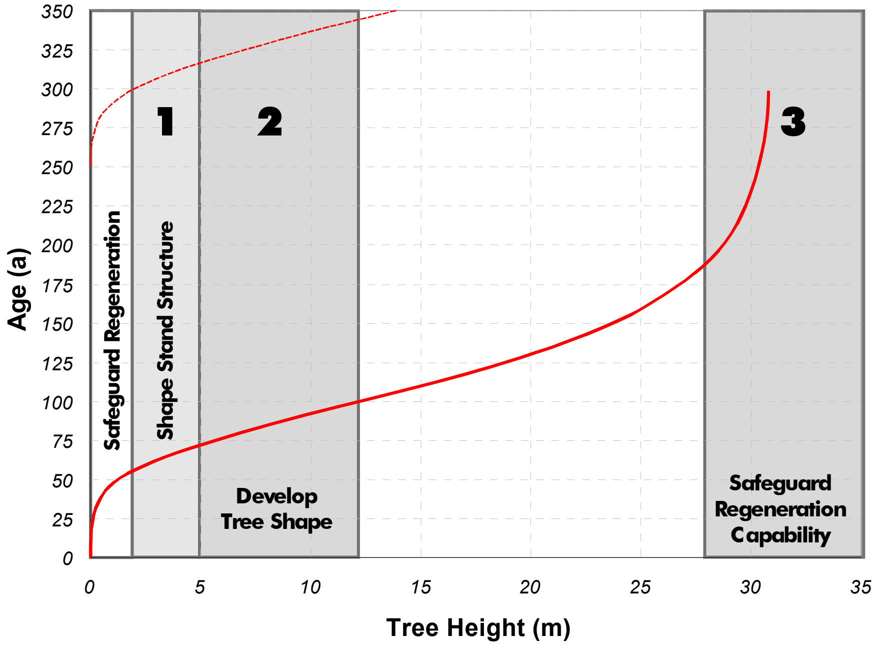


Figure 3: Silvicultural regime for high-altitude Norway Spruce forests.

Three stages of silvicultural intervention may be identified:

- The ***"stand structure shaping" phase*** (from 1.8m to about 5m of stand height) lay the foundation for the future "engineering structure" (stand structure and texture) and for the future stability of the system (Mayer and Ott 1991). About 15 to 35 clustered initial regeneration spots per hectar are needed to ensure continual renewal of the stand. In many cases there are less spots than required resulting in over-aging of the stands (Brang and Duc 2002; Wunder and Brang 2003).
- The ***"trunk and crown shaping" phase*** (from 5m of stand height to about 12m) aims at obtaining a stand texture that maximizes resistance to mechanical strain. Tending intervention have to occur in a phase of the stand's life-cycle in which trees react quickly to silvicultural stimuli. They should seek for minimal intervention and should never dissolve single clusters (Mayer and Ott 1991). Tree shaping measures should occur in an early phase of the stand's life-cycle and should end at a stand height of 10 to 12 m.
- The ***"renewal" phase"*** opens the crown surface well-aimed to initiate the establishment of seedlings of the next stand generation. Type, layout and size of openings have to consider site-specific characteristics. Openings aim at (1) bringing a sufficient amount of heat on the ground, and (2) minimizing accumulation of snow and the area exposed to the wind (Ott et al. 1997).

The "renewal" phase is decisive for planning and implementing harvesting operations, because only this tending phase produces utilizable logs. Therefore, spatial layout of regeneration-slits will be guiding for harvest planning and layout.

3. Harvest Layout Planning

3.1. Framework

Plans serve to support and improve decision-making of individuals, or group of individuals. Therefore, it is a problem-solving activity that models and anticipates consequences of actions before they are implemented in the real world. The framework that will guide the following considerations consists of a sequence of logical, rational thinking steps by decomposing the problem of harvest planning into a set of sub problems. Harvest planning usually consists of three levels:

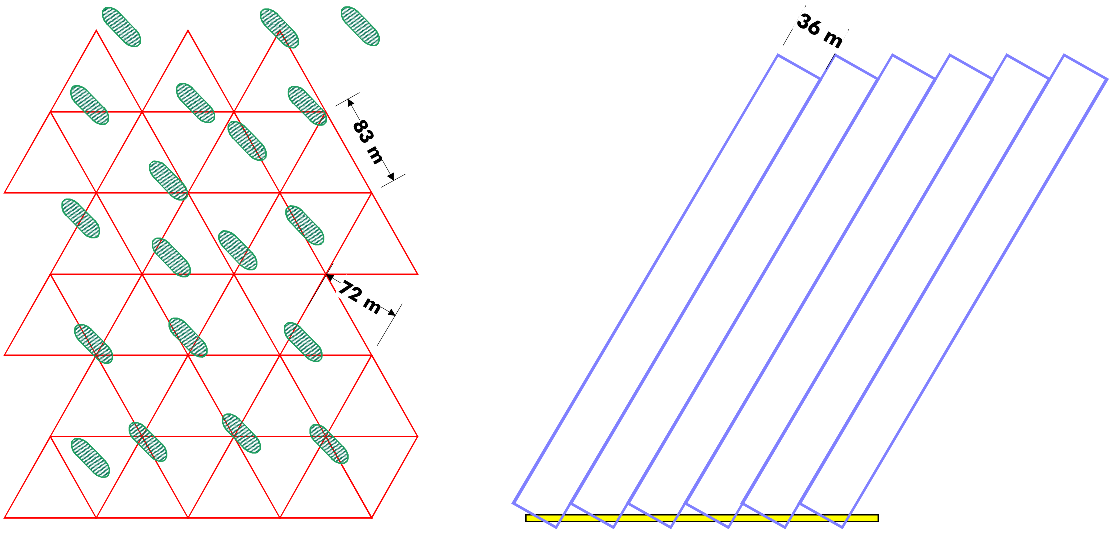
- ***Conceptual Design***. Definition of relevant design parameters, such as regeneration slit spacing, road spacing, stratification of cable-based terrain units, etc.); allocation of terrain units to harvest technology paths “ground-based”, “cable-based”, “airship-based”.
- ***Layout Design***. Spatial layout of landings for “ground-based”, “cable-based”, and “airship-based” harvesting systems; allocation of terrain units to landings; layout of the road network.
- ***Operations Design:*** Spatial layout of yarder location, anchors, and intermediate supports; analysis of the cable structure.

3.2. Conceptual Design

At present, the design of industrial manufacturing systems usually follows a concurrent engineering approach (see (Chryssolouris, 1992). It aims at coordinating product specifications with process specifications. In analogy to it, specifications of silvicultural interventions and specifications of harvesting operations have to be balanced. Planning starts with suiting silvicultural to operational specifications, building the foundation for the analysis of physical feasibility. A next steps chooses a log manufacturing (Cut-To-Length CTL, Tree-Length TL, or Full Tree FT) and an off-road extraction principle (ground-based, cable-based, airship-based).

Concurrent conceptual design defines the parameters for

- The layout of regeneration slits,
- The spatial stratification of extraction principles “ground-based”, “cable-based”, “airship-based”,
- The spacing of transportation lines (roads, cable roads, skid roads, skid trails).



Layout of Regeneration Slits **Layout of Cable Corridors**

Figure 4: Concurrent conceptual layout. Aims at making the silvicultural layout and the cable corridor layout coincident.

Conceptual design develops a model how silvicultural measures and transportation lines will be spatially arranged optimally. Figure 5 illustrates an example for cable-based terrain. It is based on the following assumptions: maximum stand age is 250 years; the time between two silvicultural interventions is 25 years; the average area per regeneration slit is o.o6 hectares; regeneration slits are evenly distributed over the area. Those assumptions result in a side length of a triangle layout of 83 meters, corresponding to a spacing of 72 m between parallel lines (figure 5). The problem to be solved is what pattern of cable corridor layout fits best to the regeneration slit layout. The model case of figure 5 shows that a corridor width of 72m would be coincident with the triangular slit grid. However, a corridor width of 72m is not acceptable due to the high lateral yarding distances. The solution is to split the 72m corridor into two 36m corridors. The derived design values are guiding the layout design activities, which will lead to a spatially feasible solution for a given area.

3.3. Layout Design

Layout design provides a harvesting solution for a given harvesting area. It aims to:

- evaluate the existing road network and fixes the locations of landings and yarders,
- allocate “harvest catchment areas” to landings,
- fix head and tail ends for each cable road (anchor points),
- define a harvest swath pattern that fits to the extraction system.

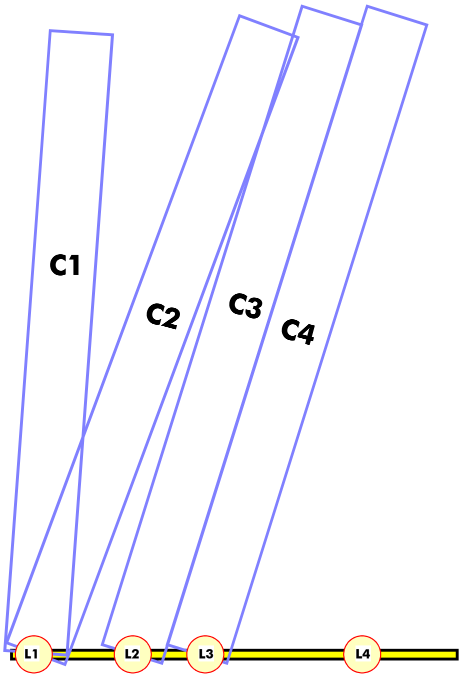


Figure 5: Layout design of cable corridors.
The process starts by identifying landing locations (L1 … L4) and then tries to find a corridor pattern (C1 … C4) that minimizes the number of corridors while maximizing the non-overlapping corridor area.

Figure 6 illustrates an example of layout design, which should result by applying the following procedure (table 1):

Table 1: Steps of layout design

Step	Activity	Problems to be solved
1	Locate regeneration slits	o Where in the terrain is it possible to locate regenerations slits ? [use information of aerial photographs and ground surveys] o What selection of possible regenerations slits results in a regeneration area that fits to the specifications of conceptual design?
2	Locate landings and yarder positions	o Where on the existing road network can 3- or 4-axle trucks run safely? o Where on the truck roads could we locate potential landings? o Where on the truck roads could we enlarge the roadbed width with minimal effort to build suitable landings and/or yarder sites?
3	Lay out cable corridors	o How do we have – starting from the landings – lay out cable corridors (1) to cover all regeneration slits with a minimum number of corridors, (2) minimize the number of intermediate supports, and (3) to minimize the overlapping area of cable corridors?
4	Survey cable roads in the terrain	o Where do we locate head anchors and tail anchors? [tower yarders require between 2 and 6 guylines, depending on the type] o Which trees will be used as anchors or as spars?
5	Identify stand cells (tree lumps) that have to be removed	o How do we have to locate regeneration slits to maximize heat falling on the ground by the morning sun, or by the afternoon sun, respectively (depending on site conditions)?

3.4. Harvest Swath Pattern Design

The next phase of layout design is to develop a harvest swath pattern model that fits to the harvesting system. The decisive factors of influence are: (1) yarding direction (uphill, downhill), and (2) the log manufacturing principle (cut-to-length CTL, full tree FT). The current practice for cable yarding is to use a full tree system for uphill yarding, and a cut-to-length system for downhill yarding. Figure 7 illustrates a harvest swath pattern model for uphill yarding with a full tree system. The cable road should run diagonally to the slope direction, resulting in some advantages. First, lateral yarding direction can follow slope direction for trees, which are lying downwards of the cable road. This minimizes impacts on residual trees. Second, diagonally running cable roads can be spaced more widely, resulting in larger yarding volume per cable road and therefore in lower cost. Third, they improve worker safety, because the risk of rolling stones and rocks decreases. Trees, which are lying above the cable road should be felled in parallel to make turning in into the cable road easier.

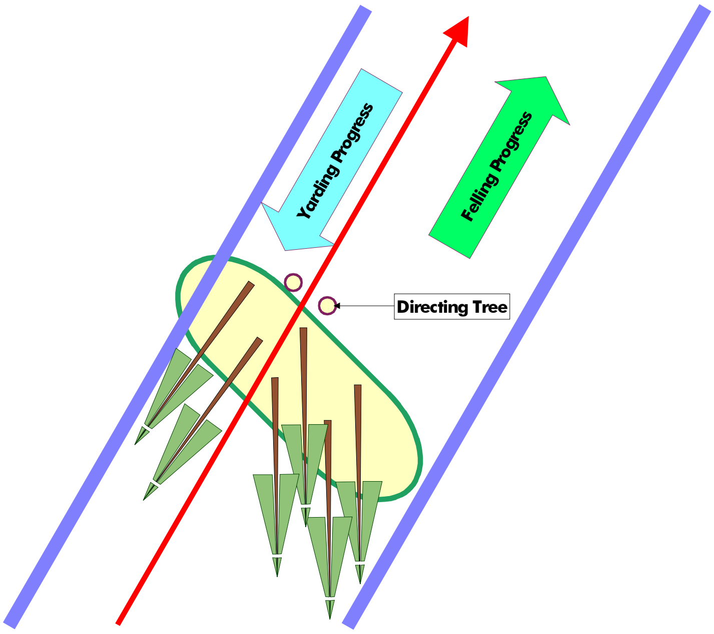


Figure 6: Harvest swath pattern for uphill yarding with a full-tree system.
Width of the cable corridor is about 30 m. Felling direction of the trees has to build an acute angle with the cable road. Trees should be topped.

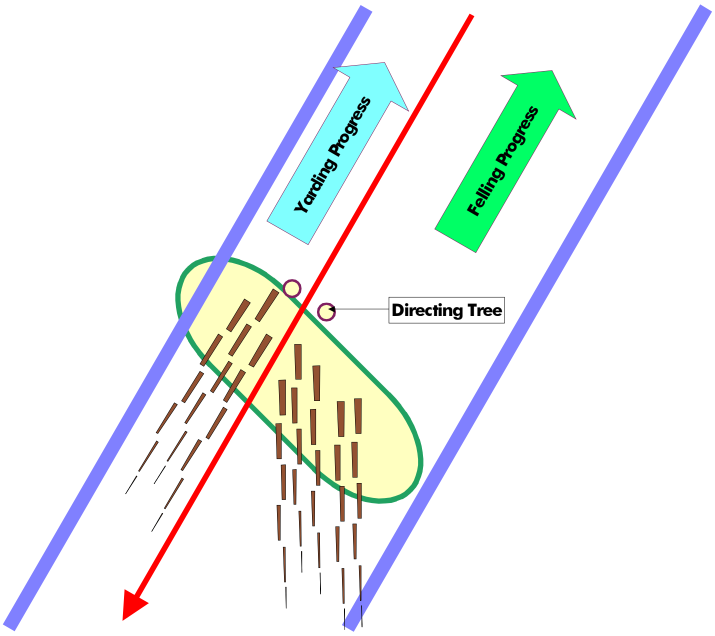


Figure 7: Harvest swath pattern for downhill yarding with a cut-to-length system
Width of the cable corridor is between 30 and 40 m. The felling direction for trees located above the cable road has to follow a direction that locates the logs as close as possible and as parallel as possible to the cable road. Felling direction of trees located below the cable road should enable logs to be laterally yarded in slope direction.

Figure 8 illustrates a harvest swath pattern model for downhill yarding by a cut-to-length system. Diagonally running cable roads have the advantage to minimize the risk of forest workers to be injured by rolling stones or rolling logs (Frauenholz and Schwendt, 1986). An optimal swath pattern results, if the felling direction of trees forms an acute angle with the cable road. Logs lying below the cable road can be yarded laterally in slope direction, whereas logs lying above the cable road can be brought to the cable road by manual skidding. Within regeneration slits, trees may be felled in parallel to the cable road and pulled in by the yarder. A felling direction sideways to the slope direction (parallel to the contour lines) may be adequate to protect initial stages of natural regeneration.

4. Conclusions

A significant share in the forest cover of the European Alps has to provide protection services to resist to natural hazards, whereas timber-provisioning services are of minor importance. The present paper investigated how silvicultural design and harvest layout design can be simultaneously suited to each other. It resulted in the following findings. (1) The renewal phase of the stand life cycle is decisive for harvest layout design, since it is the only phase at which merchantable timber is obtained as a product of silvicultural intervention. (2) Active stand regeneration aims at creating well-aimed openings into the crown surface, which take the form of slim slits that cover an area of about 0.05 ha each. (3) Concurrent layout design aims at making the silvicultural layout and the cable corridor layout coincident. Continual regeneration requires about 2 regeneration slits per hectare, corresponding to a triangular grid net of about 85 m side length. (4) Harvest swath pattern design has to define the spatial order of tree felling relating to cable road direction and to harvest system layout. It takes a corridor width of 30 to 40m as a starting point and locates the cable road diagonally to the slope line. Hence, lateral yarding from downhill may occur in slope direction, resulting in minimum residual stand damage.

The present method followed a concurrent engineering approach, attempting to make silvicultural layout and cable corridor layout coincident. Silvicultural work on protection forests (Mayer and Ott, 1991) and on cable logging planning (Aggeler, 2002) only touched the joint planning problem. The proposed approach provides a systematic procedure to derive the relevant design parameters, based on a growth and on a cluster cell model for high-altitude forest stands. However, there is still a need to get it validated through case studies. Aerial photographs and orthophotographs offer potential to support and improve layout design considerably. Future research will focus on developing computer aided engineering CAE tools for cluster cell-based silvicultural interventions. Recent work (Chung et al., 2003) could be a starting point to step forward.

5. References

Aggeler, R. (2002) Seilkrantechnik, 3., überarbeitete und erweiterte Ed. Maienfeld, BZWM Bildungszentrum Wald: CODOC Koordinations- und Dokumentationsstelle für das forstliche Bildungswesen, Lyss. div. p.

Brang, P. and Duc, P. (2002) Zu wenig Verjüngung im Schweizer Gebirgs-Fichtenwald: Nachweis mit einem neuen Modellansatz. Schweizerische Zeitschrift für Forstwesen, 152(6): 219-227.

Brassel, P. and Brändli, U.-B. Eds. (1999) Schweizerisches Landesforstinventar. Ergebnisse der Zweitaufnahme 1993-1995. Bern, Stuttgart, Wien, Haupt.

Chryssolouris, G. (1992) Manufacturing Systems. Theory and Practice Springer Texts in Mechanical Engineering. New York, etc.: Springer. 419 p.

Chung, W.; Sessions, J.; Heinimann, H. R. (2003) An application of a heuristic network algorithm to cable logging layout design. Journal of Forest Engineering.

Frauenholz, O. and Schwendt, F. (1986) Seilgelände - Verfahren, Organisation. FPP - Kooperationsabkommen Forst-Platte-Papier. Wien. Holzernte in der Durchforstung, 3. 113 p.

Heinimann, H. R.; Stampfer, K.; Loschek, J.; Caminada, L. (2001) Perspectives on Central European Cable Yarding Systems. In International Mountain Logging and 11th Pacific Northwest Skyline Symposium, eds. P. Schiess and F. Krogstad, 268-279. Seattle, WA, U.S.A. College of Forest Resources, University of Washington, Seattle, USA.

Heylighen, F. (online). Resilience [Accessed Jun-07 2003]. F. Heylighen, C. Joslyn and V. Turchin (editors). Available from WWW: [http://pespmc1.vub.ac.be/ASC/RESILIENCE.html]

Heylighen, F. (online). Stability [Accessed Jun-07 2003]. F. Heylighen, C. Joslyn and V. Turchin (editors). Available from WWW: [http://pespmc1.vub.ac.be/ASC/STABILITY.html]

Holling, C. S. (1973) Resilience and stability of ecological systems. Annual Review of Ecology and Systematics, 4: 1-23.

Mayer, H. and Ott, E. K. (1991) Gebirgswaldbau - Schutzwaldpflege. Ein waldbaulicher Beitrag zur Landschaftsökologie und zum Umweltschutz, 2., vollständig neu bearb. Aufl. Ed. Stuttgart [etc.]: Fischer. XVII, 587 pp.

Ott, E. K. (1989) Verjüngungsschlitz Prinzipskizze. Unterlagen zur Vorlesung Gebirgswaldbau.

Ott, E. K.; Frehner, M.; Frey, H.-U.; Lüscher, P. (1997) Gebirgsnadelwälder. Ein praxisorientierter Leitfaden für eine standortgerechte Waldbehandlung. Bern [etc.]: Haupt. 287 p.

Strobel, G. (1997) Rottenstruktur und Konkurrenz im subalpinen Fichtenwald eine modellhafte Betrachtung. Zürich: Schweizerischer Forstverein. 203 p.

Wasser, B. and Frehner, M. (1996) Wegleitung Minimale Pflegemassnahmen für Schutzwälder. Bundesamt für Umwelt, Wald und Landschaft (BUWAL). Bern.

Wunder, J. and Brang, P. (2003) Fichtenverjüngung im Gebirgswald: Erfolgskontrolle in Schlitzen. Informationsblatt Forschungsbereich Wald (13): 1-3.