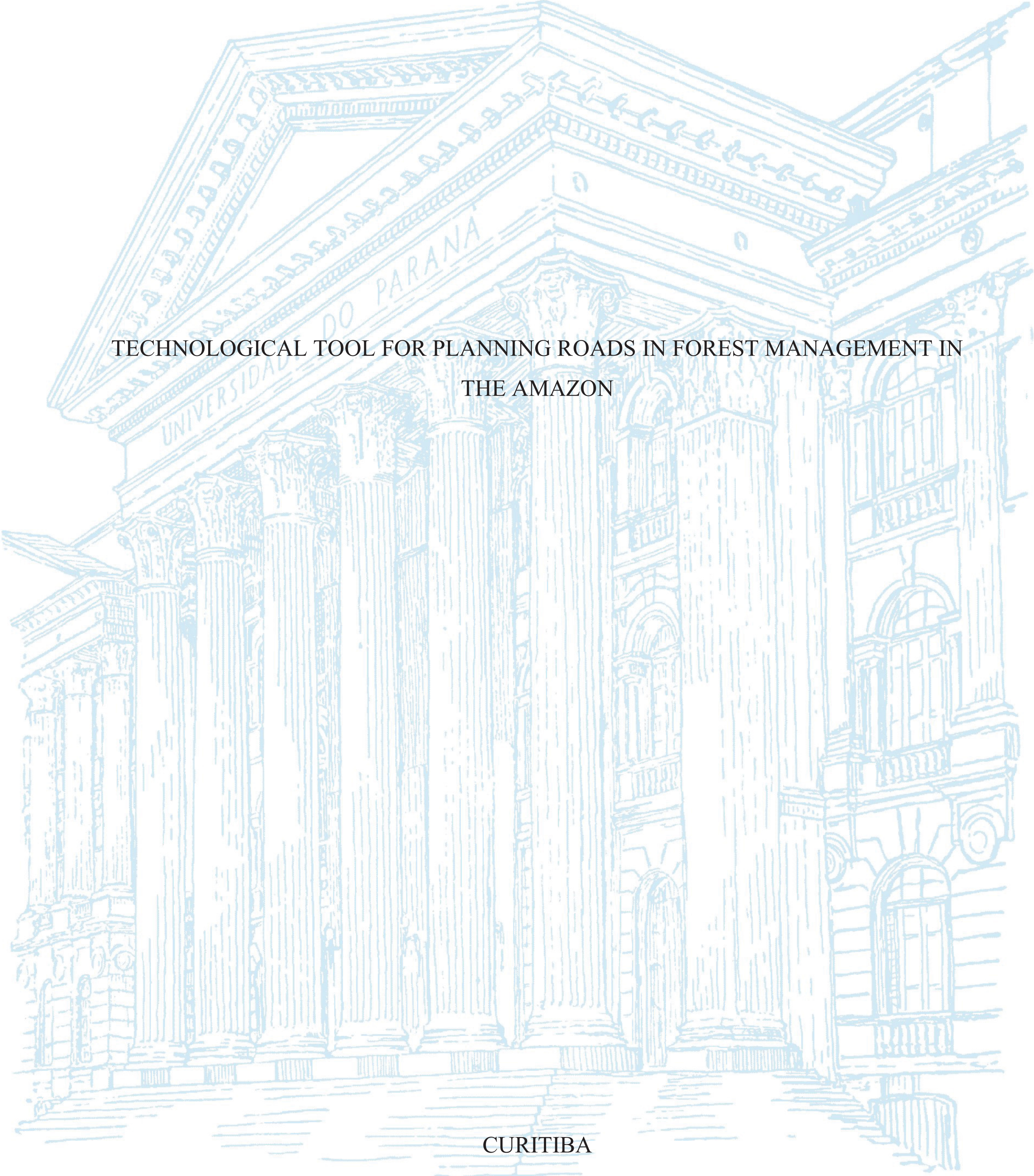
UNIVERSIDADE FEDERAL DO PARANÁ

VERÔNICA SATOMI KAZAMA



TECHNOLOGICAL TOOL FOR PLANNING ROADS IN FOREST MANAGEMENT IN THE AMAZON

CURITIBA
2021

VERÔNICA SATOMI KAZAMA

TECHNOLOGICAL TOOL FOR PLANNING ROADS IN FOREST MANAGEMENT IN THE AMAZON

Tese apresentada ao curso de Pós-Graduação em Engenharia Florestal, Setor de Ciências Agrária, Universidade Federal do Paraná, como requisito parcial à obtenção do título de Doutora em Engenharia Florestal.

Orientadora: Profa. Dra. Ana Paula Dalla Corte

Coorientadores: Prof. Dr. Carlos Roberto Sanquetta
Prof. Dr. Renato Cesar Gonçalves Robert

CURITIBA
2021

Ficha catalográfica elaborada pela
Biblioteca de Ciências Florestais e da Madeira - UFPR

Kazama, Verônica Satomi
Technological tool for planning roads in forest management in the Amazon / Verônica Satomi Kazama. - Curitiba, 2021.
1 recurso eletrônico : PDF.

Orientadora: Profa. Dra. Ana Paula Dalla Corte
Coorientadores: Prof. Dr. Carlos Roberto Sanquetta
Prof. Dr. Renato Cesar Gonçalves Robert
Tese (Doutorado) - Universidade Federal do Paraná, Setor de Ciências Agrárias, Programa de Pós-Graduação em Engenharia Florestal.
Defesa: Curitiba, 17/08/2021.
Área de concentração: Manejo Florestal.

1. Florestas - Manejo - Amazônia. 2. Estradas florestais - Planejamento - Amazônia. 3. Análise espacial (Estatística). 4. Teses. I. Dalla Corte, Ana Paula. II. Sanquetta, Carlos Roberto. III. Robert, Renato Cesar Gonçalves. IV. Universidade Federal do Paraná, Setor de Ciências Agrárias. V. Título.

CDD – 634.9
CDU – 634.0.6(811)

Bibliotecária: Berenice Rodrigues Ferreira – CRB 9/1160

MINISTÉRIO DA EDUCAÇÃO
SETOR DE CIÊNCIAS AGRÁRIAS
UNIVERSIDADE FEDERAL DO PARANÁ
PRÓ-REITORIA DE PESQUISA E PÓS-GRADUAÇÃO
PROGRAMA DE PÓS-GRADUAÇÃO ENGENHARIA FLORESTAL - 40001016015P0

TERMO DE APROVAÇÃO

Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação em ENGENHARIA FLORESTAL da Universidade Federal do Paraná foram convocados para realizar a arguição da tese de Doutorado de **VERÔNICA SATOMI KAZAMA** intitulada: **TECHNOLOGICAL TOOL FOR PLANNING ROADS IN FOREST MANAGEMENT IN THE AMAZON**, sob orientação da Profa. Dra. ANA PAULA DALLA CORTE, que após terem inquirido a aluna e realizada a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.

A outorga do título de doutor está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

CURITIBA, 17 de Agosto de 2021.

Assinatura Eletrônica
18/08/2021 14:12:07.0
ANA PAULA DALLA CORTE
Presidente da Banca Examinadora

Assinatura Eletrônica
18/08/2021 13:49:25.0
EVALDO MUÑOZ BRAZ
Avaliador Externo (EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA)

Assinatura Eletrônica
18/08/2021 15:44:07.0
VAGNER ALEX PESCK
Avaliador Externo (UNIVERSIDADE ESTADUAL DO CENTRO-OESTE)

Assinatura Eletrônica
23/08/2021 10:03:50.0
MARIANA PERES DE LIMA CHAVES E CARVALHO
Avaliador Externo (UNIV.DE SÃO PAULO/ESCOLA SUP. DE AGRICULTURA LUIZ DE QUEIROZ)

Assinatura Eletrônica
18/08/2021 20:52:00.0
KARLA DA SILVA ROCHA
Avaliador Externo (UNIVERSIDADE FEDERAL DO ACRE)

Dedico este trabalho aos meus pais Paulo e Margarida, e aos meus irmãos pelo suporte constate na minha vida.

Ao Mario pelo apoio incondicional nesta jornada de crescimento profissional.

À todos os professores que contribuíram para minha trajetória até aqui.

AGRADECIMENTOS

Agradeço à Deus pela vida.

À minha família, em especial meus pais, Paulo Mikio Kazama e Margarida Imako Aoki Kazama, aos meus irmãos Alberto, Alexandre, Priscila, Licka, Flávia e Hugo, e ao meu companheiro, Mario, e sua família pelo apoio e incentivo constante.

À minha orientadora Profa. Dra. Ana Paula Dalla Corte, pelo aceite da orientação no doutorado e do meu projeto de estudo e pela paciência, compreensão e auxílio nas diversas questões profissionais e pessoais durante essa fase, que foram fundamentais para qualidade do desenvolvimento deste trabalho.

Aos meus coorientadores Prof. Dr. Carlos Roberto Sanquetta e Prof. Dr. Renato Cesar Gonçalves Robert pelas contribuições e paciência no processo de desenvolvimento da tese.

À Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) pela bolsa de estudos concedida.

À Universidade Federal do Paraná por conceder a oportunidade de acesso gratuito ao ensino de qualidade e suporte saúde pelos profissionais da CASA 3 e 4, em especial a Dra Lúcia.

Ao Programa de Pós-Graduação em Engenharia Florestal (PPGEF) – UFPR pela oportunidade de ingressar no programa e permitir efetuar disciplinas internas e externas e desenvolver esta pesquisa.

Aos professores do PPGEF pela dedicação, inspiração e compartilhamento de seus conhecimentos, que fazem toda diferença para nossa carreira profissional.

À empresa AMATA A.S pela disponibilização dos dados e a oportunidade de acesso a unidade de manejo florestal (UMF), em Itapuã do Oeste em Rondônia, e em especial seus funcionários, Matheus, Luizinho, Christian, Cleudonar e Evilson, que me prestaram todo suporte no escritório e no campo da empresa. E ao Marcos, da empresa terceirizada – Terra Assessoria Ltda-me, pela disponibilidade de ajuda com informações técnicas das estradas florestais, que sua empresa executou na UMF da AMATA.

Aos amigos e colegas de laboratório Biofix pela companhia diária no trabalho, conversas descontraídas e troca de conhecimentos, em especial Aline, Franciel, Ana Paula, Ângela, Marks, Gabriel, Hudson, Iasmin, Adriane, Bruna, Deivison, Iací, Thiago e Maria Emília.

Ao professor Dr. Alexandre pela ajuda na verificação da análise estatística.

Aos colegas Daniel, Kauê e professor Dr. Júlio pela colaboração no trabalho, em especial ao Daniel pelo apoio na revisão do texto em inglês.

Aos amigos do PPGEF pela parceria nos eventos sociais, em especial Jorge, Franciele e Augusto que compartilharam moradia em Curitiba, pelos momentos de descontração, apoio e conversas.

Aos amigos dos grupos e salas de estudos virtual que participei durante a pandemia, em especial Lorena Barbosa, Lorena Stolle, Cátia e Rafael. Vocês foram muito importantes nessa fase difícil!

E por fim, à todas as pessoas que contribuíram de alguma forma para finalização do doutorado.

Arigatou gozaimasu!!!

“Cresça como uma árvore jovem, primeiro em altura, estudando e adquirindo conhecimentos, para depois abrir sua copa. Pois, assim como é para as árvores, as maiores oportunidades de sucesso na vida estão em maiores alturas.”

Paulo Mikio Kazama (2015)

“Feliz aquele que transfere o que sabe e aprende o que ensina.”

Cora Coralina

RESUMO GERAL

A construção de novas estradas é uma das infraestruturas florestais necessárias de maior custo e impacto ambiental. O objetivo deste estudo foi buscar avanços técnicos e científicos para subsidiar um planejamento de estradas florestais (PEF) adequado para área de Manejo Florestal Sustentável (MFS) na Amazônia, apresentado em dois capítulos. O capítulo I apresenta uma revisão da literatura mundial atual (2009-2019) sobre otimização de PEF como forma de apoiar futuras atividades de planejamento de infraestrutura viária em área de MFS na Amazônia. Por meio de uma meta-análise de 62 estudos, 45 variáveis espaciais, 11 métodos de análise de decisão espacial e 30 metodologias diferentes foram encontrados para otimizar projetos de estradas florestais. Abordagens existentes e potenciais para aplicação futura em PEF em área de MFS foram analisadas e discutidas. Os resultados encontrados no capítulo I apoiaram uma proposta metodológica para otimização espacial do planejamento e avaliação de estradas florestais, em nível do planejamento estratégico, apresentado no capítulo II. O desenvolvimento do capítulo II foi subdividido em três partes: duas primeiras partes para confecção da ferramenta de acordo com um planejamento otimizado de estradas (POE); e na terceira parte uma forma de avaliar as redes de estradas obtidas pelo POE comparado com as estradas construídas pelo planejamento tradicional (ECPT) nas áreas de estudo. As áreas de estudo foram duas unidades de produção anual (UPA): 06 e 14, localizadas em área de MFS, no estado de Rondônia, Brasil. Na parte I, foi realizada a modelagem da adequação espacial de estradas florestais (MAEEF) por meio de técnicas de Tomada de Decisão Multicritério (TDMC), com base em SIG (Sistema de Informação Geográfica). Para realizar o MAEEF, o método TDMC selecionado foi o *Analytical Hierarchy Process* (AHP), o método mais recomendado para PEF, conforme observado no capítulo I. As variáveis espaciais utilizadas (declividade, aspecto, rede hidrográfica, produtividade e cobertura e uso da terra) foram selecionadas de acordo com a literatura (capítulo I), a opinião de especialistas e uma visita em campo. Na parte II, o resultado do MAEEF foi utilizado para otimizar o traçado das estradas, com base no método *Least Cost Path Analysis* (LCPA), que foi baseado no algoritmo de Dijkstra e em três heurísticas de rede. Na parte III, para comparar e analisar as estradas definidas pelo POE e ECPT foram calculados para cada estrada: A) cinco parâmetros espaciais, que consistiam no comprimento de estrada por cada classe do mapa MAEEF (m): (i) excelente, (ii) médio, (iii) ruim, (iv) muito ruim e (v) extremamente ruim; B) sete parâmetros técnicos: (i) comprimento total; (ii) densidade de estradas; (iii) distância média entre estradas paralelas (iv) área coberta por estradas construídas; (v) número total de bueiros; (vi) número total de pontes e; (vii) número total de travessias de cursos d'água; C) seis parâmetros financeiros: (i) custo total de construção da estrada por área efetiva de APU e (ii) por hectare, (iii) custo total de instalação de bueiros e (iv) ponte, (v) custo total do curso de água travessias (bueiro + ponte), (vi) custo total de construção da rede viária. Estes parâmetros foram comparados pelo teste do qui-quadrado ($\alpha = 0{,}05$). O capítulo II mostrou que o POE permitiu reduções na densidade geral das estradas, nas travessias de cursos d'água e, consequentemente, reduções significativas nos custos totais de 5,0% (R$ 12.563,34) e 24,6% (R$ 118.261,41) da infraestrutura viária para UPAs 06 e 14, respectivamente. As melhorias encontradas na rede de estradas geral do POE foram estatisticamente significativas segundo todos os parâmetros espaciais, técnicos e financeiros em ambas as áreas. Portanto, se implementada, a ferramenta proposta para otimização espacial do projeto de estradas levará a um menor impacto ambiental sobre os recursos hídricos e do solo na Floresta. De acordo com os resultados obtidos nos capítulos I e II, é possível concluir que este estudo obteve contribuições técnico-científicas relevantes para apoiar o PEF na área de MFS na Amazônia.

Palavras-chave: Revisão sistemática. Planejamento florestal. Análise espacial. Infraestrutura florestal. Floresta Amazônica.

GENERAL ABSTRACT

The construction of new roads is one of the most costly and environmentally impactful necessary forestry infrastructures. In this sense, the present study aimed to seek technical-scientific advances to support adequate planning of forest roads in Sustainable Forest Management (SFM) areas within Amazonia, presented in two chapters. Chapter I presents a review of the current world literature (2009-2019) on Forest Roads Planning (FRP) optimization as a way to support future SFM road infrastructure planning activities in the Amazon. Through a meta-analysis of 62 studies, 45 spatial variables, 11 spatial decision analysis methods, and 30 different methodologies were found to optimize forest road designs. Existing and potential approaches for future application in FRP in SFM were analyzed and discussed. The results found in chapter I supported a methodological proposal for spatial optimization of the PEF and evaluation of roads at the strategic planning level, presented in chapter II. The development of chapter II was subdivided into three parts: two first parts to implement the tool according to an optimized road planning (ORP); and in the third part a way to evaluate the road networks obtained by the ORP compared to the roads built by the traditional planning (RBTP) in the study areas. The study areas were two annual production units (APU): 06 and 14, located in an SFM area, in the state of Rondônia, Brazil. In part I, the Forest Roads Spatial Suitability Modeling (FRSSM) was developed using Multi-Criteria Decision Making (MCDM) techniques, based on GIS (Geographic Information System). In the FRSSM, the Analytical Hierarchy Process (AHP) method was selected, which was the most recommended MCDM method for FRP, as noted in chapter I. The spatial variables used (slope, aspect, hydrographic network, productivity and land cover and use) were selected according to the literature (chapter I), expert opinion, and field reconnaissance. In part II, the result of the FRSSM was used to optimize route tracing, through the Least Cost Path Analysis (LCPA) method, which was based on the Dijkstra algorithm and three heuristics for network creation. In part III, to compare and analyze the roads by ORP and RBTP were calculated for each road: A) five spatial parameters, which consisted of the length of road for each FRSSM map class (m): (i) excellent, (ii) average, (iii) poor, (iv) very poor, and (v) extremely poor; B) seven technical parameters: (i) total length; (ii) road density; (iii) average distance between parallel roads (iv) area covered by built roads; (v) total number of culverts; (vi) total number of bridges and; (vii) total number of watercourse crossings; C) six financial parameters: (i) total cost of road construction per effective APU area and (ii) per hectare, (iii) total cost of installing culverts, (iv) total cost of the bridge, (v) total cost of watercourse crossings (culvert + bridge), (vi) total cost of construction of the road network. These parameters were compared using the chi-square test ($\alpha = 0.05$). Chapter II showed that the ORP allowed reductions in the general road density, in the crossings of watercourses and, consequently, significant reductions in the total costs of 5.0% (R$12,563.34) and 24.6% (R$ 118,261.41) of the road infrastructure for APUs 06 and 14, respectively. The improvements found in the general road network of the ORP were statistically significant according to all spatial, technical, and financial parameters in both areas. Therefore, if implemented, the proposed tool for spatial optimization of road design will lead to less environmental impact on water and soil resources in the Forest. According to the results obtained in chapters I and II, it is possible to conclude that this study obtained relevant technical-scientific contributions to support the FRP in the SFM area in the Amazon.

Keywords: Systematic review. Forest planning. Spatial analysis. Forest infrastructure. Amazon Rainforest.

LIST OF FIGURES

Chapter I

Fig. 1. Prisma Flow Diagram, workflow display of the systematic review process. 27

Fig. 2. Frequency and trend of published articles on the subject of forest road planning during the period 2009-2019. 29

Fig. 3. The number of publications by country where studies were conducted on forest road planning published during the period 2009-2019. 30

Fig. 4. The number of publications by author, combining primary authorship with co-authorship, on the subject of forest road planning published during the period 2009-2019. 31

Fig. 5. The number of publications in the period 2009-2019 classified by different optimization objectives employed in the planning of forest roads. 32

Chapter II

Fig. 1. Study site location map. 62

Fig. 2. Operational information of annual production units (APUs) 06 and 14: subdivision of work units (WU) (a); location of trees measured in the forest inventory, including commercial and non-commercial trees (b); environmental microzoning (c); and infrastructure (d). 63

Fig. 3. Methodological procedure of the study. 64

Fig. 4. Selected factors for the study (slope - SLO, hydrographic network distance - HYD, productivity - PRO, normalized difference vegetation index - NDVI, aspect - ASP) and final FRSSM map for APUs 06 and 14. 74

Fig. 5. Area in hectares (ha) and percentage (%) for each FRSSM class in APU 06 and 14...78

Fig. 6. Road built by traditional planning - RBTP (a) and optimized road planning - ORP (b) and their comparisons (c). 80

Fig. 7. Distributions of transformed values of parameters obtained from roads defined by optimized road planning (ORP') and from roads constructed by traditional planning (RBTP') for APUs 06 and 14. 81

LIST OF TABLES

Chapter I

Table 1. Multicriteria decision analysis methods used in forest road planning from articles published during the period 2009-2019..37

Table 2. Methods for optimizing the design of forest roads, publications from the period 2009-2019...39

Chapter II

Table 1. Environmental microzoning of the study area...63

Table 2. Rating table of the variables. 69

Table 3. Saaty's scale of intensity of importance..70

Table 4. Equations of technical and financial comparison parameters calculated for primary and secondary roads, as well as the road network for APUs 06 and APU 14............72

Table 5. Description of road, culvert and bridge construction costs.. 72

Table 6. Pair comparison matrix and their respective weights obtained by the AHP method.. 73

Table 7. Scores of factor classes (subfactors) used in the FRSSM map.................................75

Table 8. Other road network information defined by the traditional road planning (RBTP) and optimized road planning (ORP) for APUs 06 and 14.. 82

Table 9. The of the Chi-Square test P-values. 83

LIST OF APPENDICES

Chapter I

Table A.1. Classes of spatial variables used in the planning of forest roads, obtained from three databases of publications from the period 2009-2019. 44
Table B.1. Spatial variables most commonly used in the planning of forest roads, obtained from three databases of articles published in the period 2009-2019. 45
Table C.1 Methods for optimizing the design of forest roads, obtained from three publication databases in the period 2009-2019. 46

Chapter II

Table A.1. Calculated spatial parameters by primary and secondary roads, as well as the total road network obtained from the optimized road planning (ORP) and the road built by traditional planning (RBTP) for APUs 06 and 14. 88
Table B.1. Calculated technical parameters by primary and secondary roads, as well as the total road network obtained from the optimized road planning (ORP) and the road built by traditional planning (RBTP) for APUs 06 and 14. 89
Table C.1. Calculated financial parameters by primary and secondary roads, as well as the total road network obtained from the optimized road planning (ORP) and the road built by traditional planning (RBTP) for APUs 06 and 14. 90

SUMMARY

GENERAL INTRODUCTION 15
OBJECTIVES 20
CHAPTER I 21
GLOBAL REVIEW ON FOREST ROAD OPTIMIZATION PLANNING: SUPPORT FOR SUSTAINABLE FOREST MANAGEMENT IN AMAZONIA 22
1. Introduction 23
2. Material and methods 26
2.1. Selection of studies 26
2.2. Data analysis 28
2.2.1. Quantitative assessment 28
2.2.2. Qualitative assessment of data 28
3. Results and discussion 29
3.1. Quantitative analysis 29
3.2. Qualitative analysis 32
3.2.1. Spatial decision variables 33
3.2.2. Methods of spatial analysis 36
3.2.3. Road layout methods 38
4. Final considerations 41
Appendix 43
References 47
CHAPTER II 57
ROAD NETWORK PLANNING AND SPATIAL ASSESSMENT FOR SUSTAINABLE FOREST MANAGEMENT IN THE BRAZILIAN AMAZON: METHODOLOGICAL PROPOSAL AND CHALLENGES 58
1. Introduction 59
2. Materials and methods 61
2.1. Study area and operational planning 61
2.2. General description of the methodological procedure 63
2.3. Part I: Modeling the spatial suitability of forest roads 65
2.3.1. Definition of variables and consultation with experts 65
2.3.2. Geographic database and data pre-processing 66

2.3.3. Description of factors and classes ... *67*
2.3.3.1. Terrain slope ... *67*
2.3.3.2. Aspect ... *67*
2.3.3.3. Timber production ... *68*
2.3.3.4. Hydrographic network ... *68*
2.3.3.5. Land cover and use (LCU) ... *68*
2.3.4. Class weight calculation ... *69*
2.3.5. Calculation of factor weights ... *69*
2.3.6. Combination of factors ... *70*
2.4. Part II: Optimized road planning ... 71
2.5. Part III: Method for comparing different road networks ... 71
3. Results and discussion ... 73
3.1. Spatial suitability modeling ... 73
3.1.1. Slope factor ... *75*
3.1.2. Hydrographic factor ... *76*
3.1.3. Productivity factor ... *76*
3.1.4. Land use and cover factor ... *76*
3.1.5. Aspect factor ... *77*
3.1.6. General considerations of the FRSSM ... *78*
3.2. Analysis of optimized roads ... 79
3.3. Other contributions and challenges ... 84
4. Conclusion ... 86
Appendix ... 88
References ... 91
GENERAL CONSIDERATIONS ... 97
GERAL CONCLUSION ... 100
GERAL REFERENCES ... 101

GENERAL INTRODUCTION

The conservation of the Amazon Forest is a global concern, mainly because it is the largest continuous tropical forest in the world, which houses the greatest biodiversity on the planet and plays a key role in regulating the world's climate (Heinrich et al., 2021). The conservation of this forest has been threatened by the fragmentation of habitat and ecological processes (Haddad et al., 2015), and by deforestation for conversion into agricultural activities (Nepstad et al., 2014; Rodrigues et al., 2013). One solution to protect this heritage and its ecosystem services is through the sustainable use of forest resources and the development of a forest-based economy (Lima and Azevedo-Ramos, 2021).

In the Brazilian Amazon, the main economic activity that uses its resources sustainably takes place through Sustainable Forest Management (SFM). For a better understanding of SFM, it is important to highlight the different terminologies in forest management found in commercial use of the forest in the Brazilian Amazon (Sabogal et al., 2009). For example, timber harvesting consists of a process of harvesting forest products. When timber harvesting is not preplanned, does not use a specialized labor force and adequate equipment and machinery, it is classified as conventional timber harvesting. When timber harvesting is carried out in a properly preplanned manner, where the planning aims to promote the maintenance of the forest for future harvests through improved logging techniques, it is classified as reduced impact logging (RIL) and is considered vital to SFM. Sustainable forest management also includes activities that ensure social responsibility for the use of the forest activities (Balieiro et al., 2010; Sabogal et al., 2009).

Therefore, in summary, the SFM aims to selectively cut commercial timber species legally, through a polycyclic system implementing RIL techniques and strategies, with the aim continuous production of wood, conservation of biodiversity and promotion of social aspects. The logging techniques and management information are presented in a Sustainable Forest Management Plan (SFMP), to a competent environmental agency that evaluates and approves the SFMP, if appropriate (Brazil, 2009, 2007, 2006; IBAMA, 2007).

The SFMP consists of a process of activities (Balieiro et al., 2010; IFT, 2014; Sabogal et al., 2009), which are: a) pre-harvest activities, which consist of the survey of information about the area to be managed, in which the demarcation of the Annual Production Unit (APU), planning and construction of the main roads, delineation of the Work Units (WU), inventory 100 %, pre- harvest cutting of cipós, determining microzones, planning and construction of secondary roads, pre-selection of trees for cutting, marking of trees for cutting; b) harvest activities, which consists of the execution stage of the plan, in which directional felling, log bucking and limbing, planning and construction of log landings, planning of skid trails, skidding, decking, loading and transport are carried out; c) post-harvest activities, which consists of the evaluation of the executed project, actions to protect the area and maintenance of permanent infrastructure, which are the planning of post-harvest forestry, post- harvest cutting of cipós, thinning and release of undesirable species, surveying natural regeneration, enrichment plantations in open areas and gaps caused by harvesting, maintenance of infrastructure, report of Annual Operating Plan (OAP) activities. Also included are the activities of monitoring and control, forest development, analysis of the costs of forest operations, tin tracking, monitoring, and control of forest operations (Sabogal et al., 2009).

The implementation of these activities takes place at two different levels within the forest management process: macroplanning, at the property level; and microplanning, at the level of the production unit (Balieiro et al., 2010). The planning of the infrastructure consists of defining the layout of the roads, the log landings, and the skid trails (Papa, 2018). For effective SMF the opening of new suitable roads is essential for the success of the activity. Forest roads have the characteristics of low traffic and heavy weighted vehicles used in log hauling (Machado, 2013). These may be composed of several routes, to provide passage for forest activities, log hauling, and lowbed trailer transport of logging machinery (Corrêa et al., 2006).

The roads found in tropical forests can be classified (Braz, 1997; Heinrich, 1993; da Rocha et al., 2007) as: a) access roads: allows access to the forest management area, connecting the other areas of interest, e.g. sawmills; b) primary roads: characterized by the backbone of the road network, in general, support transport throughout the year and can be used for several years; c) secondary roads: connects log landings and primary roads, defines the maximum extraction distance according to the distances between one another of the secondary road, generally used for a short period, with a more simplified construction pattern; d) skid trails: are used for performing log extraction, that is, they connect the cutting site to the loading points and are planned according to the 100% inventory of the area.

In forest management, roads are one of the most financially expensive part of the infrastructure and cause the greatest environmental impact (Silva, 2019). Inadequate planning can contribute to long-term environmental degradation, that can compromise the production needed for future cutting cycles; it can generate high costs associated with the construction and maintenance of the road network, which have repercussions on uncompetitive products in the market, making forest management impossible, which directly impacts the local population through the loss of jobs and damage to the entire production chain (Kazama et al., 2021).

The literature classifies forest road planning into three hierarchical levels (Grigolato et al., 2017; Gromskaya and Simonenkov, 2016; Pentek et al., 2014): a) strategic planning level: which involves the complete planning of logging and other forest activities, in which access to logging sites is planned based on the existing and necessary forest road network; b) tactical planning level: the determination of timber harvesting equipment required is defined for which areas the methods of processing forest activities, which road segments to improve, maintain and/or build; c) operational planning level: construction, maintenance and decommissioning issues are resolved. Thus, for Gromskaya and Simonenkov (2016), strategic planning provides an answer to the question about what and when to do it, at the tactical level about where to do it and how to do it at the operational level.

Road network modeling is based on various spatial data models and can be based on a Geographic Information System (GIS) (Grigolato et al., 2017). Spatial data models are divided into two large groups (Gromskaya and Simonenkov, 2016) :a) vector data models: for each object, they are defined by a certain set of coordinates in a plane or space, they can also be vector non-topological models and topological models, the latter the most common are the linear node model and the transport network; b) raster data models: describe continuous data fields, such as satellite images and elevations (terrain). In a raster (cellular) data model, the entire plane is divided by a system of vertical and horizontal lines equally spaced into identical cells (pixels), each of which is associated with a code. Each pixel can store some numerical characteristic of space (e.g., elevation) or the code of the object to which the corresponding pixel belongs (Grigolato et al., 2017; Gromskaya and Simonenkov, 2016).

According to the planning level and design stage of forest roads, the following main objectives are addressed (Gromskaya and Simonenkov, 2016) :a) optimization of the forest road network; b) optimization of the total cost of the road; c) optimization of the road location; d) optimization of the longitudinal profile of the road; e) simultaneous optimization of the route plan and the longitudinal profile of the road with a minimum total cost and the conditions to indicate the design restrictions of the roads; f) optimization of the distribution of earthworks (i.e., the balance of cut and fill volume). To solve optimization problems, two main categories of methods are distinguished: exact methods that find a truly global optimal solution, if this solution exists; heuristic methods, which find the "best solution" or a range of almost optimal solutions to the problems (Gromskaya and Simonenkov, 2016).

Despite the various technologies studied internationally to optimize Forest Road Planning (FRP), there is still few studies in the literature on road network planning to minimize environmental impacts in the Amazon Forest and maximize the economic performance of timber production. Knowledge in this area is still not well defined, as it is a complex problem influenced by several economic, environmental, operational, and/or legal variables, among others, which makes management challenging (Silva, 2019).

The activities of timber harvesting and road building becomes a challenging task due to the characteristics of the Amazon forest, such as: the heterogeneity of the distribution pattern of commercial species (Emmert 2014); the low availability and resolution of the mapping of environmental aspects (Barbosa et al., 2017); the prolonged periods of rain, with high intensity of precipitation and with regions without dry seasons (Alvares et al., 2013); the presence of a diverse and dense hydrographic network, formed by rivers, streamwaters, water bodies and occurrence of seasonal floods (Keller et al. 2015); predominantly flat to gently undulating terrain (Sombroek,1980), and thus often poor drainage; to structurally poor soils, with a lack of rock for proper surfacing of roads (Sessions 2007a); and the difficult logistics of the SFM areas, because of remote locations (Keller et al. 2015). In this context, many management projects in the Amazon region end up planning roads manually and systematically, based on empirical knowledge (Keller et al., 2015).

Presented with these challenges, the present study has as its main hypothesis that the use of recent technological approaches used internationally in forest road planning can bring technical and scientific contributions to support road planning in forest management areas in the Amazon. Seeking to test this hypothesis, this thesis was divided into four parts: two chapters in article format, a general consideration, and a general conclusion (Figure 1).

The first chapter is a review of global literature on forest road planning optimization of the decade 2009-2019 as a way to support sustainable forest management in the Amazon and corresponds to an article published in the journal Forest Ecology and Management. It is important to emphasize that the inclusion of the article in this thesis is in accordance with the rights that the authors have when publishing with Elsevier. The second chapter consists of research using the technological approaches raised in chapter I, to develop a methodological procedure capable of assisting in the planning and spatial evaluation of the road network in an area of sustainable forest management in the Amazon which corresponds to an article submitted in a competent journal. Chapter II was developed in three parts, with two parts (I and II) for making the tool and a part (III) for developing a form of analysis and evaluation of road networks. The general considerations are presented as a way to indicate the links between the chapters of the thesis and comment on future work on the subject. Finally, the last part refers to the general conclusion found in this thesis.

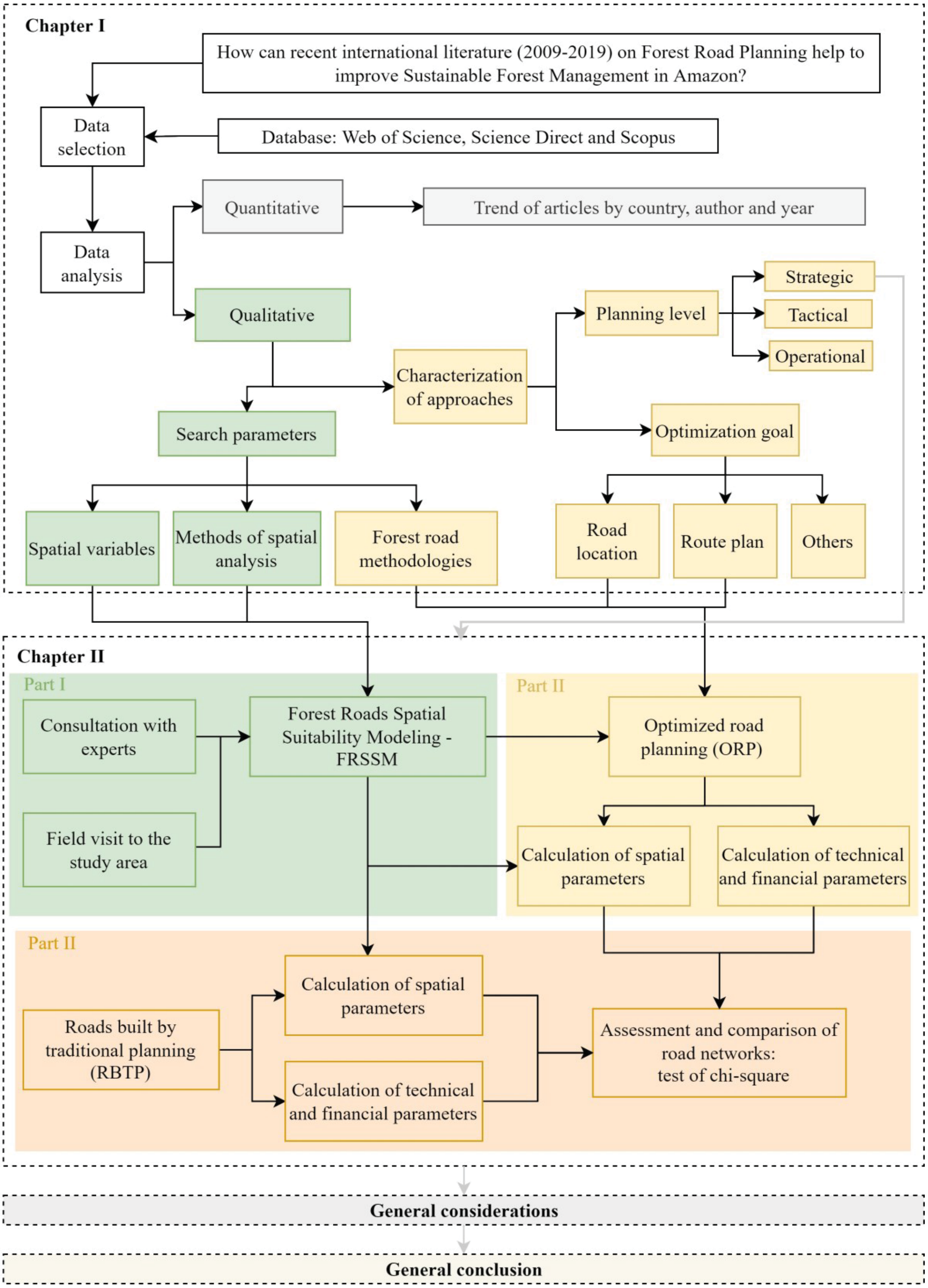


Figure 1. Schematic summary of the development of this thesis.

OBJECTIVES

The general objective of this study was to develop a tool to support the planning of a road network in an area of sustainable forest management in the Amazon, through recent optimization technologies used internationally. Thus, the specific objectives are answered in two chapters:

I. Identify the recent advances achieved in the 2009-2019 decade in forest road planning, which can support forest management in the Amazon, specifying the main spatial variables, spatial decision analysis and optimization methods for road layout used in the literature;
II. Develop a methodological procedure capable of assisting in the planning and spatial assessment of the road network in an area of sustainable forest management in the Brazilian Amazon, through a route optimization planning algorithm based on Multicriteria Decision Making (MCDM) techniques and geographic information system (GIS).

CHAPTER I

GLOBAL REVIEW ON FOREST ROAD OPTIMIZATION PLANNING: SUPPORT FOR SUSTAINABLE FOREST MANAGEMENT IN AMAZONIA*

---

* Chapter formatted and published in the magazine Forest Ecology and Management. DOI: https://doi.org/10.1016/j.foreco.2021.119159

GLOBAL REVIEW ON FOREST ROAD OPTIMIZATION PLANNING: SUPPORT FOR SUSTAINABLE FOREST MANAGEMENT IN AMAZONIA

Verônica Satomi Kazama[a]*, Ana Paula Dalla Corte[a], Renato Cesar Gonçalves Robert[a], Carlos Roberto Sanquetta[a], Julio Eduardo[a], Kauê Augusto Oliveira-Nascimento[a], Daniel DeArmond[b]

[a]Forest Sciences Department, Federal University of Paraná, Curitiba, Paraná, Brazil
[b]Tropical Forestry Department, National Institute for Research in the Amazon, Manaus, Amazonas, Brazil
*Corresponding author: veronica.kazama@gmail.com

ABSTRACT

Forest Management in the Brazilian Amazon has social, economic and environmental relevance, as it allows for the sustainable use of natural resources, while at the same time conserving a majority of the ecological processes of the forest. Among forest operations, the construction of new roads is essential for effective sustainable forest management (SFM). However, it is the most expensive part of forest infrastructure and has the greatest environmental impact. Several methods to optimize forest road planning (FRP) have been studied worldwide, although the literature is scarce on the subject of FRP in areas of SFM in Amazonia. Thus, the objective of this study was to carry out a systematic review of the global literature, on FRP optimization in the last decade (2009–2019), as a way to support future planning activities for road infrastructure in SFM in the Amazon. To guide this objective, three questions were raised to determine what the dominant factors affecting FRP in the study period, specifically what were the: (i) spatial variables; (ii) spatial decision analysis and; (iii) optimization methods for road layout. The bibliographic search was conducted according to the Prisma methodology where a set of keywords was entered into the Scopus, Science Direct and Web of Science indexing databases. In this study, all articles published in English-language journals between 2009 and 2019 were considered, resulting in 62 articles for analysis. There was a growing trend in publications, with most studies developed at the level of strategic planning (46.8%). Also, it was observed that the majority of studies occurred in the forests of Iran (33.9%). The results to the questions of this study found that: (i) there were 45 spatial variables, with slope the most studied (54.7%); (ii) Eleven methods of analysis for spatial decisions, with methods based on Analytical Hierarchy Process – AHP the most studied (36.6%) and; (iii) Thirty different methodologies for optimizing the design of forest roads, mainly methods based on Dijkstra's algorithm (40.5%). Some of the encountered methods have already been implemented in Amazonia to optimize the planning of infrastructure in areas of SFM. In this context, the combination of approaches, variables and analysis for FRP optimization that have been successfully tested in other forests of the world, could feasibly be applied in future planning of logging operations in the Amazon in order to verify the potential of these different procedures and methods, provided that they meet the objectives.

Keywords: Systematic review Forest infrastructure Road network planning Logging roads Forest planning

1. Introduction

The forest of the Brazilian Amazon is one of the five principal sources of tropical timber in the world, as well as the primary producer in Latin America with annual roundwood production estimated at 29.2 million m3 in 2017 and 2018 (ITTO, 2019). In Brazil, legal timber harvesting is conducted under the auspices of sustainable forest management (SFM), which is characterized by a polycyclic selection system (Lamprecht, 1990). The objective is to implement a selection cutting system that employs reduced impact techniques and conserves biodiversity while maintaining a continued source of timber production (Aguiar et al., 2020; Silva et al., 2020).

In Brazil, legislation allows for timber harvesting of up to a maximum of 30 m3 per hectare when utilizing heavy machinery and 10 m3 per hectare for low impact harvesting planes that do not use of machinery (Brasil, 2009). The cutting cycle for the low impact management planes is a minimum of 10 years, whereas the heavier intensity harvests are from 25 to 35 years depending on the sites growth and stocking (Brasil, 2009). In general, the sustainable forest management planes are divided into forest management units (FMU), which are then divided into annual production units (APU) and this, in turn, is divided further into working units (WU). For commercial timber species, the minimum cutting diameter is 50 cm at diameter breast height, and in each 100-hectare working unit, at least 10% of each tree species that can be harvested must be retained as a seed source. Lastly, all harvest operations must have documentation to verify the chain of custody (tracking system) for every harvested trees.

The essential infrastructure necessary to carry out SFM is composed of skid trails, log landings and haul roads. According to Silva (2019), the cost of constructing this infrastructure to facilitate logging in the Amazon region, accounts for approximately 75% of the total cost of the operation. The general specifications for planning and construction of infrastructure are established by law and contained in the sustainable forest management plan (SFMP), which must be approved by the overseeing agencies prior to any construction activities (Brasil, 2007). However, these guidelines must be improved at the planning level, especially the haul roads as they are the costliest and cause the greater environmental impact due to the excavation of subsoil, when compared to the skid trails and landings (Silva, 2019).

International literature classifies forest roads planning (FRP) in three hierarchical levels: strategic, tactical and operational (Grigolato et al., 2017; Gromskaya and Simonenkov, 2016; Pentek et al., 2014). Strategic planning consists of the initial planning, which aims to establish future guidelines over the long-term of approximately five years or more (Gromskaya and Simonenkov, 2016). This level of planning involves the definition of applicable models according to aspects of topography and an adequate road network density (Pentek et al., 2014). Also considered in the strategic planning process is access to the harvesting area and guidelines for an appropriate logging system, taking into account existing roads and if there is a need to construct new roads (Gromskaya and Simonenkov, 2016).

At the tactical level, planning is an intermediate level between strategic and operational, with a medium-term planning horizon. It involves questions such as: planning at the level of a given economic unit, which leads to planning at a more local level (D'amours et al., 2008). To minimize costs and impacts to the forest ecosystem caused by the construction of forest roads and logging operations, determining optimal networks of primary infrastructure for log hauling is essential (Pentek et al., 2014). After completing the tactical planning process, the result of which is an optimized forest road network, operational planning begins. At this level, planning involves issues such as: the construction of each type and category of forest road, according to its design, road alignment analysis and the ideal route (Pentek et al., 2014) followed by construction, excavation and maintenance (Gromskaya and Simonenkov, 2016).

During the forest road planning process, a specific planning level is commonly used to define the road layout, which is the road view stage. This level involves the use of computational resources to assist in the projection of different routes according to a three-dimensional visualization between different itineraries (guidelines) (Rogers and Schiess, 2001). This may involve studying the alignment of the road axis and the radius of the horizontal and vertical curves which would be suitable for transport, as well as visibility, which is directly related to road safety (Zakowska, 1999). There are powerful tools capable of optimizing the layout of a road according to the objective, such as finding the optimal path for the longitudinal profile at a minimum construction cost (Akay, 2004). The proper layout of a road can be obtained from various types of optimization models (Gromskaya and Simonenkov, 2016), often integrated with a geographic information system (GIS) (Grigolato et al., 2017), which allows for the simulation and visualization of several scenarios based on pre-defined parameters (cost, distance, topography, etc.) defined by the user.

The road network in any type of forest influences the viability and profitability of the timber harvesting operation (Abdi et al., 2009; Cavalli and Grigolato, 2010; Murray, 1998; Norizah and Mohd Hasmadi, 2012). Inadequate planning of forest roads causes environmental impacts to the forest, such as increased deforestation, loss of biodiversity, erosion, sediment deposition in waterways, flora and fauna disturbance, habitat fragmentation and higher costs of road construction (Çaliskan, 2017; Siqueira-Gay et al., 2020).

The literature on forest road design and planning with a focus on the minimization of impacts in the forests of Amazonia are scarce. The knowledge in this area is still not well defined due to the complexity and challenges of various influences that are economic, environmental, operational and legal in nature (Silva, 2019). Logging and road construction activities can be a daunting task in the

Amazon region due to the intrinsic nature of tropical forests. One of the primary aspects of this challenging environment is the lengthy rainy season of up to six months or more accompanied by high intensity rainfall events, and in some regions of Amazonia, there is not a distinct dry season (Alvares et al., 2013). In turn this substantial precipitation leads to the presence of a diverse and dense hydrographic network, formed by rivers, streams, bodies of water and the occurrence of seasonal floods (Keller et al., 2015; Sessions, 2007a,b). In addition, the predominantly flat to gently undulating terrain (Sombroek, 2000) complicates road drainage. Many times, there is also lack of rock for proper road surfacing (Sessions, 2007a,b). Generally, SFM occurs in logistically difficult areas, as they are in remote locations (Keller et al., 2015). In this context, the implementation of basic design needs in the planning of forest roads may become a complex task, making the planning of logging operations even more challenging.

In view of this scenario, many initiatives in the Amazon region end up carrying out road planning manually and systematically, based on empirical knowledge (Keller et al., 2015), forming a “fishbone” pattern (Edwards et al., 2017). This standard of planning is comprised of the main haul roads with secondary haul roads that branch off these followed by the skid trails system. The “fishbone” pattern has limitations in terms of being based only on maximizing profits and technical efficiency, which leads to linear road segments, according to a systematic route and do not consider the areas of greatest productivity, among other spatial restrictions (Arima et al., 2008, 2005; Braz, 2010). There exist numerous recent publications on forest road planning (FRP), but these tend to be from other types of forests throughout the world (Grigolato et al., 2017; Gromskaya and Simonenkov, 2016). These studies demonstrate the advances in the use of the geographic information system (GIS) and the various methods of decision making, analysis and optimization, which highlights the importance of research on forest roads with different variables and methodologies applied in different forests and levels of planning. However, there is still no global and quantitative assessment to determine whether these variables and analysis procedures currently being developed have the potential for application in FRP for SFM in Amazonia. For this problem, the scientific mapping by means of bibliographic methods brings a synthesis from prior research and the correlations between them. This synthesis consists of the more important works that advance this line of specific research (Zupic and Cater, 2015).

The objective of this work was to conduct a systematic review of the literature to identify the progress made in the last decade on the planning of forest roads and also, to indicate that which will improve the process of FRP in SFM within Amazonia. The three principal questions were as follows: What were the main spatial variables used? What were the main spatial decision analysis methods used? What were the main methods of optimization of the road layout used?

2. Material and methods

2.1. Selection of studies

The literature review was conducted according to the recommendations of Moher et al. (2009), defined as the PRISMA statement which consists of: (a) identification of records; (b) record screening; (c) article assessment for eligibility; and (d) inclusion of the eligible studies (Fig. 1). This process was accomplished utilizing the software Mendeley Desktop 1.19.4.

In the identification stage, three indexing databases were included, which are available to Brazilian researchers via the Coordination for the Improvement of Higher Education Personnel (Capes), namely: Web of Science, Science Direct and Scopus. The databases were searched for the period between 2009 and 2019. A decade was chosen to capture the most up-to-date and recent advancements in technology and techniques related to the current implementation of FRP globally. The results from database searches were downloaded the same day (accessed 1 March 2020). Record searches were conducted with the following key words: (“forest road” OR “logging road”) AND (“planning” OR “method” OR “optimization” OR “model” OR “analysis”) AND (“logging” OR “forest” OR “forest management”) in the title, abstract and/or key words. The search was limited to scientific articles published in English-language scientific journals, excluding other types of records (review articles, event papers, technical reports, among others). In the database search, a total of 1333 records were identified and made available by: Web of Science, 334; Science Direct, 110; and Scopus, 889. In addition to these, a relevant article recommended by an expert in this area was added. After the exclusion of duplicates, a total of 1046 records remained at the end of the identification step.

In the screening process, five criteria were applied for excluding records: (i) non-scientific texts; (ii) works not written in English; (iii) conference proceedings; (iv) literature reviews; (v) text not focused on modeling and optimization methods of forest road planning (FRP). Following the methodological example of Castaño-Villa et al. (2019), the inclusion criteria were assessed by only one person (LOB) to avoid a possible inter-evaluator bias. Based upon these criteria, 956 articles were excluded and 90 were retained for the next step.

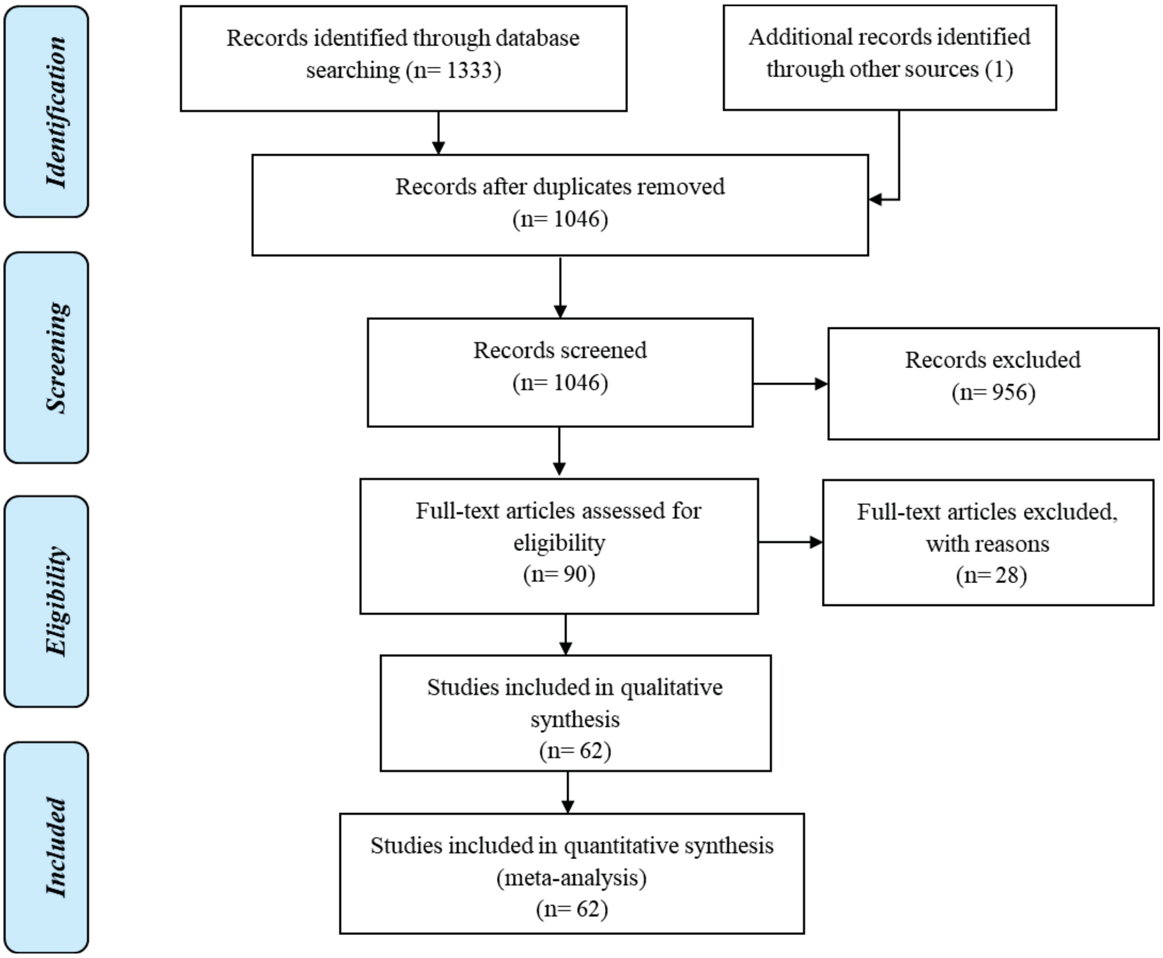


Fig. 1. Prisma Flow Diagram, workflow display of the systematic review process.

In the eligibility stage of evaluation, the 90 articles that had been retained were analyzed in light of exclusion criterion (v); therefore, works not related to modeling and optimization of FRP were excluded. In addition, studies that implemented FRP methodologies for purposes other than forestry and logging operations were excluded, such as fire prevention and suppression, recreation, etc. These exclusions are necessary as the road design standards for logging operations are quite different than those for recreation and wildland firefighting traffic. This difference is because recreational vehicles need less road surface area to operate safely than larger vehicles (Akgul et al., 2016), and firefighting vehicles may actually need greater road widths than logging traffic due to the need for extra passing lanes and turnouts (Laschi et al., 2019). Moreover, log trucks and semi-trailers for moving logging equipment have more specific road grade requirements, horizontal curve radius widths and vertical height or drop specifications than smaller vehicles (Sessions et al., 1986, 2010). As a result of applying exclusion criterion (v), there were 28 articles excluded and 62 that remained for inclusion into this review for qualitative and quantitative synthesis. These 62 articles were then placed in a database, which contained the identification data (metadata, journal name, article title and year of publication).

2.2. Data analysis

2.2.1. Quantitative assessment

Descriptive statistics were utilized to analyze the general trends related to the growth and geographical region where studies on FRP were undertaken. In this evaluation, the analyzed data consisted of the bibliographic information for the 62 journal articles, such as authors, titles and dates of publication.

2.2.2. Qualitative assessment of data

In the qualitative evaluation, the frequency of the following parameters was considered: 1) methods of spatial analysis; 2) spatial variables and; 3) forest road methodologies. When aspects of these parameters were identified in the articles, this information was summarized in a Microsoft Excel spreadsheet. The importance of the identified parameters was characterized by the frequency of use in the methodology of each study, which was analyzed during the database searches. This process helped in the determination of parameters applicable to the planning of forest roads in sustainable forest management (SFM) within Amazonia.

In addition, to obtain a general characterization of the approaches to FRP, articles were classified according to the level of planning: strategic, tactical and operational. Studies at the road visualization level were included at the operational level. Furthermore, articles were categorized according to the objective of forest road optimization and grouped by optimization of the: i) road network; ii) total road cost; iii) road location; iv) longitudinal road profile; v) route plan and longitudinal profile with minimum cost under certain design restrictions and; vi) distribution of earthworks (i.e., balance of cut and fill volume). The descriptions of the planning levels and the differences between the optimization models have been described in the studies by Gromskaya and Simonenkov (2016), Pentek et al. (2014), respectively.

3. Results and discussion

3.1. Quantitative analysis

The frequency distribution and the equation adjustment were generated for the 62 articles evaluated to determine the trend of publications throughout the studied decade (Fig. 2). The annual number of publications exhibited fluctuations with peaks in 2013 and 2018. Despite these oscillations, there was an increasing trend of publications observed, which demonstrates the relevance and growth of this topic in recent years.

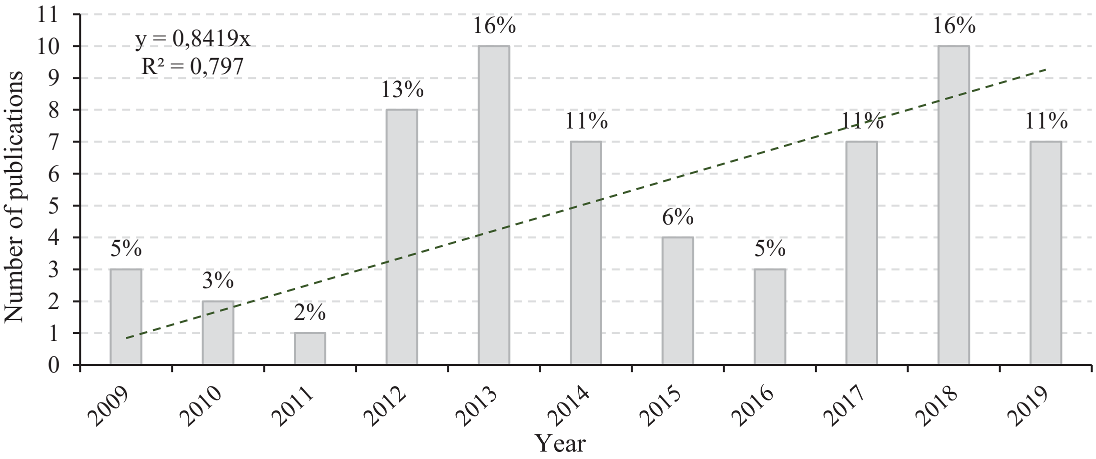


Fig. 2. Frequency and trend of published articles on the subject of forest road planning during the period 2009-2019.

The majority of the publications originated from study areas located in Iran, followed by Turkey, with percentages in relation to the total of 33.9% (n = 21) and 19.4% (n = 12), respectively (Fig. 3). These are mountainous countries with forest cover on various topographies from moderate to steep slopes composed mainly of broad-leaved tree species, but with a smaller component of coniferous species (Atalay et al., 2014; Sagheb-Talebi et al., 2014). On the contrary, the Brazilian Amazon is generally low-lying with undulating topography

(Alvares et al., 2013; Sombroek, 2000), and is dominated almost exclusively with broad-leaved species with very few conifers (ter Steege et al., 2013; Vieira et al., 2016). Despite these differences, there are commonalities. For example, the gentle topography in Amazonia is sometimes dissected by ravines and valleys with side slopes up to 100% (Irion, 1978; Chauvel et al., 1987). Optimization techniques have been proposed for these areas (Braz, 1997), but studies on this aspect of road construction in the Amazon are scarce. Thus, the challenges of topography found in mountainous countries can also be encountered throughout Amazonia, albeit to a lesser degree.

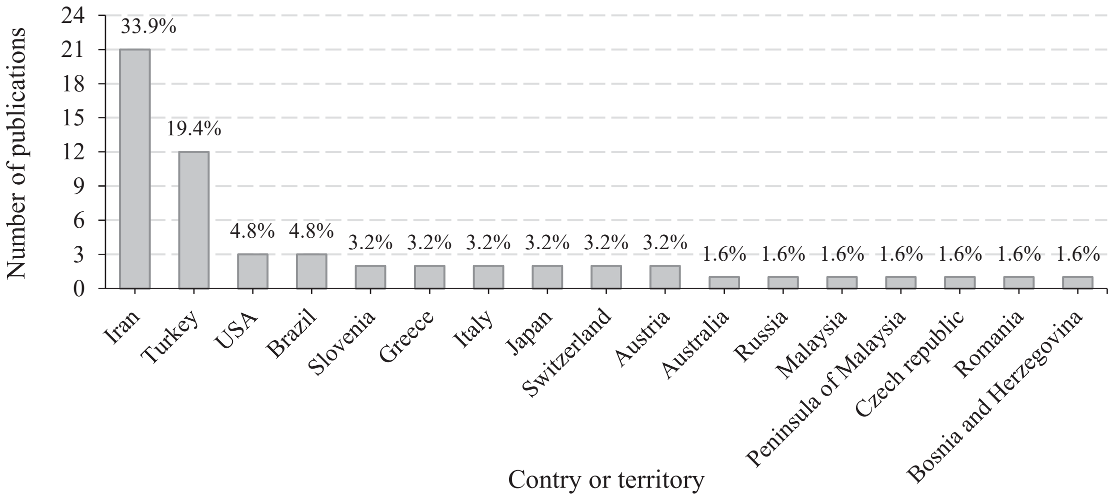


Fig. 3. The number of publications by country where studies were conducted on forest road planning published during the period 2009-2019.

Among the 62 evaluated articles, 46 were prepared by different first authors. Of these, there were five authors from institutions located in Iran and Turkey that stood out with the greatest number of publications in the following order: Babapour R., from Iran and Çalis¸kan from Turkey, both with 4 papers; Bugday E., from Turkey, Hayati E. and Parsakhoo A., both researchers from Iran with 3 papers each.

Considering the authors that had attained 3 or more published articles, including co-authorships (Fig. 4), the authors that represented the greatest share of publications on the topic of forest road planning were Ghajar, I. (n = 6) and Abdi, E. (n = 5), both Iranian researchers. Their studies were concentrated in the forested region adjacent to the Caspian Sea in Northern Iran (n = 10). This area also represented the greatest concentration of studies on this subject internationally within the studied decade.

According to the results for the number of publications by country (Fig. 3) and by author (Fig. 4), it was observed that the interest of this topic was located primarily in two countries within the Middle East: Iran and Turkey. Total articles published in these two countries represent more than 53% of all articles on this subject internationally. Consequently, it was the authors of these two countries who had prominence with the largest number of publications found, both with the first author and the sum of co-authorship and authorship.

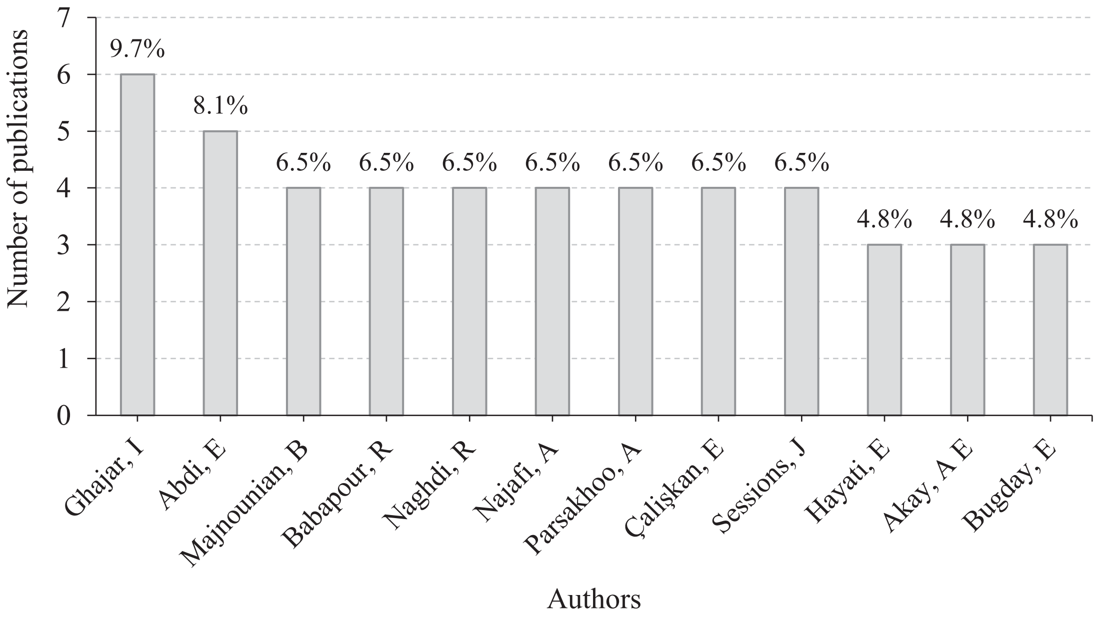


Fig. 4. The number of publications by author, combining primary authorship with co-authorship, on the subject of forest road planning published during the period 2009-2019.

The factors that led to increased research in these countries were related to the topography, soil and climate conditions encountered in these two countries, which contribute to landslide susceptibility and greater environmental fragility in areas of timber harvesting (Babapour et al., 2017; Bugday and Akay, 2019). For example, in the mountainous forests of Northern Iran landslides are common due to the combination of steep slopes and intense rainfall (Jaafari et al., 2015). Also, in these Caspian Forests, soil erosion has been exacerbated by the historic practice of clearcutting (Jourgholami and Majnounian, 2011). In fact, the two countries, Iran and Turkey, leading research in the area of FRP utilize a combination of even-aged and uneven-aged silvicultural prescriptions (Tavankar et al., 2015; Yolasigmaz and Güner, 2016;

Kooch et al., 2020; Sohrabi et al., 2020), whereas in the Brazilian Amazon only uneven-aged management is permitted (Brasil, 2009).

3.2. Qualitative analysis

The strategic planning level received the greatest amount of study at 46.8% (n = 29) in the studies reviewed, followed by the tactical planning level at 27.4% (n = 17) and operational planning level at 25.8% (n = 16), respectively. When considering the number of publications in relation to the main objective, the optimization models that applied to forest road planning were focused on ideal road location (43.5%), optimization of the road network (40.3%), total road cost (19.4%), distribution of earthworks (16.1%), longitudinal road profile (9.7%), and route planning (9.7%) (Fig. 5).

In general, it was possible to observe that the results of this analysis were associated with the number of publications by planning level. The two most researched topics were generally at a strategic level. The strategic level consisted of the initial stage of road planning, which involved analyzing the topography of the area to define models applicable to various types of terrain (Gromskaya and Simonenkov, 2016), as well as to study the density of the road network and forest access planning (Pentek et al., 2014).

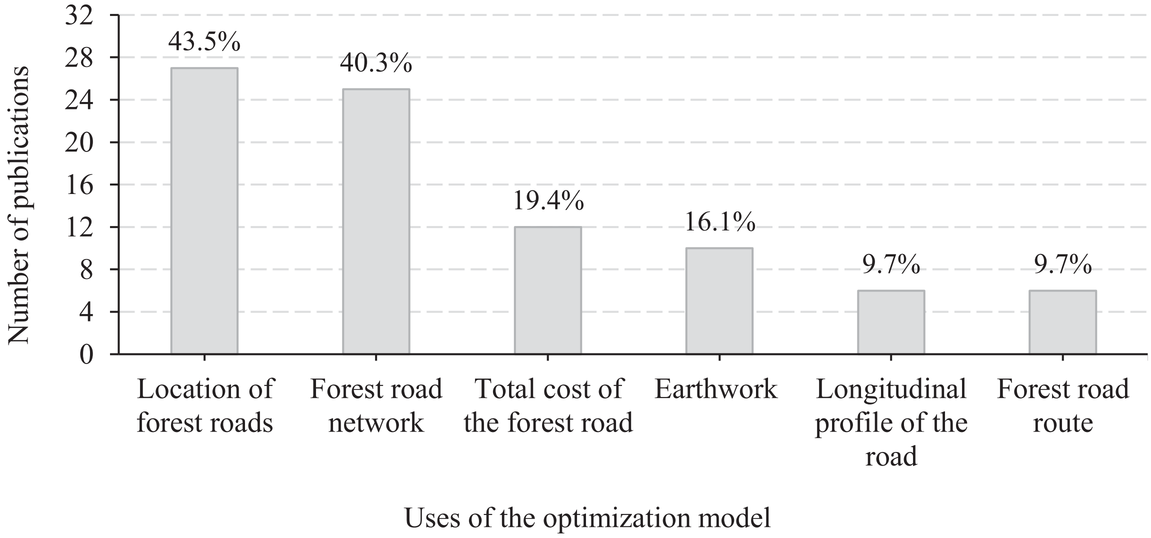


Fig. 5. The number of publications in the period 2009-2019 classified by different optimization objectives employed in the planning of forest roads.

The secondary level of planning was tactical, as were the models for optimizing the total road costs (19.4%), which were common models at this level. Since planning at the tactical level seeks results for a given economic unit, this leads to planning at a more local level (D'amours et al., 2008). In general, the aim is to justify the construction costs of forest roads such as opening and maintenance activities while also considering the minimization of the negative impacts of forest roads and logging operations on the forest ecosystem. Furthermore, it seeks to determine the optimal networks for primary infrastructure used in forest transport (Pentek et al., 2014).

In the final level, operational planning was related to the last optimization objective (Fig. 5), which were studies that sought to optimize the balance of cut and fill volumes in excavation (16.1%), longitudinal profile of the road (9.7%) and log haul routes (9.7%). The intent of operational planning is to open each type and category of road according to a specific project, which is determined by an operational polygon under the conceptual (optimal) route of the forest road, which is planned and designed with GIS and demarcated using GNSS for adequate accuracy. Lastly, a polygon associated with the road in the forest area is defined (Pentek et al., 2014) and issues for road construction, maintenance and excavation in the field are identified and included (Gromskaya and Simonenkov, 2016).

3.2.1. Spatial decision variables

A total of 53 articles, located throughout the world, were found to have utilized some form of a spatial variable for the forest road planning (FRP), of which 45 different spatial variables were observed. These were summarized in 9 categories to better group them according to subject (Table A.1). In descending order of importance, the classifications were: topography (n = 34), soil (n = 14), technical aspects (n = 14), hydrography (n = 13), forest biometry (n = 12), forest cover (n = 7), climate (n = 3), forest protection (n = 2) and social aspect (n = 2). Among the 45 variables, 8 were considered prominent as they were used in more than 7 studies. In descending order of importance, these variables were: slope (n = 29), elevation (n = 17), road density (n = 15), proximity to a hydrology network (n = 12), aspects of slope (n = 10), timber production (n = 10), distance from existing roads (n = 7) and Lithology/Petrography (n = 7) (Table B.1). The remaining variables were present in less than 3 publications each.

The variables of topography, soil, technical aspects and hydrography were the most frequently used for FRP. This is likely due to the fact that these variables affected the cost of road construction and the level of planning to mitigate environmental impact of forest roads. Besides this, these variables were used mainly at the strategic level in relation to the optimization of ideal areas for road locations, which were the most studied levels of planning and optimization. Topographic variables are still the most relevant for optimized planning in selective extraction in the Amazon (Braz, 2010; Emmert, 2014). Emmert (2014) used slope as a critical factor to optimize the location of haul roads and skid trails, to minimize the costs of extracting and transporting logs in the Amazon. In general, topography class variables were obtained using the Digital Elevation Model (DEM) and Digital Terrain Model (DTM), derived from traditional remote sensing techniques, for example, SRTM (Havimo et al., 2017) or state-of-the-art LiDAR technology. The use of LiDAR data was more frequent at the level of operational planning, which involved studies that require greater detail of the earth's surface. In this case, in the optimization of soil cut and fill volume estimates for the road construction phase and in models for optimal road alignment (Akay et al., 2014; Craven and Wing, 2014; Laschi et al., 2016; Saito et al., 2013), as well as in the planning and implementation of drainage systems (Yoshida et al., 2019).

Studies have shown the beneficial uses of LiDAR technology in the area of sustainable forest management (SFM) for the Amazon region, in determining preferred skid trail routes (Barbosa et al., 2017), identification and analysis of areas impacted by timber extraction in selectively harvested areas (Andersen et al., 2014; d'Oliveira et al., 2012; de Carvalho et al., 2017) and forest biomass estimates (Rex et al., 2018; Schuh et al., 2020). However, for commercial use in sustainable forest management plans (SFMP), the cost is still too expensive and is considered an unviable technology for many operations.

The commercial trees encountered in tropical forests many times contain very high volumes and thus weight. In SFM, the felling and skidding of the logs in too many lengthy skid trails exacerbates the environmental damage to the soil, the residual stand and the forest regeneration. Therefore, it is necessary that the management infrastructure is optimized to minimize haul road and skid trail distances, as well as landing spacing, since the low commercial volumes of Amazonian forests require large harvest areas to be viable for logging. In this sense, the use of variables of forest biometry are strongly recommended in the FRP for SFM in the Amazon, as this can help limit harvest activities to areas where there is sufficient commercial volume to sustain future entries. Although obtaining forest inventory information is laborious and costly in tropical forests, these activities are already implemented by timber companies, as they are obligated by law, since conducting a commercial forest inventory is mandatory for sustainable forest management plans (Brasil, 2007).

The forest inventory stage is an important opportunity to gather information on the terrain for the stratification of harvest units. Furthermore, since the forest inventory is carried out during the wet season, when operations are unfeasible or not permitted during a period of approximately 6 months, there is an ample time period for the thorough evaluation of the site. In practice, this process is already carried out, for example, by the company AMATA S.A. in a forest concession in Flona do Jamari, State of Rondônia, Brazil. At this location, areas that present operational challenges, such as different forest types, watercourses (SFB, 2018) and other variables which are difficult to be discerned by remote sensing technologies are identified on the ground during the forest inventory phase. This process is important to reduce the subjectivity problem at the microplanning stage for the logging units, that are characterized by a lack of specific details as related to environmental factors, a scenario caused by lower resolution satellite images and basic IBGE topographic maps currently used for the macroplanning of SFM in Amazonia (Barbosa et al., 2017).

In the category for technical aspects, the density of the road network was the studied variable that has been highlighted in recent years. This variable is related to the haul roads, maximum skidding distance of skid trails, which in turn is linked to the planned quantity of log landings (Sales et al., 2019). In the Central Amazon, road density in timber management plans is dictated by law to be no greater than 1.75% of the area, and 0.75% for landings for a combined total of 2.5% (Brasil, 2018). As much of the logging area in the Amazon basin is gentle topography (Sombroek, 2000; Alvares et al., 2013), the concerns of road density are more concerned with the resultant removal of trees and deforestation than potential road instability and landslides. Historically, the threat of heavy precipitation in Amazonia has been recognized as a threat to the road network for hauling (Costa Filho and da Costa, 1980). However, in future planning the steeper road approaches to watercourses need to be taken into account to prevent sedimentation and degradation of the water quality and aquatic habitat (Keller et al., 2015). Therefore, these various infrastructure components must be optimized together, in order to minimize costs and the environmental impact of logging operations in the Amazon. Climate change was also a concern in studies for FRP.

The variation in precipitation influences the quality of roads over the long term, since extreme precipitation events can commonly exceed the drainage capacity of structures such as culverts, drains and bridges causing erosion and sediment runoff into waterways, which can lead to increased environmental damage and maintenance costs (Hayati et al., 2013b; Jaafari et al., 2015; Yoshida et al., 2019). Therefore, this issue is relevant for consideration in the planning of permanent roads, as these extensive road networks are throughout the logging areas of the Amazon in the form of primary and secondary access roads.

The variables of the forest protection class, despite being uncommon in the international literature, compared to the other variables in tropical forests are extremely relevant and are therefore ensured by Brazilian legislation in the SFMP (Brasil, 2012). The legislation prohibits cutting trees in areas of environmental vulnerability designated as the Permanent Preservation Areas (APP), which are made up of streamside buffers, springs and steep slopes.

In the Amazon Forest, riverside communities, indigenous villages and other human settlements can be found without road access. These communities could potentially benefit from the SFM roads, for example, to transit between communities and to access non-timber forest products (NTFPs). In Brazil, NTFP extraction activities are permitted by law with prior authorization through the appropriate governing agency (Brasil, 2006). In order to complement the social value of the road system, whenever these communities access the forest to be managed, the variables that relate to the social aspects class must be considered in the FRP, such as mitigation of dust and accidents.

The selection of variables to create an adequate network of forest roads varies according to the location of the forest being managed. For example, the characteristics of the northern region of the Brazilian Amazon have topography, climate (Alvares et al., 2013), soil (Vale Júnior et al., 2011) and vegetation types (IBGE, 2012), different from other regions and such aspects must be evaluated and included in the SFM planning process. Therefore, to assist the decision-making process, in addition to a search of the relevant literature and field analysis, the recurring activity, at least in the studies analyzed, was to consult local specialists. In implementing the Delphi method and interviewing a panel of 9 forest engineering experts, Hayati et al. (2013b, 2013a) determined that there were 8 environmental criteria variables that were the most important for planning roads in forest operations in Northern Iran. Çaliskan et al. (2019) also consulted experts to obtain the ideal criteria for the planning of forest routes. In a study by Acar et al. (2017), it was concluded that by consulting specialists in combination with knowledge of the literature and field studies, it was possible to obtain a 3% increase in the success rate in the implementation of forestry operations.

3.2.2. Methods of spatial analysis

There were 41 publications encountered that employed spatial analysis techniques for forest road planning (FRP). Among these publications, 11 methods were identified that differed in their conceptual definitions and mathematical formulas. In order of importance, the methods of spatial analysis identified (Table 1) were: methods based on Analytical Hierarchy Process (AHP) (n = 15); methods based on Fuzzy Logic (FL) (n = 8); Simple Additive Weighting (SAW) (n = 4); methods based on Promethee (n = 3); methods based on Logistic Regression (LR) (n = 3); Technique For Order Preference by Similarity to Ideal Solution (TOPSIS) (n = 2); Accessibility Analysis (AA) (n = 1); Analytical Network Process (ANP) (n = 2); Sediment Model (SEDMODL) (n = 1); Weights of Evidence (WofE) (n = 1) and ; Artificial Neural Network (ANN) (n = 1).

Table 1. Multicriteria decision analysis methods used in forest road planning from articles published during the period 2009-2019.

RI	Spatial Multi-Criteria Decision Making	Reference	n	% subject	% total
1	Based on Analytical hierarchy process (AHP)	(Abdi et al., 2009; Akay et al., 2018; Babapour et al., 2014; Bugday and Akay, 2019; Bugday and Özel, 2019; Çalişkan et al., 2019; Hayati et al., 2013a, 2013b; Kamarudin et al., 2014; Laschi et al., 2016; Liampas et al., 2019; Maskani Jifroudi et al., 2009; Norizah and Mohd Hasmadi, 2012; Petković and Potočnik, 2018)	15	36.6	24.2
2	Based on Fuzzy Logic (FL)	(Acar et al., 2017; Akay et al., 2018; Bugday, 2018; Bugday and Akay, 2019; Bugday and Özel, 2019; Çalişkan et al., 2019; Hayati et al., 2013a, 2013b)	8	19.5	12.9
3	Simple Additive Weighting (SAW)	(Çalişkan et al., 2019; Çalişkan and Karahalil, 2017; Havimo et al., 2017; Mohd Hasmadi et al., 2010)	4	9.8	6.5
4	Based on Promethee	(Çalişkan et al., 2019)	3	7.3	4.8
5	Based on Logistic Regression (LR)	(Babapour et al., 2015; Bugday and Akay, 2019; Eker and Aydin, 2014)	3	7.3	4.8
6	Technique for order preference by similarity to ideal solution (TOPSIS)	(Çalişkan, 2017; Çalişkan et al., 2019)	2	4.9	3.2
7	Accessibility analysis (AA)	(Laschi et al., 2016; Picchio et al., 2018)	2	4.9	3.2
8	Analytical network process (ANP)	(Parsakhoo, 2016)	1	2.4	1.6
9	Sediment model (SEDMODL)	(Akay et al., 2014)	1	2.4	1.6
10	Weights of evidence (WofE)	(Jaafari et al., 2015)	1	2.4	1.6
11	Artificial neural network (ANN)	(Babapour et al., 2015)	1	2.4	1.6
Sub-total		-	41	100.0	-
Total		-	62	-	100.0

RI = ranking of importance

These methods are internationally recognized and known as Multi-Criteria Decision Making (MCDM) or Multi-Criteria Analysis (MCA) or Multi-criteria Evaluation (MCE). When combined with GIS analysis, they are named Spatial MCDM (S-MCDM). The MCDM covers a series of techniques that provide users with the benefit of determining the various criteria alternatives, including qualitative or quantitative aspects (Abdi et al., 2009) and objectives with multiple and complex structures (Çaliskan, 2017; Çaliskan et al., 2019).

The Analytical Hierarchy Process (AHP) was the preferred method in studies for forest roads, which helped users divide complicated decisions into a hierarchy (Hayati et al., 2013a). However, prior to the use of this method, all required criteria for the planning and evaluation of forest roads must be defined and standardized, based on an efficient approach. Therefore, in this method, the analysis can be subjective, since the factors are controlled by the restrictions specified by the user (Pourghasemi et al., 2016). In this sense, the AHP method possess a modified approach (M-AHP), which enables the user to exclude subjectivity from a given situation (Bugday and Ozel, 2019). The M-AHP approach does not require expert opinion and allows the normalization of factors, making the comparison of criteria more successful in the decision phase (Bugday and Ozel, 2019; Nefeslioglu et al., 2013; Pourghasemi et al., 2016).

The AHP method has already proven efficient in determining the optimal locations for log landings, in sustainable forest management (SFM) areas within the Amazon (Silva et al., 2018). Another method that has already been used successfully in timber harvest planning in the Amazon, was Simple Additive Weighting (SAW), tested for optimization of log landings by Martinhago (2012) and for optimization of skid trails by Barbosa et al. (2017).

Among the articles evaluated, the study by stood out by comparing the greatest number of S-MCDM methods, for route planning on Turkish forest roads. Between the five methods tested (AHP, SAW, Fuzzy overlay, Promethee and TOPSIS), Çaliskan et al. (2019) found that the best results were found through employing the Promethee method, which was recommended for use in other regions.

3.2.3. Road layout methods

A total of 40 studies were encountered that analyzed the planning of the forest road layout, as a way to improve the harvesting process and/or forest transport systems. Of these, 3 publications did not work directly with the use of optimization methods, but is accomplished with a semi-autonomous (Akgul et al., 2018) and manual approach (Silva et al., 2018; Enache et al., 2013), utilizing digital GIS tools. For the remaining 37 studies, 30 different methodologies were presented. These were then classified and placed into 3 groups, according to the form of optimization (Table C.1). In order of importance, the classes were: 1) automated GIS methods (n = 21); 2) exact solution methods (n = 12) and; 3) heuristic solution methods (n

= 5). It was observed that 52.5% of the studies integrated GIS for planning the layout of forest roads, while the others utilized topological analyses. There were three methods, of exact solution, that stood out for having been utilized to a greater degree in recent publications, namely: methods based on the Dijkstra algorithm (n = 15), least cost path analysis (LCPA) (n = 8) and the Pegger tool (n = 7) (Table 2). The other methodologies were only observed in two or less studies, as was the case with heuristic methods.

The method used in the majority of studies was Djkstra's algorithm. In a logging area within the Amazon, the study by Aguiar et al. (2019) highlighted this algorithm as best for efficiency, when compared to 3 algorithms other for forest road layout (Integer Linear Programming, Variable Neighborhood Search and AS). Also, in this same forest, Sales et al. (2019) obtained satisfactory results using Djkstra's algorithm with support from GIS to minimize skidding distances, densities of skid trails and haul roads, which enabled an ideal skidding distance to a greater number of logs.

Table 2. Methods for optimizing the design of forest roads, publications from the period 2009-2019.

RI	Methods optimization of forest road	Reference	n	% subject	% total
1	Based on Dijkstra's algorithm	(Abdi et al., 2009; Babapour et al., 2014; Bont et al., 2018; Çalişkan et al., 2019; Eastaugh and Molina, 2011; Ghaffarian et al., 2009, Hayati et al., 2013a, 2013b; Hosseini et al., 2012; Jaafari et al., 2015; Ljubojević et al., 2018; Meignan et al., 2012; Parsakhoo, 2016; Parsakhoo and Jajouzadeh, 2016; Sales et al., 2019)	15	40.5	24.2
2	Least cost path analysis (LCPA)	(Acar et al., 2017; Çalişkan, 2017; Çalişkan et al., 2019; Çalişkan and Karahalil, 2017; Kamarudin et al., 2014; Liampas et al., 2019; Picchio et al., 2018; Saito et al., 2013)	8	21.6	12.9
3	Pegger tool	(Abdi et al., 2009; Babapour et al., 2014; Hayati et al., 2013a, 2013b; Hosseini et al., 2012; Jaafari et al., 2015; Parsakhoo, 2016)	7	18.9	11.3
	Sub-total	-	37	100.0	-
	Total	-	62	-	100.0

RI = ranking of importance

The Djkstra Algorithm also supported some GIS tools of the LCPA methods. LCPA stands out for integrating S-MCDM methodologies, which allow generating a cost surface including a series of factors and associated criteria, in which this surface in raster format is used to trace the road segments, according to the best route between two points consisting of the least accumulated cost pixels. In the Amazon, Barbosa et al. (2017), and Arima et al. (2008, 2005) tested this method to determine extraction routes.

In the study by Barbosa et al. (2017), they used fictional trees as reference points, and therefore, recommend the validation of the methodology using the location of real trees and analysis with existing extensions. Arima et al. (2008) demonstrated improvements in modeling the road network regarding the distribution of harvest volume absent in the previous research by Arima et al. (2005). These authors identified five limitations involved in FRP, in general, the scope of the extraction areas and the precise identification of the hydrological network and other environmental attributes, which are a challenge to survey across large areas, but which influence the construction of roads.

Emmert (2014) studied spatial planning in two areas of authorized timber harvesting in the Amazon (a private and a public forest), with the objective of developing forest planning models, integrating computational GIS tools with mathematical optimization models, such as LCPA. The author outlined minimum cost trajectory problems, using the socalled minimum spanning tree road network, while considering environmental penalties. A heuristic solution was used for this problem, using the method of searching for the minimum cost paths for the flow of wood, based on the hydrological concept applied to a cost surface by GIS platform tools. Forest planning reduced the necessary infrastructure (e. g., haul roads) for logging operations in both private and public forests in the Amazon by 16.5% and 7.0%, respectively (Emmert, 2014).

The automation feature of FRP methodologies in GIS were used mainly in the stages of route optimization (Çaliskan et al., 2019; Saito et al., 2013) and ideal locations for roads (Hosseini et al., 2012; Kühmaier and Stampfer, 2010; Meignan et al., 2012). According to these studies, this resource represents a relevant tool for forest planners, as it allows simulating various scenarios with practicality. According to Yoshida et al. (2019), there currently exists an urgent need to develop automatic FRP systems to accelerate the process for the construction of forest roads.

Among the automation methods, the Pegger tool was the most widely used throughout the world within the last decade. The tool was developed by Rogers, 2005 and consists of a methodology implemented in GIS, for rapid analysis of various alternatives of preliminary routes for forest roads, based on contour lines. However, Barbosa et al. (2017) found that this tool had limitations for planning in natural forests because it does not consider site conditions, such as differences in volume per hectare, which can result in increased environmental damage and reduced operational profit.

Other optimization methodologies that have been employed for road design in SFM in the Amazon, such as the Ordered Tree and Minimum Spanning Tree Road network approaches (Arima et al., 2008; Walker et al., 2013). Within the analyzed period of this research, the indexing and databases used, only 3 articles were developed for SFM in the Amazon, namely (Silva et al., 2018; Sales et al., 2019; Walker et al., 2013), directly and indirectly involving road network planning. The aforementioned authors stressed that the successful optimization of previously allocated log landings may also favor decision-making in the optimal allocation of forest roads and skid trails, also emphasized by (Aguiar, 2019).

In this context, optimization tools for timber harvest planning are increasingly necessary, as the forests of Amazonia are extremely heterogeneous and complex, which presents challenges for modelling and requires computational support for technical decision-making, based on methods that are measurable and replicable, of a known precision and accuracy.

Without the implementation of the tools presented in this work, the sustainability of a SFM may be compromised. This is due to the high costs generated by inadequate planning of infrastructure, which can make timber harvesting unfeasible. This, in turn, can directly impact the local population by the loss of economic opportunity and the subsequent losses to the entire production chain. In addition, the intensified environmental degradation caused by inadequate long-term planning potentially compromises and degrades the forest site and production that is necessary for future cutting cycles.

4. Final considerations

Generally speaking, it could be said that the subject of forest road planning (FRP) has seen an increasing trend in publications. It is not surprising given the technological advances now available to FRP and concern globally due to the various environmental impacts caused by forest roads. Over the last decade, it can be concluded that the main spatial variables used in FRP studies were: slope, elevation, density of roads, proximity to watercourses, slope inclination, timber production, lithology or petrography and distance from existing roads. The main methods of spatial decision-making analysis were AHP and FL based methods, while the main road mapping methodologies were based on Dijkstra’s algorithm and the LCPA and

Pegger tools. However, there is still a need to utilize variables and approaches that are more sensitive to the objectives of sustainable forest management (SFM), such as including social aspects (e.g., local communities), the maintenance of biodiversity, protection of hydrological functions and the reduction of greenhouse gas emissions.

In the decision process to optimize FRP, the principal strategies that were encountered in the recent literature could also contribute to the improvement of SFM in the Amazon region, they are as follows:

- The use and degree of the importance placed on spatial decision variables must be adapted to consider the locality of the project, therefore, consultations with local specialists in the area enabling their contribution to the decision-making process. If this resource is not available, it is recommended to use techniques such as M-AHP, as these techniques do not require expert input, but will still provide suitable analysis;
- The essential description of environmental factors through field surveys, carried out simultaneously with the forest inventory, helps to reduce the subjectivity of micro-planning, in addition to improving the estimation of road construction costs and minimizing environmental impacts;
- The optimization of the road network is closely related to the distribution of log landings and skid trails; therefore, the planning must consider the balance of these various infrastructure components;
- The existing tools available for the analysis for planning the layout of roads in GIS are conducive for the simulation of several potential scenarios with greater practicality. However, there are still challenges for SFM in the Amazon, so the development of specific tools for the diversity of different forest types of the biome are recommended.

CRediT authorship contribution statement

Verônica Satomi Kazama: Conceptualization, Methodology, Investigation, Data curation, Visualization, Writing - original draft, Writing - review & editing. Ana Paula Dalla Corte: Methodology, Writing - original draft, Project administration, Supervision, Writing - review & editing. Renato Cesar Gonçalves Robert: Supervision, Writing - review & editing. Carlos Roberto Sanquetta: Supervision, Writing - review & editing. Julio Eduardo Arce: Writing - review & editing. Kauê Augusto Oliveira-Nascimento: Validation, Writing - review & editing. Daniel DeArmond: Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES) - Financing Code 001 and the Center of Excellence in Research on Carbon Fixation in Biomass (BIOFIX), Forest Inventory Laboratory (LIF), Laboratory of Wood Supply and Forestry Mechanization (LAMEC) and the Graduate Program in Forest Engineering (PPGEF) at the Federal University of Paran´a (UFPR); and the Forest Management Laboratory and the Graduate Program in Tropical Forest Science (PPG - CFT) at the National Institute for Research in the Amazon (INPA).

Appendix

See Tables A.1, B.1, C.1.

Table A.1. Classes of spatial variables used in the planning of forest roads, obtained from three databases of publications from the period 2009-2019.

RI	Classes	Description of the spatial decision variables	Reference	n	% subject	% total
1	Topography	Slope, elevation, slope aspect, slope length, plan curvature, digital terrain model, topographic humidity index, susceptibility to landslides, susceptibility to erosion	(Abdi et al., 2009; Acar et al., 2017; Babapour et al., 2014; Bugday, 2018; Bugday and Akay, 2019; Bugday and Özel, 2019; Çalişkan, 2017, 2013; Çalişkan and Karahalil, 2017; Contreras et al., 2012; Craven and Wing, 2014; Enache et al., 2013; Eskandari and Hosseini, 2013; Ghaffarian et al., 2009; Ghajar et al., 2013; Havimo et al., 2017; Hayati et al., 2013b, 2013a; Hosseini et al., 2012, 2018; Jaafari et al., 2015; Kamarudin et al., 2014; Laschi et al., 2016; Liampas et al., 2019; Ljubojević et al., 2018; Maskani Jifroudi et al., 2009; Mohd Hasmadi et al., 2010; Norizah and Mohd Hasmadi, 2012; Parsakhoo, 2016; Parsakhoo and Jajouzadeh, 2016; Petković and Potočnik, 2018; Tampekis et al., 2015; Turk, 2019; Yoshida et al., 2019)	34	64.2	54.8
2	Soil	Geology, lithology, soil texture, soil depth, rock bed petrography, fertility class, soil erosion, runoff power index, soil type and distance to geological faults	(Abdi et al., 2009; Babapour et al., 2014; Bugday and Akay, 2019; Bugday and Özel, 2019; Çalişkan, 2013; Hayati et al., 2013b, 2013a; Jaafari et al., 2015; Laschi et al., 2016; Liampas et al., 2019; Maskani Jifroudi et al., 2009; Parsakhoo, 2016; Saito et al., 2013; Tampekis et al., 2015)	14	26.4	22.6
3	Technical Aspects	Optimal forest road density, distance to roads, winching distance, skidding distance, extraction distance, forwarding distance, road spacing, skidding area, optimal forest accessibility, distance to existing forest road and efficiency coefficient of the forest road network	(Acar et al., 2017; Bont et al., 2018; Bugday and Akay, 2019; Çalişkan and Karahalil, 2017; Eastaugh and Molina, 2011; Enache et al., 2013; Ghaffarian et al., 2009; Havimo et al., 2017; Hosseini et al., 2018; Kamarudin et al., 2014; Ljubojević et al., 2018; Norizah and Mohd Hasmadi, 2012; Petković and Potočnik, 2018; Tampekis et al., 2015)	14	26.4	22.6
4	Hydrography	Proximity to the hydrographic network	(Babapour et al., 2014; Bont et al., 2015; Bugday, 2018; Bugday and Akay, 2019; Çalişkan, 2017, 2013; Hayati et al., 2013a, 2013b; Jaafari et al., 2015; Kamarudin et al., 2014; Norizah and Mohd Hasmadi, 2012; Parsakhoo, 2016; Yoshida et al., 2019)	13	24.5	21.0
5	Forest biometrics	Timber production (growing stock, volume of stand per hectare, annual increment), tree height, forest age and number of trees per hectare	(Abdi et al., 2009; Babapour et al., 2014; Bugday, 2018; Çalişkan, 2013; Ghajar et al., 2013; Havimo et al., 2017; Hayati et al., 2013b; Hosseini et al., 2012; Laschi et al., 2016; Liampas et al., 2019; Maskani Jifroudi et al., 2009; Tampekis et al., 2015)	12	22.6	19.4
6	Forest cover	Land use, NDVI, forest type, canopy and plant index groups	(Acar et al., 2017; Babapour et al., 2014; Bugday, 2018; Jaafari et al., 2015; Liampas et al., 2019; Maskani Jifroudi et al., 2009; Tampekis et al., 2015)	7	13.2	11.3
7	Climate	Precipitation	(Hayati et al., 2013b; Jaafari et al., 2015; Yoshida et al., 2019)	3	5.7	4.8
8	Forest protection	Forest protection percentage and Protection of ecologically important areas	(Enache et al., 2013; Tampekis et al., 2015)	2	3.8	3.2
9	Social Aspects	Neighboring the villages and Accessibility for touristic, local or cultural points of interest	(Bugday, 2018; Enache et al., 2013)	2	3.8	3.2
Sub-total		-	-	53	100.0	-
Total		-	-	62	-	100.0

RI = ranking of importance

Table B.1. Spatial variables most commonly used in the planning of forest roads, obtained from three databases of articles published in the period 2009-2019.

RI	Spatial decision variable	Reference	n	% subject	% total
1	Slope	(Abdi et al., 2009; Acar et al., 2017; Babapour et al., 2014; Bugday, 2018; Bugday and Akay, 2019; Bugday and Özel, 2019; Çalişkan, 2017, 2013; Çalişkan and Karahalil, 2017; Craven and Wing, 2014; Enache et al., 2013; Eskandari and Hosseini, 2013; Ghaffarian et al., 2009; Hayati et al., 2013a, 2013b; Hosseini et al., 2012, 2018; Jaafari et al., 2015; Kamarudin et al., 2014; Laschi et al., 2016; Liampas et al., 2019; Ljubojević et al., 2018; Maskani Jifroudi et al., 2009; Mohd Hasmadi et al., 2010; Norizah and Mohd Hasmadi, 2012; Parsakhoo, 2016; Parsakhoo and Jajouzadeh, 2016; Petković and Potočnik, 2018; Tampekis et al., 2015)	29	54.7	46.8
2	Elevation	(Abdi et al., 2009; Acar et al., 2017; Babapour et al., 2014; Bugday, 2018; Bugday and Akay, 2019; Bugday and Özel, 2019; Çalişkan, 2013; Çalişkan and Karahalil, 2017; Contreras et al., 2012; Craven and Wing, 2014; Ghajar et al., 2013; Havimo et al., 2017; Hayati et al., 2013b; Jaafari et al., 2015; Kamarudin et al., 2014; Mohd Hasmadi et al., 2010; Norizah and Mohd Hasmadi, 2012)	17	32.1	27.4
3	Forest road density	(Acar et al., 2017; Bont et al., 2018; Çalişkan, 2013; Çalişkan and Karahalil, 2017; Eastaugh and Molina, 2011; Ghaffarian et al., 2009; Havimo et al., 2017; Hayati et al., 2012; Hosseini et al., 2012, 2018; Jourgholami et al., 2013; Krč and Beguš, 2013; Kühmaier and Stampfer, 2010; Petković and Potočnik, 2018; Tampekis et al., 2015)	15	28.3	24.2
4	Proximity to the hydrographic network	(Babapour et al., 2014; Bont et al., 2015; Bugday, 2018; Bugday and Akay, 2019; Çalişkan, 2017, 2013; Hayati et al., 2013a; Jaafari et al., 2015; Kamarudin et al., 2014; Norizah and Mohd Hasmadi, 2012; Picchio et al., 2018; Yoshida et al., 2019)	12	22.6	19.4
5	Slope aspect	(Acar et al., 2017; Babapour et al., 2014; Bugday and Akay, 2019; Çalişkan, 2013; Çalişkan and Karahalil, 2017; Hayati et al., 2013b; Hosseini et al., 2012, 2018; Jaafari et al., 2015; Maskani Jifroudi et al., 2009; Tampekis et al., 2015)	10	18.9	16.1
6	Timber production	(Abdi et al., 2009; Babapour et al., 2014; Bugday, 2018; Çalişkan, 2013; Havimo et al., 2017; Hayati et al., 2013b; Hosseini et al., 2012; Laschi et al., 2016; Liampas et al., 2019; Maskani Jifroudi et al., 2009; Tampekis et al., 2015)	10	18.9	16.1
7	Existing forest road	(Acar et al., 2017; Bont et al., 2018; Bugday and Akay, 2019; Hosseini et al., 2018; Kamarudin et al., 2014; Krč and Beguš, 2013; Norizah and Mohd Hasmadi, 2012)	7	13.2	11.3
8	Lithology/Petrography	(Abdi et al., 2009; Babapour et al., 2014; Bugday and Akay, 2019; Bugday and Özel, 2019; Çalişkan, 2013; Jaafari et al., 2015; Maskani Jifroudi et al., 2009)	7	13.2	11.3
Sub-total		-	53	100.0	-
Total		-	62	-	100.0

RI = ranking of importance

Table C.1. Methods for optimizing the design of forest roads, obtained from three publication databases in the period 2009-2019.

RI	Classes	Optimization methods observed	Reference	n	% subject	% total
1	GIS-based methods	Pegger tool, Least cost path analysis, FOROR tool and 3D forest road alignment optimization model (TRACER)	(Abdi et al., 2009; Acar et al., 2017; Akay et al., 2014; Babapour et al., 2014; Çalişkan, 2017; Çalişkan et al., 2019; Çalişkan and Karahalil, 2017; Hayati et al., 2013b, 2013a; Hosseini et al., 2012; Jaafari et al., 2015; Kamarudin et al., 2014; Kühmaier and Stampfer, 2010; Liampas et al., 2019; Parsakhoo, 2016; Picchio et al., 2018; Saito et al., 2013)	21	52.5	33.9
2	Exact solution optimization methods	Dijkstra's algorithm, Weighted-graph algorithm, Minimum spanning tree, Ordered tree, Mixed Integer Linear Programming (MILP), Linear Programming, Mixed Integer Programming (MIP) and Dynamic programming	(Akay et al., 2014; Bont et al., 2018, 2015; Eastaugh and Molina, 2011; Ghaffarian et al., 2009; Ljubojević et al., 2018; Meignan et al., 2012; Najafi and Richards, 2013; Parsakhoo and Jajouzadeh, 2016; Parsakhoo and Lotfalian, 2017; Saito et al., 2013; Walker et al., 2013)	12	30.0	19.4
3	Heuristic optimization methods	Genetic algorithm (GA), Simulated Annealing (SA), Particle swarm optimization (PSO), Greedy Randomized Adaptive Search Procedure (GRASP), Average distance heuristic (ADH), Dual ascent heuristic (DAH), Distance network heuristic (DNH), Kruskal-based heuristic (KBH), Longest path heuristic (LPH), Minimum spanning tree heuristic (MSTH), Shortest path heuristic (SPH), Shortest path heuristic with 3BASIC (SPH-3b), Repetitive shortest path heuristics -V (SPH-V), Repetitive shortest path heuristics - Z (SPH-Z), Repetitive shortest path heuristics - zZ (SPH-zZ), Repetitive shortest path heuristics -ZZ (SPH-ZZ), Shortest paths with origin heuristic (SPOH) and Y-heuristic YH	(Akay et al., 2014; Babapour et al., 2018; Bont et al., 2018; Meignan et al., 2012; Shirasawa and Hasegawa, 2014)	5	12.5	8.1
Sub-total		-	-	40	100.0	-
Total		-	-	62	-	100.0

RI = ranking of importance

References

Abdi, E., Majnounian, B., Darvishsefat, A., Mashayekhi, Z., Sessions, J., 2009. A GIS-MCE based model for forest road planning. J. For. Sci. 55, 171–176.

Acar, H.H., Dursun, E., Gulci, S., Gumus, S., 2017. Assessment of road network planning by using gis-based multi-criteria evaluation for conversion of coppice forest to high forest. Fresenius Environ. Bull. 26, 2380–2388.

Aguiar, M.O., 2019. Otimização do planejamento integrado de infraestrutura na exploração florestal na Região Amazônica. Tese (Doutorado em Engenharia Florestal) - Universidade Federal do Espírito Santo.

Aguiar, M.O., Fernandes da Silva, G., Mauri, G.R., Ferreira da Silva, E., Ribeiro de Mendonça, A., Martins Silva, J.P., Silva, R.F., Santos, J.S., Lavagnoli, G.L., Figueiredo, E.O., 2020. Metaheuristics applied for storage yards allocation in an Amazonian sustainable forest management area. J. Environ. Manage. 271 https://doi.org/10.1016/j.jenvman.2020.110926.

Akay, A.A., 2004. New methodology in designing forest roads. Turkish J. Agricul. Forest. 28, 273–279.

Akay, A.E., Wing, M.G., Sessions, J., 2014. Estimating sediment reduction cost for low-volume forest roads using a LiDAR-derived high-resolution DEM. Balt. J. Road Bridg. Eng. 9, 52–57. https://doi.org/10.3846/bjrbe.2014.07.

Akay, A.O., Demir, M., Akgul, M., 2018. Assessment of risk factors in forest road design and construction activities with fuzzy analytic hierarchy process approach in Turkey. Environ. Monit. Assess. 190 https://doi.org/10.1007/s10661-018-6948-0.

Akgul, M., Demir, M., Ozturk, T., Topatan, H., Budak, Y.E., 2016. Investigation of recreational vehicles maneuverability on forest roads by computer-aided driving analysis. Balt. J. Road Bridge E. 11, 111–119. https://doi.org/10.3846/ bjrbe.2016.13.

Akgul, M., Yurtseven, H., Gulci, S., Akay, A.E., 2018. Evaluation of UAV- and GNSS- based DEMs for earthwork volume. Arab. J. Sci. Eng. 43, 1893–1909. https://doi.org/10.1007/s13369-017-2811-9.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., De Moraes Gonçalves, J.L., Sparovek, G., 2013. Koppen's climate classification map for Brazil. Meteorol. Zeitschrift 22, 711–728. https://doi.org/10.1127/0941-2948/2013/0507.

Andersen, H.E., Reutebuch, S.E., McGaughey, R.J., d'Oliveira, M.V.N., Keller, M., 2014. Monitoring selective logging in Western Amazonia with repeat LiDAR flights. Remote Sens. Environ. 151, 157–165. https://doi.org/10.1016/j.rse.2013.08.049.

Arima, E.Y., Walker, R.T., Perz, S.G., Caldas, M., 2005. Loggers and forest fragmentation: Behavioral models of road building in the Amazon basin. Ann. Assoc. Am. Geogr. 95, 525–541. https://doi.org/10.1111/j.1467-8306.2005.00473.x.

Arima, E.Y., Walker, R.T., Sales, M., Souza, C., Perz, S.G., 2008. The fragmentation of space in the Amazon basin: emergent road networks. Photogramm. Eng. Remote Sensing 74, 699–709. https://doi.org/10.14358/PERS.74.6.699.

Atalay, I., Efe, R., ¨Ozturk, M., 2014. Ecology and classification of forests in Turkey. Procedia Soc. Behav. 120, 788–805. https://doi.org/10.1016/j.sbspro.2014.02.163.

Babapour, R., Naghdi, R., Ghajar, I., Ghodsi, R., 2017. New strategies for estimation of cut and fill areas in road design with different ground cross-section offsets. Scand. J. For. Res. 33, 178–187. https://doi.org/10.1080/02827581.2017.1338748.

Babapour, R., Naghdi, R., Ghajar, I., Ghodsi, R., 2015. Modeling the proportion of cut slopes rock on forest roads using artificial neural network and ordinal linear regression. Environ. Monit. Assess. 187 https://doi.org/10.1007/s10661-015-4688- y.

Babapour, R., Naghdi, R., Ghajar, I., Mortazavi, Z., 2018. Forest road profile optimization using meta-heuristic techniques. Appl. Soft Comput. J. 64, 126–137. https://doi.org/ 10.1016/j.asoc.2017.12.015.

Babapour, R., Naghdi, R., Salehi, A., Ghajar, I., 2014. A decision support system for allocation of mountain forest roads based on ground stability. Arab. J. Sci. Eng. 39, 199–205. https://doi.org/10.1007/s13369-013-0833-5.

Barbosa, R.P., Rodriguez, L.C.E., Gorgens, E.B., 2017. Multi-criteria optimization for log extraction in Amazon based on airborne laser scanning data. Scientia Forestalis. 45.

Bont, L.G., Fraefel, M., Fischer, C., 2018. A spatially explicit method to assess the economic suitability of a forest road network for timber harvest in steep terrain. Forests 9. https://doi.org/10.3390/f9040169.

Bont, L.G., Heinimann, H.R., Church, R.L., 2015. Concurrent optimization of harvesting and road network layouts under steep terrain. Ann. Oper. Res. 232, 41–64. https:// doi.org/10.1007/s10479-012-1273-4.

Brasil, 2018. Resolução/CEMAAM N. 30 de 31 de outubro de 2018. Conselho Estadual do Meio Ambiente, CEMAAM, Brasil.

Brasil, 2012. Lei no. 12.651 de 25 de Maio de 2012. Dispõe sobre a proteção da vegetação nativa; altera as Leis nos 6.938, de 31 de agosto de 1981, 9.393, de 19 de dezembro de 1996, e 11.428, de 22 de dezembro de 2006; revoga as Leis nos 4.771, de 15 de setembro de 196. Brasília.

Brasil, 2009. Resolução No 406, de 02 de fevereiro de 2009. Conselho Nacional do Meio Ambiente, CONAMA, Brasil.

Brasil, 2007. Norma de Execução no 1, de 24 Abril de 2007 do Instituto Brasileiro do Meio Ambiente e Recursos Hídricos. https://www.normasbrasil.com.br/norma/no rma-de-execucao-1-2007_90937.html.

Brasil, 2006. Instrução Normativa no 05 de 11 de dezembro de 2006. Ministério do Meio Ambiente. 1–14.

Braz, E.M., 2010. Subsídios para o planejamento do manejo de florestas tropicais da Amazonia 237p. Tese (Doutorado em Engenharia Florestal) - Universidade Federal de Santa Maria.

Braz, E.M., 1997. Otimização de rede de estradas secundarias em projetos de manejo sustentável de floresta tropical. Circular Técnica 15, Rio Branco, Embrapa-CPAF/AC, 36 p.

Bugday, E., 2018. Application of artificial neural network system based on Anfis using GIS for predicting forest road network suitability mapping. Fresenius Environ. Bull. 27, 1656–1668.

Bugday, E., Akay, A.E., 2019. Evaluation of forest road network planning in landslide sensitive areas by GIS-based multi-criteria decision making approaches in Ihsangazi Watershed, Northern Turkey. Sumar. List 143, 325–336. https://doi.org/10.31298/ sl.143.7-8.4.

Bugday, E., Özel, H.B., 2019. Utilizing a fuzzy inference system (FIS) and modified analytical hierarchical analysis for forest road network planning in afforested lands. Polish J. Environ. Stud. 28, 1579–1589. https://doi.org/10.15244/pjoes/89611.

Çaliskan, E., 2017. Planning of environmentally sound forest road route using & S- MCDM. Sumar. List 141, 583–591.

Çaliskan, E., 2013. Planning of forest road network and analysis in mountainous area. Life Sci. J. 10, 2456–2465.

Çaliskan, E., Bediroglu, S., Yildirim, V., 2019. Determination forest road routes via GIS- based spatial multi-criterion decision methods. Appl. Ecol. Environ. Res. 17, 759–779. https://doi.org/10.15666/aeer/1701_759779.

Çaliskan, E., Karahalil, U., 2017. Evaluation of forest road network and determining timber extraction system using gis: a case study in Anbardağ planning unit. Sumar. List 141, 163–171.

Castaño-Villa, G.J., Estevez, J.V., Guevara, G., Bohada-Murillo, M., Fontúrbel, F.E., 2019. Differential effects of forestry plantations on bird diversity: a global assessment. For. Ecol. Manage. 440, 202–207. https://doi.org/10.1016/j.foreco.2019.03.025.

Cavalli, R., Grigolato, S., 2010. Influence of characteristics and extension of a forest road network on the supply cost of forest woodchips. J. For. Res. 15, 202–209. https:// doi.org/10.1007/s10310-009-0170-4.

Chauvel, A., Lucas, Y., Boulet, R., 1987. On the genesis of the soil mantle of the region of Manaus, Central Amazonia, Brazil. Experientia. 43, 234–241. https://doi.org/ 10.1007/BF01945546.

Contreras, M., Aracena, P., Chung, W., 2012. Improving accuracy in earthwork volume estimation for proposed forest roads using a high-resolution digital elevation model. Croat. J. For. Eng. 33, 125–142.

Costa Filho, P.P., da Costa, H.B., 1980. Construção de estradas florestais e transporte florestal rodoviário na região Amazônica. Circular Técnica 6, Belém, Embrapa- CPATU, 30 p.

Craven, M., Wing, M.G., 2014. Applying airborne LiDAR for forested road geomatics. Scand. J. For. Res. 29, 174–182. https://doi.org/10.1080/02827581.2014.881546.

D'amours, S., Ronnqvist, M., Weintraub, A., 2008. Using Operational Research for supply chain planning in the forest products industry. INFOR 46, 265–281. https://doi.org/10.3138/infor.46.4.265.

d'Oliveira, M.V.N., Reutebuch, S.E., McGaughey, R.J., Andersen, H.E., 2012. Estimating forest biomass and identifying low-intensity logging areas using airborne scanning lidar in Antimary State Forest, Acre State, Western Brazilian Amazon. Remote Sens. Environ. 124, 479–491. https://doi.org/10.1016/j.rse.2012.05.014.

de Carvalho, A.L., D'Oliveira, M.V.N., Putz, F.E., de Oliveira, L.C., 2017. Natural regeneration of trees in selectively logged forest in western Amazonia. For. Ecol. Manage. 392, 36–44. https://doi.org/10.1016/j.foreco.2017.02.049.

Eastaugh, C.S., Molina, D., 2011. Forest road networks: metrics for coverage, efficiency and convenience. Aust. For. 74, 54–61. https://doi.org/10.1080/ 00049158.2011.10676346.

Edwards, F.A., Finan, J., Graham, L.K., Larsen, T.H., Wilcove, D.S., Hsu, W.W., Chey, V. K., Hamer, K.C., 2017. The impact of logging roads on dung beetle assemblages in a tropical rainforest reserve. Biol. Conserv. 205, 85–92. https://doi.org/10.1016/j.biocon.2016.11.011.

Eker, R., Aydin, A., 2014. Assessment of forest road conditions in terms of landslide susceptibility: a case study in Yigilca Forest Directorate (Turkey). TURKISH J. Agric. For. 38, 281–290. https://doi.org/10.3906/tar-1303-12.

Emmert, F., 2014. Combinação de dados de campo e métodos computacionais para o planejamento da exploração florestal na Amazônia. Tese (Doutorado em Engenharia Florestal) - Universidade de Brasília.

Enache, A., Kühmaier, M., Stampfer, K., Ciobanu, V.D., 2013. An integrative decision support tool for assessing forest road options in a mountainous region in Romania. Croat. J. For. Eng. 34, 43–60.

Eskandari, S., Hosseini, S.A., 2013. Assessment of drainage system standards of forest roads in Iran using GIS. Polish J. Environ. Stud. 22, 675–682.

Ghaffarian, M.R., Stampfer, K., Sessions, J., 2009. Comparison of three methods to determine optimal road spacing for forwarder-type logging operations. J. For. Sci. 55, 423–431. https://doi.org/10.17221/79/2008-jfs.

Ghajar, I., Najafi, A., Karimimajd, A.M., Boston, K., Ali Torabi, S., 2013. A program for cost estimation of forest road construction using engineer's method. Forest Sci. Technol. 9, 111–117. https://doi.org/10.1080/21580103.2012.759163.

Grigolato, S., Mologni, O., Cavalli, R., 2017. GIS applications in forest operations and road network planning: An overview over the last two decades. Croat. J. For. Eng. 38, 175–186.

Gromskaya, L.Y., Simonenkov, M.V., 2016. Current Status of Modeling and Optimization of Forest Roads. Lesnoy Zhurnal (Russian Forestry Journal) 108–122. https://doi.org/10.17238/issn0536-1036.2016.5.108.

Havimo, M., Monkonen, P., Lopatin, E., Dahlin, B., 2017. Optimizing forest road planning to maximise the mobilisation of wood biomass resources in Northwest Russia. Biofuels 8, 501–514. https://doi.org/10.1080/17597269.2017.1302664.

Hayati, E., Abdi, E., Majnounian, B., Makhdoum, M., 2013a. Application of sensitivity analysis in forest road networks planning and assessment. J. Agric. Sci. Technol. 15, 781–792.

Hayati, E., Majnounian, B., Abdi, E., 2012. Qualitative evaluation and optimization of forest road network to minimize total costs and environmental impacts. iForest- Biogeosci. For. 5, 121–125. https://doi.org/10.3832/ifor0610-009.

Hayati, E., Majnounian, B., Abdi, E., Sessions, J., Makhdoum, M., Makhdom, M., 2013b. An expert-based approach to forest road network planning by combining Delphi and spatial multi-criteria evaluation. Environ. Monit. Assess. 185, 1767–1776. https://doi.org/10.1007/s10661-012-2666-1.

Hosseini, S.A., Mazrae, M.R., Lotfalian, M., Parsakhoo, A., 2012. Designing an optimal forest road network by consideration of environmental impacts in GIS. J. Environ. Eng. Landsc. Manag. 20, 58–66. https://doi.org/10.3846/16486897.2012.662748.

Hosseini, S.A.O., Gorgandipur, M., Nikooy, M., 2018. Forest road network assessment using lookoutpoints orienting in Hyrcanian forest using GIS - Short communication. J. For. Sci. 64, 402–408. https://doi.org/10.17221/45/2018-JFS.

Instituto Brasileiro de Geografia e Estatística - IBGE, 2012. Manual T´ecnico da Vegetaç˜ao Brasileira, Produção da Pecuária Municipal. https://doi.org/ISSN 0101-4234.

International Tropical Timber Organization - ITTO, 2019. Biennial review and assessment of the world timber situation 2017-2018.

Irion, G., 1978. Soil infertility in the Amazonian rain forest. Naturwissenschaften 65, 515–519. https://doi.org/10.1007/BF00439791.

Jaafari, A., Najafi, A., Rezaeian, J., Sattarian, A., Ghajar, I., 2015. Planning road networks in landslide-prone areas: A case study from the northern forests of Iran. Land use policy 47, 198–208. https://doi.org/10.1016/j.landusepol.2015.04.010.

Jourgholami, M., Abdi, E., Chung, W., 2013. Decision making in forest road planning considering both skidding and road costs: a case study in the Hyrcanian forest in Iran. iForest-Biogeosci. Forest. 6, 59–64. https://doi.org/10.3832/efor0640-006.

Jourgholami, M., Majnounian, B., 2011. Harvesting systems in Hyrcanian Forest, Iran; limitations and approaches. The forest engineering network (Formec, Austria, Proceedings) October 9–13, 1–9.

Kamarudin, N., Ismail, M.H., Jusoff, K., 2014. Quantification of least cost path analysis for best forest road planning. Malaysian For. 77, 101–110.

Keller, G., Sherar, J., Zweede, J., 2015. Overview of Amazon Basin Forest Roads Manual. Transp. Res. Rec. 2472 (1), 56–63. https://doi.org/10.3141/2472-07.

Kooch, Y., Moghimian, N., Wirth, S., Haghverdi, K., 2020. Effects of shelterwood and single-tree cutting systems on topsoil quality and functions in northern Iranian forests. For. Ecol. Manag. 468, 118188. https://doi.org/10.1016/j. foreco.2020.118188.

Krc, J., Begus, J., 2013. Planning forest opening with forest roads. Croat. J. For. Eng. 34, 217–228.

Kühmaier, M., Stampfer, K., 2010. Development of a multi-attribute spatial decision support system in selecting timber harvesting systems. Croat. J. For. Eng. 32, 75–88.

Lamprecht, H., 1990. Silvicultura nos Trópicos. Cooperação Técnica-RFA, Eschborn, p. 343.

Laschi, A., Foderi, C., Fabiano, F., Neri, F., Cambi, M., Mariotti, B., Marchi, E., 2019. Forest road planning, construction and maintenance to improve forest fire fighting: a review. Croat. J. For. Eng. 40, 207–219.

Laschi, A., Neri, F., Montorselli, N.B., Marchi, E., 2016. A methodological approach exploiting modern techniques for forest road network planning. Croat. J. For. Eng. 37, 319–331.

Liampas, S.-A.G., Stamatiou, C.C., Drosos, V.C., 2019. Forest road network planning for biomass exploitation and fire preventions: a least cost path analysis. Agric. Eng. Int. CIGR J. 21, 33–42.

Ljubojevic, D., Danilovic, M., Marceta, D., Petkovic, V., 2018. Winching distance in function of the optimization of skid network. South-East Eur. For. 9, 97–106. https://doi.org/10.15177/seefor.18-14.

Martinhago, A.Z., 2012. Otimização para alocação de pátios de estocagem para exploração de impacto reduzido na Amazˆonia brasileira. Tese (Doutorado em Engenharia Florestal) - Universidade Federal de Lavras.

Maskani Jifroudi, H.R., Naghdi, R., Firozan, A., Haghighi, M., 2009. The assigning of suitable model for valuation of effective factors in forest roads network planning (Shanderman forest, Northern Iran). J. Appl. Sci. 9, 3364–3370. https://doi.org/ 10.3923/jas.2009.3364.3370.

Meignan, D., Frayret, J.-M., Pesant, G., Blouin, M., 2012. A heuristic approach to automated forest road location. Can. J. For. Res. 42, 2130–2141. https://doi.org/ 10.1139/x2012-140.

Mohd Hasmadi, I., Pakhriazad, H.Z., Mohamad, F.S., 2010. Geographic information system-allocation model for forest path: a case study in ayer hitam forest reserve, Malaysia. Am. J. Appl. Sci. 7, 376–380.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., Altman, D., Antes, G., Atkins, D., Barbour, V., Barrowman, N., Berlin, J.A., Clark, J., Clarke, M., Cook, D., D'Amico, R., Deeks, J.J., Devereaux, P.J., Dickersin, K., Egger, M., Ernst, E., Gøtzsche, P.C., Grimshaw, J., Guyatt, G., Higgins, J., Ioannidis, J.P.A., Kleijnen, J., Lang, T., Magrini, N., McNamee, D., Moja, L., Mulrow, C., Napoli, M., Oxman, A., Pham, B., Rennie, D., Sampson, M., Schulz, K.F., Shekelle, P.G., Tovey, D., Tugwell, P., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 6 https://doi.org/10.1371/journal.pmed.1000097.

Murray, A.T., 1998. Route planning for harvest site access. Can. J. For. Res. 28, 1084–1087. https://doi.org/10.1139/cjfr-28-7-1084.

Najafi, A., Richards, E.W., 2013. Designing a forest road network using mixed integer programming. Croat. J. For. Eng. 34, 17–30.

Nefeslioglu, H.A., Sezer, E.A., Gokceoglu, C., Ayas, Z., 2013. A modified analytical hierarchy process (M-AHP) approach for decision support systems in natural hazard assessments. Comput. Geosci. 59, 1–8. https://doi.org/10.1016/j. cageo.2013.05.010.

Norizah, K., Mohd Hasmadi, I., 2012. Developing priorities and ranking for suitable forest road: Allocation using Analytic Hierarchy Process (AHP) in peninsular Malaysia. Sains Malaysiana 41, 1177–1185.

Parsakhoo, A., 2016. Metric measurements for optimization of forest road network alternatives in GIS-based programs. Forest Sci. Technol. 12, 153–161. https://doi.org/10.1080/21580103.2016.1141718.

Parsakhoo, A., Jajouzadeh, M., 2016. Determining an optimal path for forest road construction using Dijkstra’s algorithm. J. For. Sci. 62, 264–268. https://doi.org/ 10.17221/9/2016-JFS.

Parsakhoo, A., Lotfalian, M., 2017. Locating log depots and forest roads using a weighted-graph optimization algorithm. Nov. Meh. Sumar. 38, 67–77.

Pentek, T., Neveˇcerel, H., Ecimovíc, T., Lepoglavec, K., Papa, I., Tomaˇsi´c, ˇZ., 2014. Strategic planning of forest road network in Croatia - analysis of present situation as basis for future activities. Nov. Meh. Sumar. 35, 63–78.

Petkovic, V., Potocnik, I., 2018. Planning forest road network in natural forest areas: a case study in Northern Bosnia and Herzegovina. Croat. J. For. Eng. 39, 45–56.

Picchio, R., Pignatti, G., Marchi, E., Latterini, F., Benanchi, M., Foderi, C., Venanzi, R., Verani, S., 2018. The application of two approaches using GIS technology implementation in forest road network planning in an Italian mountain setting. Forests 9. https://doi.org/10.3390/f9050277.

Pourghasemi, H., Beheshtirad, M., Pradhan, B., 2016. A comparative assessment of prediction capabilities of modified analytical hierarchy process (M-AHP) and Mamdani fuzzy logic models using Netcad-GIS for forest fire susceptibility mapping. Geomatics. Nat. Hazards Risk 7, 861–885. https://doi.org/10.1080/ 19475705.2014.984247.

Rex, F.E., Dalla Corte, A.P., Debastiani, A.B., Kazama, V.S., Sanquetta, C.R., 2018. Uso de dados LiDAR na estimativa de vari´aveis biofísica na Amazˆonia, sob diferentes resoluç˜oes espaciais. Nativa 6, 841. https://doi.org/10.31413/nativa.v6i0.6312.

Saito, M., Goshima, M., Aruga, K., Matsue, K., Shuin, Y., Tasaka, T., 2013. Study of automatic forest road design model considering shallow landslides with lidar data of funyu experimental forest. Croat. J. For. Eng. 34, 1–16.

Sales, A., Gonzales, D.G.E., Guilherme Vaz Martins, T., Silva, G.C.C., Spletozer, A.G., de Almeida Telles, L.A., Siviero, M.A., Lorenzon, A.S., 2019. Optimization of skid trails and log yards on the Amazon Forest. Forests 10, 1–11. https://doi.org/10.3390/ f10030252.

Schuh, M., Favarin, J.A.S., Marchesan, J., Alba, E., Fernando Berra, E., Soares Pereira, R., 2020. Machine learning and generalized linear model techniques to predict aboveground biomass in Amazon rainforest using LiDAR data. J. Appl. Remote Sens. 14, 034518. https://doi.org/10.1117/1.jrs.14.034518.

Sessions, J., 2007a. Harvesting Operations in the Tropics. Springer, New York., p. 170
Sessions, J., 2007b. Forest road operations in the Tropics. Springer, New York., p. 170
Sessions, J., Stewart, R., Anderson, P., Tuor, B., 1986. Calculating the maximum grade a log truck can climb. West. J. Appl. For. 1, 43–45. https://doi.org/10.1093/wjaf/ 1.2.43.

Sessions, J., Wimer, J., Costales, F., Wing, M.G., 2010. Engineering considerations in road assessment for biomass operations in steep terrain. West. J. Appl. For. 25, 144–153. https://doi.org/10.1093/wjaf/25.3.144.

SFB. Serviço Florestal Brasileiro. 2018. Execuç˜ao T´ecnica: Documentos. http://www.florestal.gov.br/documentos/concessoes-florestais/concessoes-florestais-florestas-so b-concessao/flona-do-jamari/producao-2/amata/execucao-tecnica-2/3412-amata- jamari-umf3-poa14-2017-2018/file.

Shirasawa, H., Hasegawa, H., 2014. A comparative study of heuristic algorithms for the multiple target access problem. J. For. Res. 19, 437–449. https://doi.org/10.1007/ s10310-013-0432-z.

Silva, E.F., 2019. Planejamento da exploraç˜ao em florestas nativas manejadas da Amazˆonia por meio de pesquisa operacional (Tese (Doutorado em Ciˆencias Florestais)). Centro de Ciˆencias Agr´arias e Engenharias, Universidade Federal do Espírito Santo, Jerˆonimo Monteiro.

Silva, E.F., Silva, G.F., Figueiredo, E.O., Mendonça, A.R. de, Santana, C.J. de O., Fiedler, N.C., Silva, J.P.M., Aguiar, M.O., Santos, J.S., 2020. Optimized forest planning: allocation of log storage yards in the Amazonian sustainable forest management area. For. Ecol. Manage. 472, 118231. https://doi.org/10.1016/j.foreco.2020 .118231.

Silva, E.F., Silva, G.F., Figueiredo, E.O., Binoti, D.H.B., de Mendonça, A.R., Torres, C.M. M.E., Pezzopane, J.E.M., da Silva, G.F., 2018. Allocation of storage yards in management plans in the Amazon by means of mathematical programming. Forests 9, 127. https://doi.org/10.3390/f9030127.

Siqueira-Gay, J., Sonter, L.J., S´anchez, L.E., 2020. Exploring potential impacts of mining on forest loss and fragmentation within a biodiverse region of Brazil's Northeastern Amazon. Resour. Policy 67. https://doi.org/10.1016/j.resourpol.2020.101662.

Sohrabi, H., Jourgholami, M., Jafari, M., Shabanian, N., Venanzi, R., Tavankar, F., Picchio, R., 2020. Soil recovery assessment after timber harvesting based on the sustainable forest operation (SFO) perspective in Iranian temerate forests. Sustainability 12, 2874. https://doi.org/10.1093/wjaf/25.3.144.

Rogers, L.W., 2005. Automating contour-based route projection for preliminary forest road designs using GIS. University of Washington.

Rogers, L., Schiess, P., 2001. PEGGER & ROADVIEW - A New GIS Tool To Assist Engineers In Operations Planning. The International Mountain Logging and 11th Pacific Northwest Skyline Symposium 2001 177–182. Sagheb-Talebi, Kh., Sajedi, T., Pourhashemi, M., 2014. Forests of Iran: a treasure from the past, a hope for the future. Springer, New York., p. 149

Sombroek, W., 2000. Amazon landforms and soils in relation to biological diversity. Acta Amazon. 30, 81–100. https://doi.org/10.1590/1809-43922000301100.

Tampekis, S., Sakellariou, S., Samara, F., Sfougaris, A., Jaeger, D., Christopoulou, O., 2015. Mapping the optimal forest road network based on the multicriteria evaluation technique: the case study of Mediterranean Island of Thassos in Greece. Environ. Monit. Assess. 187 https://doi.org/10.1007/s10661-015-4876-9.

Tavankar, F., Bonyad, A.E., Majnounian, B., 2015. Affective factors on residual tree damage during selection cutting and cable-skidder logging in the Caspian forests, Northern Iran. Ecol. Eng. 83, 505–512. https://doi.org/10.1016/j. ecoleng.2015.07.018.

ter Steege, Hans, et al., 2013. Hyperdominance in the Amazonian tree flora. Science 342, 1243092. https://doi.org/10.1126/science.1243092.

Turk, Y., 2019. Forest road design with cad software: a case study in the Western Black Sea region of Turkey. Fresenius Environ. Bull. 28, 1743–1751.

Vale Júnior, J.F. do, Souza, M.I.L. de, Nascimento, P.P.R.R., Cruz, D.L. de S., 2011. Solos da Amazônia: etnopedologia e desenvolvimento sustentável. Rev. Agro@mbiente On-Line 5, 158. https://doi.org/10.18227/1982-8470ragro.v5i2.562.

Vieira, L.N., Rogalski, M., Faoro, H., Fraga, H.P.F., Anjos, K.G., Picchi, G.F.A., Nodari, R. O., Pedrosa, F.O., Souza, E.M., Guerra, M.P., 2016. The plastome sequence of the endemic Amazonian conifer, Retrophyllum piresii (Silba) C.N.Page, reveals different recombination events and plastome isoforms. Tree Genet. Genomes. 12, 1–11. https://doi.org/10.1007/s11295-016-0968-0.

Walker, R., Arima, E., Messina, J., Soares-Filho, B., Perz, S., Vergara, D., Sales, M., Pereira, R., Castro, W., 2013. Modeling spatial decisions with graph theory: logging roads and forest fragmentation in the Brazilian Amazon. Ecol. Appl. 23, 239–254. https://doi.org/10.1890/11-1800.1.

Yolasigmaz, H.A., Güner, S., 2016. The process of silviculture planning in Turkey: Hisar case study. Sumar. List 140, 503–514. https://doi.org/10.31298/sl.140.9-10.7.

Yoshida, M., Sakurai, R., Sakai, H., 2019. Forest road planning using precision geographic data under climate change. Int. J. For. Eng. 30, 219–227. https://doi.org/10.1080/14942119.2018.1498687.

Zakowska, L., 1999. Road curve evaluation based on road view perception study. Transportation Res. Rec., 1689, 68–72. https://doi-org.ez22.periodicos.capes.gov.br/10.3141/1689-10.

Zupic, I., Cater, T., 2015. Bibliometric methods in management and organization. Organ. Res. Methods 18, 429–472. https://doi.org/10.1177/1094428114562629.

CHAPTER II

ROAD NETWORK PLANNING AND SPATIAL ASSESSMENT FOR SUSTAINABLE FOREST MANAGEMENT IN THE BRAZILIAN AMAZON: METHODOLOGICAL PROPOSAL AND CHALLENGES*

* Chapter formatted to Land Use Policy journal.

ROAD NETWORK PLANNING AND SPATIAL ASSESSMENT FOR SUSTAINABLE FOREST MANAGEMENT IN THE BRAZILIAN AMAZON: METHODOLOGICAL PROPOSAL AND CHALLENGES

Verônica Satomi Kazama[a]*, Ana Paula Dalla Corte[a], Renato Cesar Gonçalves Robert[a], Carlos Roberto Sanquetta[a], Daniel DeArmond[b]

[a]Forest Sciences Department, Federal University of Paraná, Curitiba, Paraná, Brazil
[b]Tropical Forestry Department, National Institute for Research in the Amazon, Manaus, Amazonas, Brazil
*Corresponding author: veronica.kazama@gmail.com

ABSTRACT

The objective of this study was to develop a methodological procedure capable of assisting in the planning and spatial evaluation of the road network in an area of sustainable forest management in the Brazilian Amazon. This was accomplished by identifying aspects and challenges inherent to the traditional road planning process through interviews with specialists in the Amazon. The development of a new optimized road planning (ORP) procedure was based on approaches recommended in the recent global literature for spatial optimization of forest roads. In this approach, a method of least-cost path analysis (LCPA) was used, based on a raster of road suitability obtained by means of a Multi-Criteria Decision Making (MCDM) technique based on GIS (Geographic Information System), Dijkstra's algorithm, and heuristics for network creation. Also, consultation of specialists in forest management in the Amazon was conducted through an electronic form. This study was carried out in two annual production units (APU) of a timber concession area located in the Brazilian state of Rondônia. The following spatial decision variables were defined and used: slope, aspect, hydrographic network, timber productivity and land cover and use. In the evaluation of ORP, five spatial, seven technical and six financial parameters were calculated. These were then compared to the equivalent parameters obtained from roads built with traditional road planning (RBTP) methods. Statistical differences were determined through the chi-square test. The results demonstrated that the developed methodological procedure for planning and delineation of logging roads was obtained with greater spatial precision than with traditional approaches. The techniques developed in this research reduced the overall density of roads, watercourse crossings and, consequently, reduced total costs by up to 24.6% for the logging operations studied. The improvements to the road networks through implementation of the ORP were statistically significant across all spatial, technical and financial parameters. Additionally, consultation with area specialists identified several relevant aspects to the forest road planning (FRP) process performed, which helped in the design of the FRP approach proposed in the study. Also identified, was the need for public policies that promote the training of environmental managers and professionals in FRP. Therefore, the present study concludes that the implementation of the proposed variables and methodological procedures for planning and evaluation were successfully applied to road networks in Amazonia. This approach can be considered a viable tool that helps to support sustainable forest management.

Keywords: Forest planning, forest optimization, forest road, timber harvesting, Amazon rainforest.

1. Introduction

The Brazilian Amazon biome consists of the largest continuous tropical forest on earth, covering 3% of the earth's surface (Heinrich et al., 2021). This forest has been threatened by processes of fragmentation and conversion for agricultural activities and pastures (Haddad et al., 2015; dos Santos et al., 2019). A solution to conserve the Amazon can be found through the sustainable use of forest resources and the development of a forest-based economy (Lima and Azevedo-Ramos, 2020). One such use that contributes to this economic activity is Sustainable Forest Management (SFM).

The utilization of SFM is an important form of land use, which allows for the use of forest goods, such as timber and non-timber products alike. In terms of timber production, the Brazilian Amazon is the fourth largest producer of tropical wood in the world (ITTO, 2020). In Brazil, the SFM harvesting system is polycyclic, which selectively harvests commercial trees, while also implementing reduced impact logging techniques (Souza and Soares, 2013). To help ensure the continuous production of wood products, SFM promotes forest conservation and contributes to the development of the local, regional and national economies while providing legal protections for the workforce (Sabogal et al., 2009). Technical management information is described and presented in a sustainable forest management plan (SFMP), which is evaluated by the relevant environmental agency (Brasil, 2009, 2007, 2006; IBAMA, 2007). Once an SFMP is approved, the responsible company must submit an annual operation plan (AOP) for the areas where operational activities will take place in a given year.

In SFMPs, the forest management unit (FMU) is divided into annual production units (APU) and this, in turn, is subdivided into 100-hectare work units (WU) to calculate the cutting intensity by species, which is generally 10% of the commercial trees inventoried. The SFMP is carried out at the scale of macro-planning for the property level, and micro-planning for the production unit (APU) level (Balieiro et al., 2010; Sabogal et al., 2009). Brazilian legislation permits timber harvesting of up to 30 m^3 ha^{-1} for SFMPs with a cutting cycle that varies from 25 to 35 years, which depends on site productivity that is calculated from the annual growth increment (Brazil, 2009). In SFMPs, activities are subdivided into three stages (Balieiro et al., 2010; Espada et al., 2013; Sabogal et al., 2009). The first stage is the pre-harvest stage where information is gathered for the management area, such as demarcation of WUs and APUs, road planning and construction, and forest inventory. Next is the harvest stage where directional felling of trees, construction of log landings, as well as log skidding and loading for transport to sawmills occurs. Last is the post-harvest stage, which is the evaluation of work areas completed that were described in the AOP such as the site-specific protection measures and maintenance infrastructure. The AOP also includes monitoring and control activities for the application of silvicultural treatments, forest operations, log tracking, as well as cost analysis (Sabogal et al., 2009).

In the Brazilian Amazon, one option for guiding forest management and logging operations, is the Modeflora process (digital model of forest exploitation) developed by researchers from the Brazilian Agricultural Research Agency (Embrapa) (Figueiredo et al., 2007). Modeflora is used to georeference and geomonitor all processes involved in management, from project design to execution, through the integration of geotechnologies such as Geographic Information System (GIS), remote sensing (RS), Global Navigation Satellite System (GNSS) among others (Emmert, 2014). The goal of Modeflora is precision management, thus discarding the traditional method of false coordinates, and promoting the use of GNSS and RS images for environmental zoning of the site (Figueiredo et al., 2008). For forest road planning (FRP), it presents general recommendations such as calculating the optimal density and restrictive aspects of the management area (SUDAM, 1978; Braz 1997; FAO,1974) and for spatial distribution it uses the PEGGER tool, while highlighting the environmental limitations necessary for inclusion in the analysis. By adhering to the Modeflora logging guidelines, the area directly affected by logging can be reduced from 22.2% to 14.8% (de Carvalho et al., 2017; Figueiredo, 2008).

In FRP, there are three levels: strategic, tactical and operational (Gromskaya and Simonenkov, 2016). The strategic level is the first stage of planning with the objective of verifying the ideal location and density of the road network based on the harvesting system, environmental aspects and existing roads (Pentek et al. al., 2014). The tactical level is an intermediate level, which aims at planning the economic unit level to be site specific (D'amours et al., 2008). Lastly, the operational level is where the road alignment is planned in the field to minimize excavation (Gromskaya and Simonenkov, 2016; Pentek et al., 2014).

In the Amazon, there are several environmental factors that make FRP for log transport a challenging task, such as: periods of intense rains; dense and diversified hydrologic network; predominantly flat to gently undulating topography which often leads to poor drainage; lack of rock for road surfacing; areas of difficult logistical access due to the remote locations of the SFM (Keller et al., 2015; Sessions, 2007). Despite this, there is a scarcity of research aimed at optimizing the location of roads with GIS support for FRP in for SFM areas within the Amazon. The few studies on FRP in the Brazilian Amazon, have used SR images (Landsat-5) and algebraic operators to analyze the influence of the road network on the spatial distribution of logging areas (Espírito-Santo et al., 2004), and more recently, the effectiveness of computational methods in FRP (Aguiar et al., 2021). Therefore, there is a need for more studies on the subject, especially for the spatial optimization of road network planning in SFM throughout Amazonia.

In this context, the objective of this study was to develop a methodological procedure to support the planning and evaluation of roads in an area of sustainable forest management in the Amazon. In furtherance of this endeavor, aspects inherent to traditional road planning processes and the existing challenges were identified through interviews with professionals and researchers who specialize in this area within the Amazon. For the optimized road planning (ORP) it was based on technologies recommended in the recent global literature on FRP optimization (Kazama et al., 2021), such as consultation with experts, the use of Least Cost Path Analysis (LCPA) tools combined with Multi Criteria Decision Making (MCDM) in GIS and data obtained from areas by SR and in the field.

2. Materials and methods

2.1. Study area and operational planning

The study area was composed of two annual production units (APU), APU 06 (1,827.54 ha) and APU 14 (1,846.82 ha), located in the municipality of Itapuã do Oeste, in the state of Rondônia, Brazil. These units were within a forest management unit (FMU-III) of 46,184 ha (Fig. 1) in the Jamari National Forest (Flona) comprising 220,000 ha. The logging operations were carried out by a private company, AMATA S.A., holder of the forest concession. The Jamari National Forest is an important forest conservation unit for the region with policies that help protect the land base from the pressures of deforestation. The climate in the region is Am according to the Köppen classification system, with a well-defined dry period between the months of June and August. The average annual temperature is 26.2ºC and the average annual precipitation is 2,418.4 mm yr-1 (Alvares et al., 2013). The dominant soil type is a dystrophic red-yellow Latosol soil, with some soils classified as Latosols and others as Ultisols (Santos, 2011). The dominant vegetation in the study area is Submontane Open Ombrophilous Forest (IBGE, 2012).

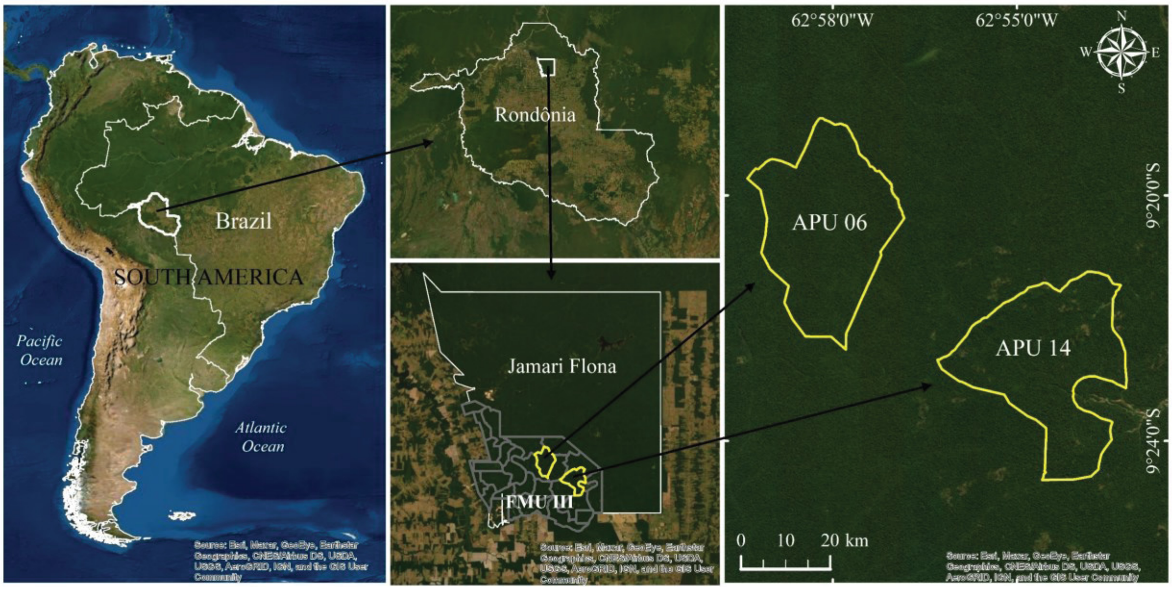


Fig. 1. Study site location map.

For the planning of operations, the FMU-III was subdivided into 25 APUs, with APUs 06 and 14 selected as the study sites for the present research. The APUs were subdivided into work units (WUs) of 100 ha each, identified with letters A through R (Fig. 2a). The forest inventory included all trees ≥ 40 cm in diameter at breast height (DBH) (Fig. 2b). The minimum cutting diameter (MCD) was ≥ 50 cm DBH for all commercial species, which is the limit permitted by law. The environmental microzoning of the APUs was quantified during the forest inventory activities (Table 1). The inventory crew obtained tree positions by use of the Global Navigation Satellite System (GNSS), wherein the areas with operational limitations were also identified such as Non-Operational Areas (NOAs) and Permanent Preservation Areas (PPAs). The NOAs and PPAs are designated as such due to the presence of rock outcrops, watercourses, springs or steep slopes. (Fig. 2c). According to Brazilian legislation, areas with slopes greater than 45°, as well as rivers, watercourses and springs are considered PPAs (Brasil, 2006, 2012). The logging infrastructure built in the APUs consisted of log landings, primary and secondary roads (Fig. 2d). The widths of the primary and secondary roads were 8 and 4 m, respectively. The log landing dimensions were 20 x 25 meters.

The harvesting system was semi-mechanized. The logging operations of the APUs were carried out by the timber company in 2017. The operational planning of the harvest activities relied on Modeflora procedures (Figueiredo, 2008). In this procedure, the roads were built through traditional planning (RBTP), which relied on the determination of road locations based on a Digital Elevation Model (DEM), generated by the Shuttle Radar Topography Mission

(SRTM) image of 30 m precision, interpolated by Morisson Valeriano and Fátima Rossetti in 2012.

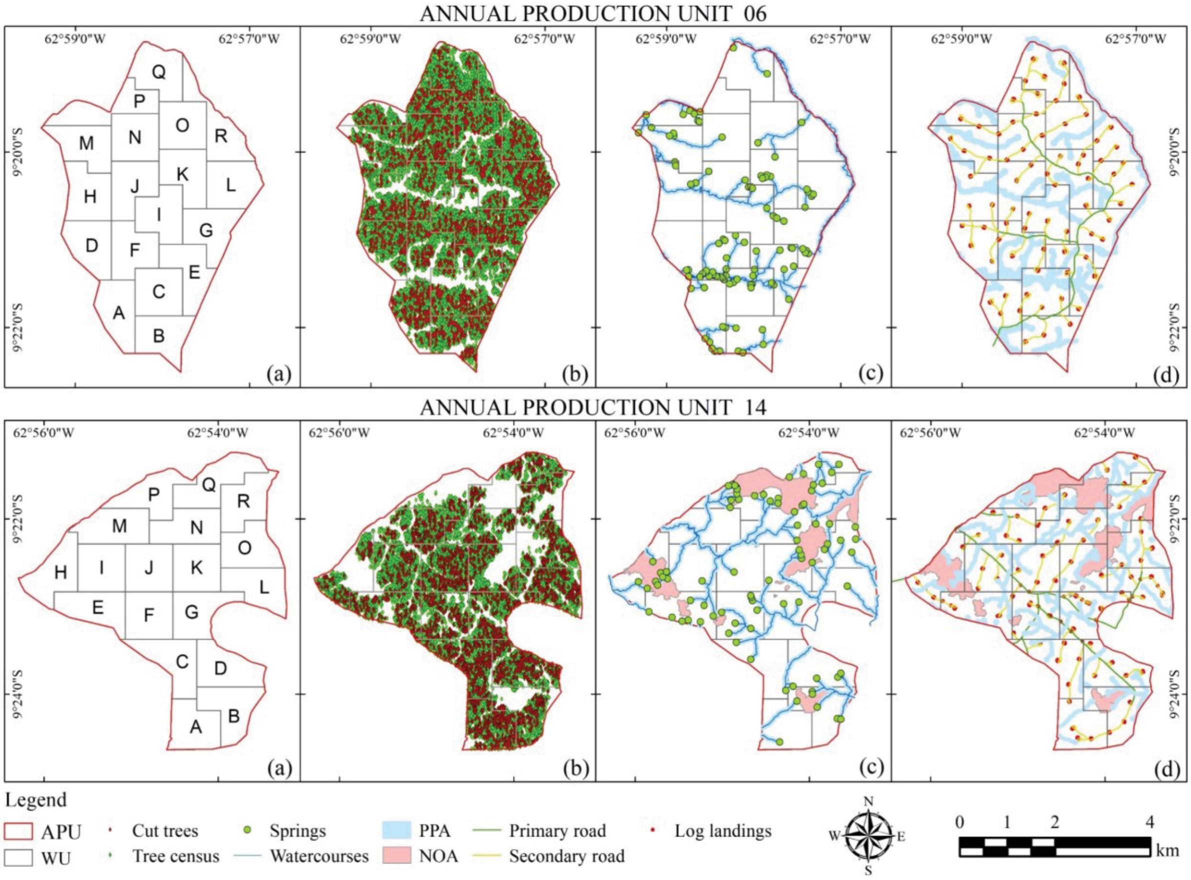


Fig. 2. Operational information of annual production units (APUs) 06 and 14: subdivision of work units (WU) (a); location of trees measured in the forest inventory, including commercial and non-commercial trees (b); environmental microzoning (c); and infrastructure (d).

Table 1. Environmental microzoning of the study area.

APU	Watercourses (m)	Total number of springs (n)	Non-operational area (ha)	Permanent preservation area (ha)
06	38,918	100	0	229
14	44,495	84	223	283

Source: SFB (2016; 2017).

2.2. General description of the methodological procedure

The present study was based on the recent literature review by Kazama et al., 2021 (Fig. 3a). In the review, data were characterized at the planning level and for different optimization objectives. For the present study, the information used was in regard to the optimization of forest road locations for planning at a strategic level (Fig. 3b). The methodological procedure for this study was divided into Parts I, II and III (Fig. 3) described in detail in sections 2.3, 2.4 and 2.5 respectively. In consideration of the aspects inherent to the process of traditional road planning currently carried out in management areas in the Amazon, the questions of interest were described in section 2.3.1.

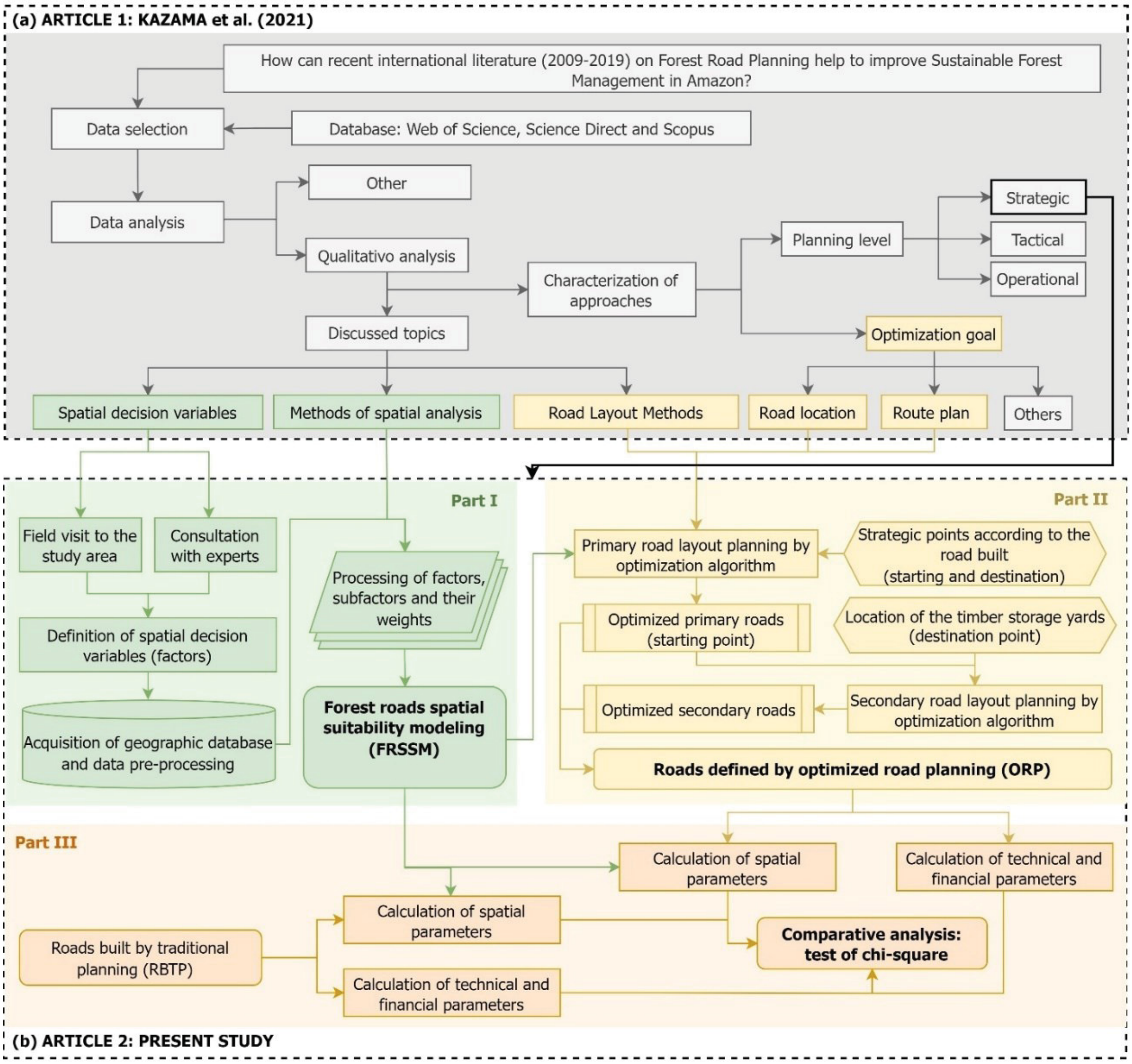


Fig. 3. Methodological procedure of the study.

2.3. Part I: Modeling the spatial suitability of forest roads

In Part I, the Forest Roads Spatial Suitability Modeling (FRSSM) was developed using the following steps: definition of spatial decision variables (factors), according to the literature (Kazama et al., 2021), recognition of the field of study and consultation with experts in the area (Section 2.3.1); database acquisition and pre-processing (Section 2.3.2); description (Section 2.3.3) and processing of factor weights and their classes (Section 2.3.4) and the combination of factors (2.3.4).

2.3.1. Definition of variables and consultation with experts

To gather knowledge from specialists in the area of planning forest roads for forest management in the Amazon, professionals who work and conduct research in the sector were interviewed. In order to fully meet the criteria for ethical research involving people, the project was submitted and approved by the Ethics Committee for Research on Human Beings for the Health Sciences Sector of the Federal University of Paraná and the National Research Ethics Committee of Brazil, under document number 3115657, dated 01/18/2019. The consultation was carried out through an electronic form (Google Forms) sent by email in 2019. To send the electronic form, the contact from the target audience was determined by research on institutional public websites and publications of scientific works that provide a form of contact, such as telephone and/or e-mail. All respondents accepted the Free Informed Consent Term (ICF), which guarantees that the opinion will be kept anonymous, and used for research purposes only.

In the form, the challenges of the work were explained and the five spatial variables that are essential for minimizing costs and environmental impacts in forest road planning (FRP) were presented. Among many variables found in the literature (Kazama et al., 2021), these five were selected as the most suitable for conditions encountered in the Amazon Forest, supported with a field reconnaissance trip to FMU-III in 2018. Those variables were slope, aspect, hydrographic network, timber productivity and land cover and use. Respondents were asked to weight lower the least important factors and weight higher the more important factors on a scale that was suited to the Analytic Hierarchy Process (AHP) methodology (Saaty, 2005). This Multi Criteria Decision Making (MCDM) method was the most recommended in the literature for spatial optimization of FRP (Kazama et al., 2021).

To support the development of this study and identify aspects inherent to the forest infrastructure planning process carried out in Sustainable Forest Management (SFM) areas in the Amazon currently, the form also had an inquiry with the following questions:

1. Can the five spatial variables indicated, and the weights assigned in the form really be used for both cost analysis and environmental impact analysis?
2. Can the five spatial variables mentioned, and the weights assigned in the form be used in both primary and secondary road planning?
3. Is the planning and allocation of log landings considered important for the initial planning and allocation of roads?
4. Are you aware of the Modeflora procedure (Figueiredo et al., 2007) and if so, has it already been used in sustainable forest management plans SFMPs?

In the analysis of the forms, two exclusion criteria were used: 1) Randomness of the assigned weights and evasive justifications and 2) The lack of practical experience in carrying out some road planning in FMUs within Amazonia.

2.3.2. Geographic database and data pre-processing

In order to process the selected decision variables, the following data were acquired: (i) image from the ALOS satellite, PALSAR sensor, with a spatial resolution of 12.5m, scene dated 01/21/2011, obtained free of charge (https:/ /search.asf.alaska.edu/#/), to generate the DEM, which is considered one of the most accurate globally open access (Jalal et al., 2020); (ii) images from the Sentinel-2 satellite, Multispectral Instrument (MSI) sensor, with a resolution of up to 10 m, scene dated 08/25/2015, without the presence of clouds, obtained free of charge (http://earthexplorer.usgs. gov); (iii) locations of trees measured in the inventory demarcated in the field with a GNSS and; (iv) information on the environmental microzoning of the APUs. Vector data (iii and iv) were provided by Amata S.A.

Data processing was performed using programming codes and supported by QGIS software tools, in Datum SIRGAS 2000, UTM FUSO 20S Projection. In the data pre-processing step, the ALOS-PALSAR image was corrected for image errors by the “Fill” method, which removed image imperfections, such as dips and peaks. In Sentinel-2/MSI images, atmospheric corrections were performed using the Dark Object Subtraction (DOS) method. The ALOS-PALSAR image was standardized to 10 m pixel size Sentinel-2/MSI image resolution by the bilinear resampling method. Then, the images were cut (boundary box) according to the contour of the APUs to reduce the processing time. Vector layers were converted to raster with the same default pixel size.

2.3.3. Description of factors and classes

2.3.3.1. Terrain slope

This is one of the most important factors to consider in a forest road project in terms of suitability for the various construction sites (Petković; Potočnik, 2018). The slope directly affects labor time and road construction costs (Bugday and Özel, 2019). Furthermore, slope also affects the amount of excavation volume as well as soil erodibility (Çalişkan, 2013). The slope factor was subdivided into 5 slope classes based on degrees as proposed by the IUFRO (International Union of Forestry Research Organizations) for forest roads. The 5 slope classes were: 0-5.71°, 5.71-13.80°, 13.80-21.88°, 21.88-31.99° and > 32° (Erdaş, 2008; Buğday and Akay, 2019). The slope and aspect were produced using DEM.

2.3.3.2. Aspect

Aspect consists of the direction of a slope in relation to the sun, which influences the shading intensity and sun exposure of the terrain. The direction of the slope aspect is relevant because it is a factor that affects soil moisture, temperature, vegetation establishment, soil degradation and susceptibility to erosion (Hosseini et al., 2018). Higher solar radiation increases the evaporation of rainwater from the road surface, so that roads remain dry. This is advantageous to prevent roads from turning into a muddy bog, which is caused by constant heavy vehicle traffic in areas with standing water or saturated soils. As the study area is located in the Southern Hemisphere and the logging operations take place in winter (period of less precipitation), slopes facing north receive more solar radiation than slopes facing south. West-facing slopes are better for roads than east-facing slopes due to increased radiant energy flow and temperature in the afternoon from sunset (da Silva Seabra and Cruz, 2014). In the present study, the aspect was stratified into 9 classes: North (0-22.5º and 337.5-360º); Northeast (22.5-67.5º); East (67.5-112.5º); Southeast (112.5-157.5º); South (157.5-202.5º); Southwest (202.5-247.5º); West (247.5-292.5°); Northwest (292.5-337.5º) and the flat (-1º) (Bugday and Akay, 2019).

2.3.3.3. Timber production

This factor is used to determine minimum standards for forest roads to be built and to make transport planning decisions (Bugday, 2018). In SFM, the distribution of commercial volume is a relevant factor for calculating the road density, as it is related to the forest stocking (Çalişkan, 2013). Productivity information for this study was generated from data collected in the forest inventory of commercial trees and spatialized by the Kernel density method, with weighting of volume values. In which the quartic model was used (Silverman, 1986) and an adjustment radius of 350 m, as it is the maximum average skidding (i.e., log dragging) distance to log landings, according to studies for SFM in the Amazon (Silva et al., 2020, 2018). To assess the distribution of production density, a subdivision of 5 classes was implemented using the Jenks Natural Breaks classification method (Sarp and Duzgun, 2015).

2.3.3.4. Hydrographic network

The hydrographic network is a proximity factor often used in suitability mapping studies, as it affects susceptibility to landslides (Bugday, 2018; Demir, 2019; Kamarudin et al., 2014). In the Amazon rainforest, due to high rainfall usually concentrated in a period of 6 months (Keller et al., 2015), rivers often overflow causing flooding and erosion. The distances from the hydrographic network were generated from data based on the demarcation of watercourses carried out during the environmental microzoning. The distances to the hydrographic network were subdivided into 5 classes that were implemented by a buffer for each class. For the first class, a buffer strip of 30 m on each side of the watercourse to the limit of the permanent protection area, to comply with Brazilian forest legislation, and for each successive class a value was doubled, up to a buffer of 240 m.

2.3.3.5. Land cover and use (LCU)

The LCU factor is also relevant for understanding the challenge posed by the elements that are distributed throughout the surface of the project area. As this is a part of APU-level planning, the surface is generally characterized by a predominance of lush forest. From the point of view of the traditional classification of LCU, it can be constituted by only one class, that of forest, as was the case considered in the present study. Therefore, to better describe this variable, the Normalized Difference Vegetation Index (NDVI) was estimated, which allows inferences about the spatial variation of aboveground forest biomass (Spadoni et al., 2020; Zhao et al., 2021). Sentinel-2 images were used to generate the NDVI. NDVI values were subdivided into 5 classes, namely (Garcia et al., 2019): I) NDVI <0; II) 0≤ NDVI < 0.2; III) 0.2 ≤ NDVI < 0.5; IV) 0.5 ≤ NDVI < 0.72; V) NDVI ≥ 0.72. Then, after classification the NDVI layer was joined to the NOA and APP layers, generating the final LCU layer. Existing roads are relevant information and can be added to this LUC layer in future studies. Due to the lack of information on existing roads in the study area, it was not considered in the present study.

2.3.4. Class weight calculation

In FRSSM, factors were standardized by weighting their classes (subfactors), based on the classification table for sustainable planning on forest roads described by Acar et al. (2017) adapted to the conditions of the present study (Table 2). In this classification, the weight is distributed according to the suitability of the road network: "1" expresses the best suitability value for forest roads; “10” expresses the worst value and “100” expresses the worst location, however, in certain circumstances it may be necessary to use locations considered not ideal, such as crossing watercourse crossings (Table 2).

Table 2. Rating table of the variables.

Score	Objective Function	Road network suitability classes	Description
1 - 3	Very suitable area for road planning	Excellent	Location with suitable criteria for the road
4 - 6	Suitable areas for road planning	Average	Location reasonably acceptable for road
7 - 9	Slightly suitable areas for road planning	Poor	Location which is suitable for road construction, but a more suitable location is preferable
10	Very slightly suitable areas for road Planning	Very poor	Location which is preferable for road construction in mandatory situations
100	Areas for which road planning should be avoided	Extremely poor	Extremely inadequate location for road construction, but in extreme circumstances it may be necessary, such as a river crossing.

Source: Adapted from Acar et al (2017).

2.3.5. Calculation of factor weights

In calculating the factor weights, the geometric mean was used to incorporate the decision makers' ratings. The geometric mean of the values was used to allow for the maintenance of the characteristics of weights and their reciprocals (Aczel and Saaty, 1983). Then, according to the importance relationship scale (Saaty, 2005), the pairwise comparison matrices, inconsistency analysis and weights were derived using the eigenvector method (Saaty, 1980) (Table 3). The evaluation of opinions was obtained by calculating the consistency index (CI), which must be less than 0.10 (CI ≤ 0.10) (Saaty, 1980). The CI indicates the probability that the comparisons were generated randomly (Saaty and Vargas, 1991).

Table 3. Saaty's scale of intensity of importance.

Intensity of importance	Numerical evaluation (aij) (alternative i in relation to j)	Reciprocal (1 / aij) (alternative j in relation to i)
Extreme importance	9	1/9
Very, very strong	8	1/8
Very strong or demonstrated importance	7	1/7
Strong plus	6	1/6
Strong importance	5	1/5
Moderate plus	4	1/4
Moderate importance	3	1/3
Weak or slight	2	1/2
Equal importance	1	1/1

Source: Saaty (2005).

2.3.6. Combination of factors

The calculation of the factor weights was done through combination using weighted linear combination (WLC) (Eastman, 2003) (Equation 2).

$$S = \sum_{i}^{n} W_i X_i \quad (2)$$

Where: S = final score value; wi = factor weight and xi = factor normalized value.

In the FRSSM layer, classification into 5 classes (excellent, average, poor, very poor and extremely poor) was performed according to the Geometric classification method. After the process of combining layers and classifying the raster layer, the “salt and pepper” effect often occurs, when, for example, only one isolated pixel is classified with a different value from the others (Lillesand et al., 2015). This effect can confuse the interpretation of the tracking algorithm, therefore, to remove this noise, a median filter was applied.

2.4. Part II: Optimized road planning

For the optimized road planning (ORP) proposed in this study, the Least Cost Path Analysis (LCPA) method tested was the “Forest Roads Network Creation” tool, developed by Clément Hardy (2019). This tool creates a network of forest roads based on a raster cost layer, the areas desired for access, the preferred connecting roads, Dijkstra's algorithm and three network creation heuristics. The methodology also allows taking into account the displacement angle from one pixel to another to avoid sharp curves, which was also tested in the present study. The raster layer used was the FRSSM map, which is related to the costs and environmental impact of constructing a forest road.

To define ORP, similar road reference points found on roads built by traditional planning (RBTP) were considered to allow for comparison. On the main road in the ORP, the point where the RBTP intercepts the boundary of the APUs was used as a starting point, and as for the destination points, the points where the RBTP ended. Except, in the case of APU 14 where there were two extremely close points in WU-C (Fig. 2d), which was considered only one point for this area. Also, when the possibility of relocating a section was identified to avoid crossing a watercourse, as was the case at the points of WU A, J, M and R. Finally, for the layout of secondary roads in the ORP, the polygons for log landings are considered as an origin point and as a destination point on the primary road line obtained in the ORP.

2.5. Part III: Method for comparing different road networks

To compare and evaluate the roads, an adapted method was developed based on the work of Babapour et al., (2014). Where the road network defined by traditional planning (RBTP) and optimized planning (ORP) had their spatial, technical and financial parameters calculated. These variants were calculated for primary and secondary roads, as well as for the road network in its entirety. The latter consists of the sum of primary and secondary roads. To determine the spatial parameters, the forest roads were superimposed and classified based on the FRSSM map. In this way, the length of each road that passed through one of the FRSSM's five suitability classes (excellent, average, poor, very poor and extremely poor) was defined.

In the technical evaluation, the following parameters were calculated: (i) total length; (ii) road density (Equation 3); (iii) average distance between parallel roads (Equation 4), where the maximum skidding distance is half the road spacing, and; (iv) area covered by built roads (Equation 5); (v) total number of culverts (Equation 6); (vi) total number of bridges (Equation

7); and (vii) total number of watercourse crossings (Equation 8) (Table 4). For the financial evaluation, the following parameters were calculated: (i) total cost of road construction per effective APU area (Equation 9) and (ii) per hectare (Equation 10); (iii) total cost of installing culverts (Equation 11); (iv) total cost of the bridge (Equation 12); (v) total cost of watercourse crossings (culvert + bridge) (Equation 13); (vi) total cost of construction of the road network (Equation 14) (Table 4).

Table 4. Equations of technical and financial comparison parameters calculated for primary and secondary roads, as well as the road network for APUs 06 and APU 14.

Technical parameters	Equation	Financial parameters	Equation
• $RD = L/T$	(3)	• $CR = L*cr$	(9)
• $RS = 10.000/RD$	(4)	• $CH = CA/T$	(10)
• $A = (L * W)/10000$	(5)	• $CC = \sum(nb * cc)$	(11)
• $Nc = \sum nc$	(6)	• $CB = \sum(nb * cb)$	(12)
• $Nb = \sum nb$	(7)	• $CBC = CB + CC$	(13)
• $Nbc = Nc + Nb$	(8)	• $CRI = CR + CBC$	(14)

Where: RD = road density (m/ha), L = total length of roads in APU (m), T = total utilizable area (ha); RS = road spacing (m); A= area of constructed roads (ha); W = road opening width (m); Nc = total number of culverts (nc) in the APU; Nb = total number of bridges (nb) in the APU; Ncb = total number of culverts and bridges; CR = total cost of road construction (R$) per APU and per hectares (CH); cc = unit cost (R$) per culvert and per bridge (cb); CC = total cost of culvert (R$); CB = total cost of bridge (R$); CBC = total cost of culvert and bridge (R$); CRI = total cost of road infrastructure (R$).

Table 5. Description of road, culvert and bridge construction costs.

Description	**Cost (R$.km^{-1})**	**Description**	**Cost (R$/unit)**
Primary road	10,700.00*	Culvert	7,527.78**
Secondary road	4,000.00*	Bridge	27,769.95**

Reference year in *2019 and **2021.

To verify the significant differences between the RBTP and ORP variants, the chi-square test was used, an appropriate non-parametric test (Andrade and Ogliari, 2013), with a significance level of 5%. One of the requirements for the application of this test is the need for the variables to be in the same units. Therefore, to meet this condition, the parameter values obtained from the RBTPs were transformed into a reference value of 100 (RBTP'). And the parameters obtained from the ORP were transformed into values relative to 100 (ORP', Equation 15).

$$\mathrm{ORP'}_i = \left(\frac{\mathrm{ORP}_i}{\mathrm{RBTP}_i}\right) * 100 \tag{15}$$

Where: ORP' = transformed value of parameter i, obtained from roads defined by optimized planning (ORP); RBTP = value of parameter i, obtained from roads built by traditional planning; ORP = value of parameter i, obtained in ORP.

3. Results and discussion

3.1. Spatial suitability modeling

The spatial suitability modeling for road allocation, Forest Roads Spatial Suitability Modeling (FRSSM), for the present study had the participation of 32 specialists in the area. After application of the exclusion criteria, 19 responses were retained for calculation of the weights and factors. This made it possible to create a paired comparison matrix and evaluate their respective weights obtained by the Analytic Hierarchy Process (AHP) method (Table 6). The matrix was evaluated and resulted in a consistency ratio value of 0.078 (CR ≤ 0.10). This means that the weights listed by the experts in this study were considered logically plausible for analysis, that is, there was no need to return to the evaluation process (Saaty and Vargas, 1991).

Table 6. Pair comparison matrix and their respective weights obtained by the AHP method.

Fator	SLO	HYD	PRO	LUC	ASP	Weight
SLO	1	2	3	4	7	0,418
HYD	1/2	1	2	3	6	0,265
PRO	1/3	1/2	1	2	5	0,167
LUC	1/4	1/3	1/2	1	4	0,108
ASP	1/7	1/6	1/5	1/4	1	0,041

Where: SLO = Slope; HYD = Hydrographic network; PRO = Productivity; LUC = Land use and cover; ASP = Aspect.

Once the data was processed for each APU (Fig. 4a, b, c, d and e), the factors were classified and weighted (Table 7). Then, the obtained Weighted Linear Combination (WLC) model (Equation 16) was applied, which generated the final FRSSM map of both study sites (Fig. 4f).

$$FRSSM = 0{,}418*SLO+0{,}265*HYD+0{,}167*PRO+0{,}108*LUC+0{,}041*ASP \quad (16)$$

Where: SLO = Slope; HYD = Hydrograph; PRO = Productivity; LUC = Land use and cover; ASP = Aspect.

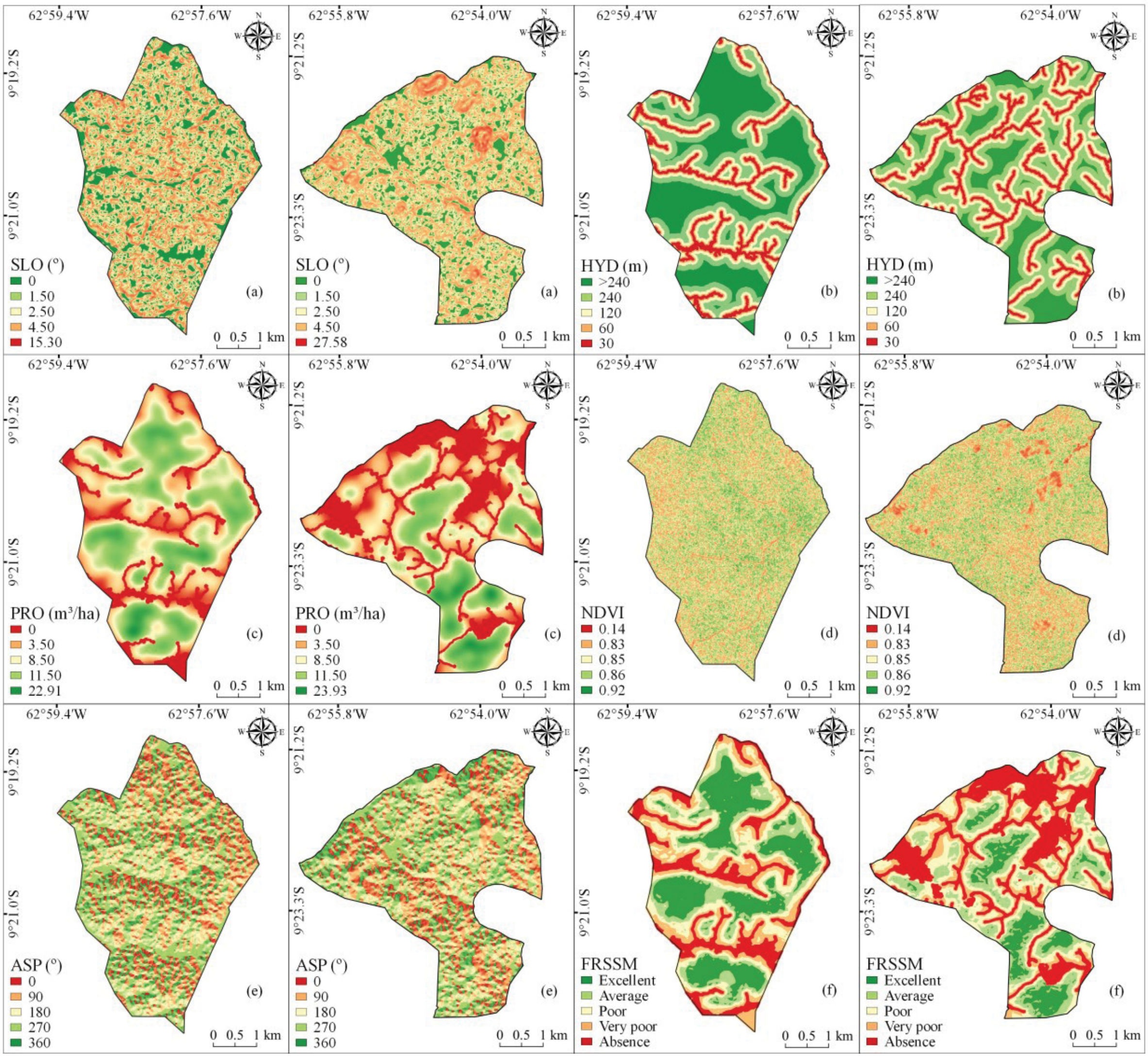


Fig. 4. Selected factors for the study (slope - SLO, hydrographic network distance - HYD, productivity - PRO, normalized difference vegetation index - NDVI, aspect - ASP) and final FRSSM map for APUs 06 and 14.

Table 7. Scores of factor classes (subfactors) used in the FRSSM map.

Factor	Subfactors	Score	Factor	Subfactors	Score	Factor	Subfactors	Score
SLO (º)	0 - 5.71	1	HYD (m)	0 - 30	100	ASP (°)		
	5.71 - 13.80	5		30 - 60	7		Flat	1
	13.80 - 21.88	7		60 - 120	5		North	1
	21.88 - 31.99	10		120 -240	3		Northeast	3
	> 32	100		> 240	1		East	5
LUC	NDVI class I	1					Southeast	9
	NDVI class II	2	PRO (m^3/ha)	Class I	10		South	10
	NDVI class III	5		Class II	7		Southwest	7
	NDVI class IV	7		Class III	5		West	3
	NDVI class V	10		Class IV	3		Northwest	2
	NOA and PPA	100		Class V	1			

Where: SLO = Slope; LUC = Land use/cover; HYD = Hydrographic network distance; ASP = Aspect; PRO = Productivity; NOA = Non-operational area; PPA = permanent preservation area; NDVI = Normalized Difference Vegetation Index.

3.1.1. Slope factor

The comparison matrix reveals that the Slope (SLO) was the most important factor (w = 0.418). The factor SLO was also highlighted by the consulted experts as having the greatest influence on road planning in management areas within the Amazon (Table 6), which is also in agreement with the literature (Kazama et al., 2021). Nevertheless, for the current study sites, the greatest spatial restriction in operational terms were the factors hydrographic network (Fig. 4b) and productivity (Fig. 4c) when observing the final map of the FRSSM (Fig. 4f). Since the area does not have steep terrain and the majority of slopes are below 7.91% (Fig. 4a), the variation in the maximum slope for log transport roads was minimal. The study site roads were on the low end of the established values in the literature for the maximum slope for primary roads at 8 to 10% (4.6 to 5.7°) and for secondary roads at 10 to 12% (5.7 to 6.8°) (Heinrich, 1975; Braz, 1997; Rocha et al., 2007, Sessions, 2007).

Slope on the ground is often considered a negative for FRP, because the greater the slope of a road grade, the greater the amount of eroded material (Machado et al., 2003). However, according to the “Manual on Introduction to Forest Roads” (FTCI, 2010), which is considered state-of-the-art material on FRP in South America by IUFRO (2021), actually for some road locations, sloped ground may be more appropriate. This is because one of the biggest challenges for FRP in tropical forests is the high volume of rainfall (Sessions, 2007), a slight slope allows for good cross-drainage and can provide the advantage of balanced cut-and-fill road construction that involve minimal movement of soil and heavy machinery (FTCI, 2010). However, it should be noted that when crossing watercourses, the lowest possible slope is ideal (Keller; Sherar, 2003).

3.1.2. Hydrographic factor

The second highest weighted factor was the Hydrographic Network (HYD) factor (Fig. 4b). According to the experts, this was because the placement of roads near watercourses should be avoided because of increased environmental impacts caused by bogs and erosion. Also, watercourse crossings cause disruption to fauna, as riparian forests help to maintain ecological connectivity (Nunes et al., 2019). Moreover, with increasing distance from watercourses, the important composition of some site-specific species in this region can be conserved (Schietti et al., 2014; Guimaraes et al., 2021). In addition, crossing watercourses also entail the highest cost of construction and maintenance of the road network, due to the need for excavation (Keller et al., 2015; Sessions, 2007).

3.1.3. Productivity factor

Regarding the Productivity (PRO) factor (Fig. 4c), despite being in third place of general importance, this factor had a strong influence on the spatialization of the ideal areas for Forest Road Planning (FRP) in the FRSSM. This factor is important for limiting harvesting activities to areas where there is sufficient commercial volume to sustain future operations (Kazama et al., 2021). In addition, minimal impacts to the forest can be achieved by maintaining the harvesting operation at a shorter distance from the harvesting area, which also results in lower costs (Holmes et al. 2002).

3.1.4. Land use and cover factor

The Land Use and Cover (LUC) factor was highlighted in the FRSSM due to the inclusion of the Normalized Difference Vegetation Index (NDVI), which contributed to the environmental sustainability of the analysis (Fig. 4d). This allows for the identifying of areas where the FRP can minimize the removal of the carbon stock incorporated in the biomass of the forest remnant. The NDVI has already been used in other forests for the FRP (Bugday, 2018; Jaafari et al., 2015), in which a positive correlation of the LUC variable with the occurrence of landslides in areas with steep slopes was emphasized (Yilmaz, 2009). Noteworthy, is that there are several types of vegetation indexes (https://www.indexdatabase.de/db/i.php) that can be explored in future research for the FRP in forest management areas.

The LUC layer must include information on areas that make road planning difficult, such as rock outcrops, cliffs, perennially saturated surface soils and other features that may present construction challenges (FTCI, 2010). Other obstructions can also be encountered in the SFM area, such as the location of residual crop trees, trees protected by law, and nesting sites. In a study of road optimization, Aguiar et al., (2021) found that these obstacles were successfully considered in their model in an SFM area in the state of Pará. While, in the use of the present study for FRP, these deviations can be considered at the next level of planning between tactical and operational, which aims for a greater level of detail in the road alignment in the field, following the recommendations of Amaral et al., (1998) and Lima et al., (2020).

3.1.5. Aspect factor

Ultimately, the Aspect (ASP) factor (Fig. 4e) was of the least importance. According to the experts interviewed, this was due to the high average annual temperatures that occur in the Amazon (Alvares et al., 2013). Also, timber harvesting activities occurs during the period of lowest rainfall (Keller et al., 2015), so the angle of solar incidence on the road surface may have little influence on the FRP. The priority to consider for the slope is surface drainage, in this way the ASP factor ends up being less favored, however, the opening of roads in the east-west direction is sought for more frequent exposure to direct solar radiation. However, it was also mentioned that depending on the relief of the region and type of soil, such as clayey versus sandy, this variable can reduce maintenance costs, especially on roads that are used during in rainy periods. According to a study by Ceddia et al., (2015) carried out in the Central Amazon region, the ASP factor was correlated with several soil attributes, such as a slight negative correlation with soil clay content. Therefore, the use of this factor should be optional in the spatial analysis for FRP in similar areas, but will vary according to the study area.

3.1.6. General considerations of the FRSSM

Among the study sites, UPA 06 had the highest amount of area (26.8%) in the best suitability class for roads in the FRSSM, with a decreasing trend for lower suitability classes (Fig. 5). On the other hand, UPA 14 had the highest amount of area (30.9%) in the worst suitability class, with a decreasing trend in relation to other better suitability classes (Fig. 5). This was related to the environmental characteristics present in UPA 14, such as the occurrence of non-operational areas, characterized by rocky outcrops, and a denser hydrographic network. Despite the proximity between the two areas, there were distinct differences in environmental microzoning characteristics (Fig 4f and Fig 5) that could be expressed by the FRSSM process. This data is contained in a single evaluation layer, which brings together the five relevant factors, expressed numerically in each pixel. The pixels with low values indicate more suitable zones and higher values are the most critical zones for the adequacy of the allocation of road networks.

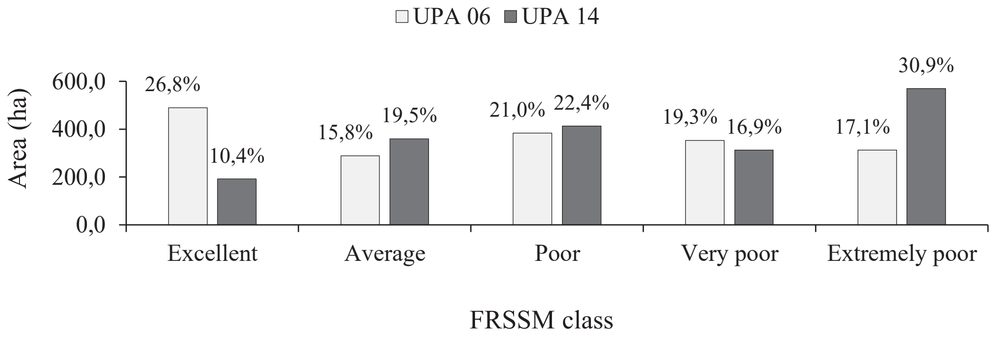


Fig. 5. Area in hectares (ha) and percentage (%) for each FRSSM class in APU 06 and 14.

Studies such as the FRSSM stand out for the capability to be able to make classifications of the harvest area at different levels of suitability (Fig 5), allowing the optimization of the appropriate allocation of forest road networks in areas of different operational feasibility, environmental and economic scenarios. The FRSSM classification process can help in the environmental sustainability of a road project because it permits the organization of restricted and priority areas according to the factors used, conserving the forest ecosystem and future commercial stocking. Therefore, this procedure can be used to support professionals in forestry engineering, civil engineering and associated disciplines.

The selection of variables for proper FRP varies depending on the location of the forest being managed. Despite the different environmental characteristics present in the vast Amazon rainforest, the FRSSM procedure can be applied to any region, as it allows for the necessary adjustments to any environment. However, according to Norizah and Mohd Hasmadi (2012), although the Analytic Hierarchy Process (AHP) method, used in the FRSSM, provides decision makers with a structured and flexible means of incorporating professional judgments and scientific information, it is necessary for the decision maker to have a clear understanding of the consequences for specific situations. This is because the overall score for each factor can be used as a measure of the relative value of a given factor in relation to the target. In addition, it should be noted that the AHP was developed to support the strategic-level planning of forest roads, which may not be useful to infer, for example, decisions at the operational planning level, as it requires more local information. Thus, the AHP method is recommended for future applications to test additional variables and methodological approaches for the spatial analysis raised in Kazama et al., (2021) and other studies.

The AHP method has been recommended for FRP in management areas of the most varied forest types (Kazama et al., 2021) as well as in other tropical forests (Kamarudin et al., 2014; Norizah and Mohd Hasmadi, 2012). This method demonstrated satisfactory results according to the series of factors used and some aspects are similar to the present study, such as the slope factor which was most important. In the Brazilian Amazon, multi-criteria analysis has already been used for decision making in other studies in infrastructure planning for sustainable forest management (SFM), such as the allocation of log landings (Silva et al., 2018) and skid trails (Barbosa et al., 2017). Considering comparisons with traditional approaches, the present study brings novel techniques such as the use of spatial variables processing techniques (i.e., Kernel Density and NDVI), with the use of SR images for an improved spatial resolution, which is freely accessible to the public (ie Alos- Palsar and Sentinel-2). Several FRP researchers have highlighted the importance of consulting experts, as was done for this study, as a way to obtain improvements in their forest road projects (Hayati et al., 2013b, Hayati et al., 2013a; Çalişkan et al., 2019; Acar et al., 2019; Acar et al. 2017). Lastly, the forest inventory and zoning data used were of adequate quality, since the Modeflora procedures were followed.

3.2. Analysis of optimized roads

For comparative analysis, the road networks defined by the optimized planning (ORP) proposed in the present study and the roads constructed by the traditional planning (RBTP) were superimposed in the different suitability classes of the FRSSM map in APU 06 and 14 (Fig. 6). From this, the values for spatial parameters (LE, LA, LP, LVP and LEP; see appendix,

Table A.1), technical parameters (L, RD, RS, A, NC, NB and NCB; see appendix, Table B.1) and financial parameters (CR, CH, CC, CB, CCB and CRI; see appendix, Table C.1) were obtained for different roads and areas.

In the comparative analysis of the transformed parameters for road networks (Fig. 7), many of the values for the parameters obtained from the ORP' are lower than RBTP', which indicates that the values calculated by the methodological process in the present study demonstrate reductions in in relation to the values of the planning carried out on the ground.

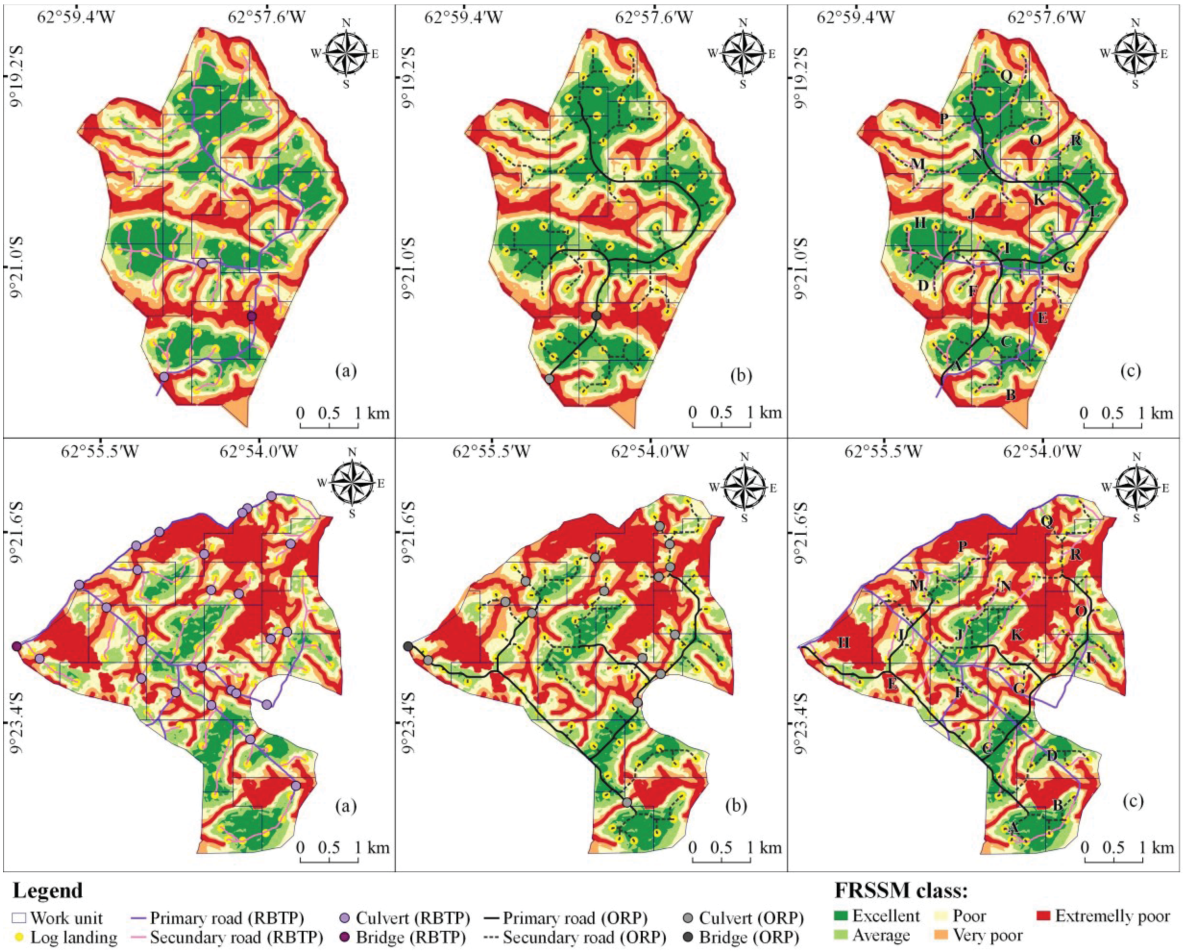
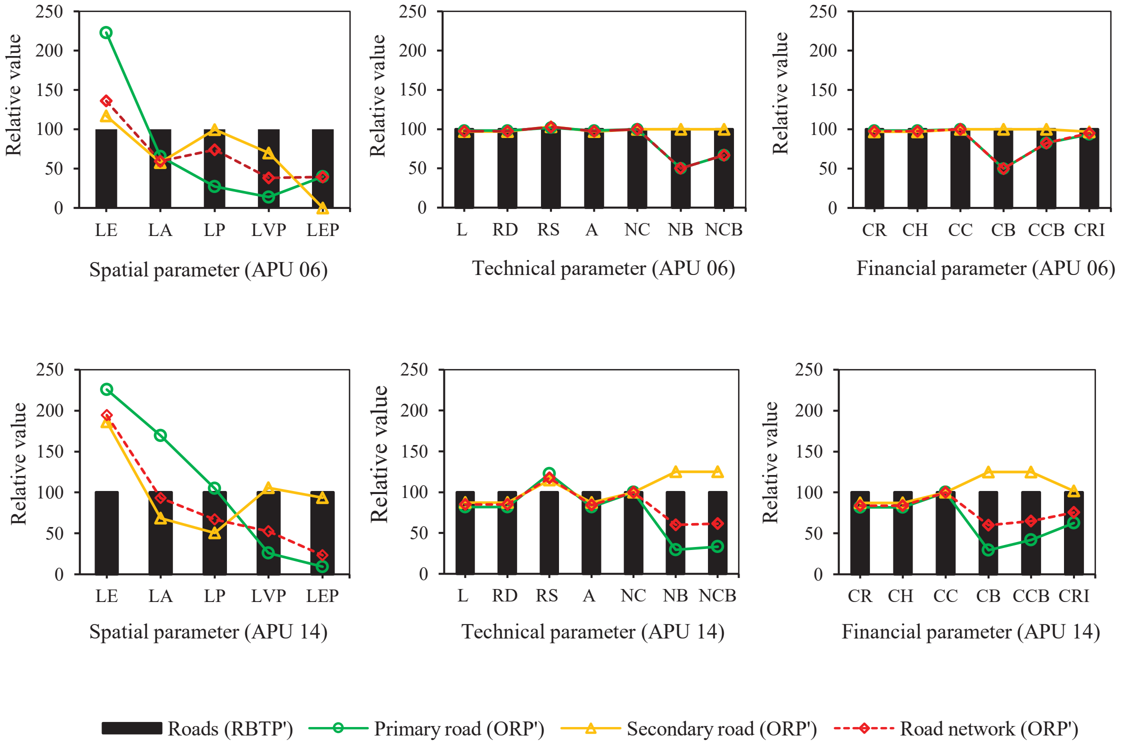


Fig. 6. Road built by traditional planning - RBTP (a) and optimized road planning - ORP (b) and their comparisons (c).

The results show that the methodological procedure of the present study developed for the ORP, presented a tendency to increase the overall length of the road network. This was because of the reductions of road length (L) in the classes with lower suitability and increases in road lengths for the excellent class (LE) in the FRSSM map (Fig.7). The increase in the LE class was higher for APU 14 (94.6%) than for APU 06 (36.1%) (Table A.1) due to different site-specific environmental factors. In addition, there were reductions in area occupied (m ha^{-1}), for road density, road length, and number of watercourse crossings. Consequently, there were reductions in total costs of 5.0% (R$12,563.34) and 24.6% (R$ 118,261.41) for the road infrastructure for UPA 06 and 14, respectively (Table B.1 and C.1).



Where: L = total length of road in APU (m); RD = road density (m ha^{-1}); T = total utilizable area (ha); RS = road spacing (m); A = area of road coverage (ha); NC = total number of culverts in the APU; NB = total number of bridges in the APU; NCB = total number of culverts and bridges; CR = total cost of road construction (R$) per APU and per hectares (CH); CC = total cost of culvert (R$); CB = total cost of bridges (R$); CCB = total cost of culverts and bridges (R$); CRI = total cost of road infrastructure (R$). And length of road by FRSSM map class (m): LE = Excellent; LA = Average; LP = Poor; LVP = Very poor; LEP = Extremely poor.

Fig. 7. Distributions of transformed values of parameters obtained by roads defined by optimized road planning (ORP') and roads built by traditional planning (RBTP') for APUs 06 and 14.

Also, in the ORP when there was a need to cross waterways with roads, secondary roads were preferred, due to the reduced width of construction in relation to the primary road, which explains increases of some values for the technical and financial parameters of these roads and reductions in primary roads in relation to the RBTP (Fig. 7). This helped to minimize the area of ground disturbance (m ha^{-1}) (Table 8) and, consequently, the general density of roads in the

ORP. Consequently, there was a lower environmental impact and cost for the road network in the ORP, when compared to the RBTP. In respect to law, the 1.12 to 1.42% of the effective harvest area covered by roads (m ha^{-1}), was well below the limit established by Brazilian legislation, which is 1.75% (Brasil, 2018).

Despite the reduction in area and density of roads, it is important to point out that the reduction of these values, specifically for secondary roads, directly influences the maximum skidding distance (Dmax) of the logs and subsequently incurs higher costs (Braz, 2010). Therefore, it is ideal that there is a balance in planning between forest roads and skid trails (Silva et al., 2018; Braz, 2010). Although the Dmax values of the present study showed a slightly higher value in relation to RBTP (Table 9), these values are still within the range found in the literature of 350 to 385 m (Aguiar et al., 2020; Silva et al., 2018; Braz et al., 2018) for SFM areas in the Brazilian Amazon.

Table 8. Other road network information defined by the traditional road planning (RBTP) and optimized road planning (ORP) for APUs 06 and 14.

Description	**APU 06**		**APU 14**	
	RBTP	ORP	RBTP	ORP
$A_{\%}$	1.15	1.12	1.69	1.42
D_{max}	298.07	307.80	321.55	368.73

Where: $A_{\%}$ = percentage of road network area in relation to the effective harvest area; D_{max} = maximum distance (m) from stump to landing.

The road density (RD) values found in the ORP for primary (5.91 to 9.66 m ha^{-1}), secondary (13.56 to 16.24 m ha^{-1}) and total (22.15 to 25.86 m ha^{-1}) roads (see appendix, Table B.1) were in agreement with the values found in the literature for different management areas for the same forest (Braz, 2010; Figueiredo, 2008; Braz et al., 2018; Aguiar, 2019). However, before comparisons can be made to the literature, it is important to clarify that RD can present three different estimated values during the planning prior to the construction of the roads. The first RD1 value is calculated for the project based on technical and financial aspects, according to the formulas for the optimal or ideal density recommended for SFM in the Brazilian Amazon (SUDAM, 1978; Braz, 1997; Figueiredo et al., 2007; FAO, 1974). The second RD2 value is when the spatial distribution of the road layout is carried out for the project, respecting the operational and environmental obstructions mapped on the ground and including the RD1 value. And finally, the third RD3 value consists of the actual road density constructed in the field. Therefore, the RD can vary according to environmental factors, quantity and distribution of timber stock present in the harvesting area.

In this sense, it is worth noting that the present study brings further contributions to the optimization of RD2 values according to the aspects of an SFM area in the Amazon. Also noteworthy, is that the RD2 value obtained for the ORP is in accordance with the ideal and real values. Moreover, the density values of the ORP road network are 2.8 to 14.9% below the values for the RBTP (Table B.1). These values for ORP were in agreement with their RD1 design values. According to Braz (2010), the real density can be greater than the ideal design density, as long as it stays within 20% of the variation, which can occur due to topography and differences in the distribution and quantity of commercial trees, density of watercourses, and other operational and environmental constraints. The same author recommended a density of 18.49 m ha^{-1} for the project and obtained 21 m ha^{-1} in the field, in the state of Amazonas, for a region with gentle topography and some steep slopes. In the state of Acre Figueiredo (2008), recommended a road density of 20.24 m ha^{-1} whereas in Mato Grosso Braz et al., (2018) recommended a density of 26 m ha^{-1}. In another study on FRP Aguiar (2019), found that the best scenario for forest road density ranges from 6.44 to 11.23 m ha^{-1} for primary roads and 6.44 to 12.65 m ha^{-1} for secondary roads in the state of Pará.

These improvements obtained in the ORP, when compared to the RBTP, were statistically significant according to all the road parameters analyzed for both study sites (Table A.1, B.1 and C.1), except for the technical and financial parameters of the secondary roads in APU 06 (Table 9). This occurred because the application of the ORP obtained greater improvements in terms of location of the road network. That is, the overall impact to the soil and forest was minimized at costs that are statistically similar to those performed by the company using the Modeflora procedure. Therefore, the results reinforce the contribution to the Modeflora procedure in the optimization of the location of the road network layout.

Table 9. The of the Chi-Square test P-values.

APU	Comparison parameters	P-values		
		Primary road	Secondary road	Road network
06	Spatial	$1.81\ 10^{-69}$	$4.27\ 10^{-27}$	$4.14\ 10^{-23}$
	Technical	$2.49\ 10^{-06}$	0.99880*	$2.29\ 10^{-06}$
	Financial	0.00003	0.99765*	0.00003
14	Spatial	$3.46\ 10^{-73}$	$1.08\ 10^{-22}$	$2.26\ 10^{-38}$
	Technical	$2.82\ 10^{-21}$	$3.31\ 10^{-03}$	$2.93\ 10^{-02}$
	Financial	$6.84\ 10^{-21}$	$2.12\ 10^{-03}$	$1.88\ 10^{-07}$

*There is no significant difference at the 5% probability level (P-value > 0.05).

According to Gromskaya and Simonenkov (2016), modeling road networks using multi-criteria optimization methods and spatial analysis based on raster models are the most effective methods in strategic planning, which was also the approach used in the present study. Other studies that successfully used this approach in FRP were Çalişkan et al. (2019), which tested a series of multi-criteria methods combined with the FOROR system and Çalişkan (2013), who used the AHP method associated with the RoadEng tool. Also, Babapour et al. (2014) and Abdi et al. (2009) that also used this same multi-criteria method combined with the Pegger tool. The PEGGER tool (Rogers, 2005) has been the most utilized application in FRP (Kazama et al., 2021). However, most of the aforementioned tools require the purchase of costly license applications. That makes the procedure developed in the present study more easily obtainable by the general public due to the ease of access to the public through the use of free and open access technology. Therefore, it can be considered a viable procedure for supporting the community in FRP while at the same time minimizing environmental impacts and costs for sustainable management in the Amazon.

3.3. Other contributions and challenges

The consultation with specialists helped to identify important aspects in the FRP strategy for management areas in Amazonia. Of the 32 respondents, the majority (75.0%) agreed that the same spatial variables and weights, assigned in this study, can be used to analyze costs and environmental impacts, as well as for planning primary and secondary roads. This supports the successful performance of the FRSSM procedure developed in the present study. Some interviewees did not agree with these assessments stating that the primary roads are a permanent infrastructure, and may be more associated with permanent variables, such as relief and hydrography. While secondary roads are temporary infrastructure and often do not require drainage and paving structures, so the variables related to the current cutting cycle, such as commercial production and even the aspect of the slope, may have greater importance than the other variables. These aspects should be tested in future research.

In another important question, most experts (59.4%) found the allocation of log landings to be important for the initial of the location of roads. The justifications were that it is easier to plan the interconnection of secondary roads with the main road, if the landing location is known. In addition, it was mentioned that this helps production and operational logistical planning, as the allocation of log landings is necessary to determine the number of trees and volume that will be harvested in each unit, which minimizes the cost of extraction and construction of the skid trails. To the contrary, 31.3% of respondents disagreed with this approach, as they felt that roads have a higher construction cost and should have priority, especially permanent roads, as temporary roads will have other log landings in future cutting cycles. The remaining 9.4% of experts did not give an opinion on the issue.

According to Aguiar (2019), there are two strategies that can be used in the planning of infrastructure for SFM in the Amazon: A) First, determine locations of log landings based on commercial trees and then from the log landings determine access to the logging area, defining the road network and skid trails; or B) The primary roads are initially located, then the log landings, and from these the secondary roads and the skid trails are determined based on the commercial trees. In order to analyze these two distinct strategies, the author tested different mathematical optimization models based on the location of commercial trees and a digital elevation model (DEM) (Aguiar, 2019). According to the author, in general, although strategy B was more flexible, strategy A resulted in greater environmental protection, with fewer watercourses crossing. In this regard, the present study adhered to the most advantageous strategy according to many experts and the literature (Aguiar, 2019), when the proposed methodological process was based on the location of the log landings to define the road network. It is recommended to use log landing optimization methods together with this optimization method for future studies.

Regarding the question about the Modeflora system for SFM planning, 21.9% of respondents were unaware of this methodology. Meanwhile, only 28.1% knew the system and had already used the procedure to prepare their projects. The most frequent use of the methodology was in the state of Acre, where the research emerged and due to political support for technology transfer. Some 37.5% of respondents said that they knew the Modeflora system, however, they used standard techniques of reduced impact logging in their planning. According to these last interviewees, the main reason for not using the Modeflora system was described as the lack of support from environmental agencies in certain Brazilian states, especially the states of Mato Grosso and Pará. In these states, it was reported that the use of this procedure was not acceptable to the environmental agency, which may be related to the fact that environmental analysts are unprepared to evaluate projects prepared differently from the conventional way, which generally consist of planning roads in a systematic, equidistant and manual way. In addition, the non-use of the Modeflora procedure was also justified by the lack of qualified professionals to manage the recommended geotechnologies and the difficulty of accessing the GIS on which the procedure is based, which consists of an onerous license software.

The results of this last question involving the Modeflora system highlights the need for a policy change in the process of planning and evaluating management plans in Amazonia, in order to reduce the gap between environmental agencies and scientific knowledge promoted by universities and researchers. Initiatives that promote the transfer of technology are recommended, such as the implementation of courses, among other technical and continuous training subjects, at regular periods, for environmental analysts who evaluate SFMP, as well as consultants and entrepreneurs in the forest sector. Consequently, it is recommended that government agencies make resources available to finance technology transfer projects, as well as research and development on the subject to support researchers in the advancement of technological knowledge. It is noteworthy that these initiatives could be of great relevance to drive the market into being guided by these current technologies, supporting future SFM activity to be more attractive and safer for investors and entrepreneurs in the forest sector by optimizing resources, as well as contributing to lower environmental impacts in the Amazon.

This study demonstrates that it is possible to use accessible and free technologies, combined with the data collected with appropriate survey inventories, to optimize the planning of forest roads. Therefore, it is expected that the present study could guide and contribute to future proposed road networks in the management plans throughout Amazonia. This work could also assist analysts of environmental and certifying agencies in the qualitative and quantitative assessment of the road networks of submitted SFMPs, to verify if roads are properly located based on the proposed assessment methodology.

4. Conclusion

The present study confirms that implementation of the most recommended variables and methodological procedures in the last decade for optimization of road layout and design were successfully applied in sustainable management of the Amazon Forest. These techniques, in combination with the opinion of regional experts in forest management allowed us to obtain a method of planning and designing logging roads with greater spatial precision than traditional approaches. This contributed to the strategic planning of the road project and the micro-planning of the management plan. Furthermore, the developed techniques reduced the overall density of roads, watercourse crossings and, lastly, costs. Therefore, if implemented, our approach to road design optimization will lead to a lighter environmental impact on water and soil resources in the Amazon.

The road network layout comparison methodology that was developed in the present study allowed for the successful evaluation of different plans under spatial, technical and financial scenarios. In addition, the improved approaches presented here utilize open access technology that is easily accessible to the public, which allows for a wide range of users. The consultation of experts in the field also allowed us to identify important challenges and limitations in the strategies currently applied in the planning of roads in the Brazilian Amazon. The need for public policies on the part of the Brazilian governmental agencies to support further development and application of current technologies, such as the one developed in the present study, was highlighted, with the aim of boosting market development and promoting the sustainability of forest management activity in the Amazon region.

CRediT authorship contribution statement

Verônica Satomi Kazama: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Visualization, Writing - Original Draft, Writing-Reviewing and Editing. Ana Paula Dalla Corte: Conceptualization, Methodology, Supervision, Project administration. Renato Cesar Gonçalves Robert: Conceptualization, Methodology, Supervision. Carlos Roberto Sanquetta: Conceptualization, Supervision. Daniel DeArmond: Writing- Reviewing and Editing

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES) - Financing Code 001 and the Center of Excellence in Research on Carbon Fixation in Biomass (BIOFIX), Forest Inventory Laboratory (LIF), Laboratory of Wood Supply and Forestry Mechanization and the Graduate Program in Forest

Engineering (PPGEF) at the Federal University of Paraná (UFPR); and the Forest Management Laboratory and the Graduate Program in Tropical Forest Science (PPG - CFT) at the National Institute for Research in the Amazon (INPA).

Appendix

See Tables A.1, B.1, C.1.

Table A.1. Calculated spatial parameters by primary and secondary roads, as well as the total road network obtained from the optimized road planning (ORP) and the road built by traditional planning (RBTP) for APUs 06 and 14.

APU	Spatial parameter	Primary road		Secondary road		Road network	
		RBTP	ORP	RBTP	ORP	RBTP	ORP
06	LE	3,116.40	6,949.15	14,263.62	16,696.92	17,380.01	23,646.07
	LA	1,980.85	1,294.94	6,858.55	3,966.81	8,839.41	5,261.75
	LP	2,251.90	611.91	4,047.64	4,039.24	6,299.54	4,651.15
	LVP	1,548.40	213.82	1,193.74	833.16	2,742.14	1,046.98
	LEP	550.77	219.38	5.85	-	556.62	219.38
14	LE	1,162.26	2,623.65	4,293.57	7,990.68	5,455.83	10,614.33
	LA	3,026.51	5,132.04	9,459.65	6,500.41	12,486.16	11,632.44
	LP	3,406.16	3,570.39	7,927.09	4,001.60	11,333.25	7,571.99
	LVP	3,936.77	1,017.80	1,960.86	2,072.18	5,897.63	3,089.98
	LEP	4,034.43	374.48	803.08	751.29	4,837.51	1,125.77

Where: Length of road by FRSSM map class (m): LE = Excellent; LA = Average; LP = Poor; LVP = Very poor; LEP = Extremely poor.

Table B.1. Calculated technical parameters by primary and secondary roads, as well as the total road network obtained from the optimized road planning (ORP) and the road built by traditional planning (RBTP) for APUs 06 and 14.

APU	Technical parameter	Primary road		Secondary road		Road network	
		RBTP	ORP	RBTP	ORP	RBTP	ORP
06	L	9,448.32	9,289.21	26,369.40	25,536.13	35,817.72	34,825.34
	RD	6.01	5.91	16.77	16.24	22.78	22.15
	RS	1,663.79	1,692.29	596.15	615.60	438.89	451.40
	A	7.56	7.43	10.55	10.21	18.11	17.65
	NC	1.00	1.00	0	0	1.00	1.00
	NB	2.00	1.00	0	0	2.00	1.00
	NCB	3.00	2.00	0	0	3.00	2.00
14	L	15,566.14	12,718.36	24,444.24	21,316.16	40,010.39	34,034.52
	RD	11.83	9.66	15.55	13.56	30.40	25.86
	RS	845.60	1,034.94	643.10	737.47	328.98	386.75
	A	12.45	10.17	9.78	8.53	22.23	18.70
	NC	1.00	1.00	0	0	1,0	1,0
	NB	17.00	5.00	8.00	10.00	25,0	15,0
	NCB	18.00	6.00	8.00	10.00	26,0	16,0

Where: L = total length of road in APU (m); RD = road density (m ha^{-1}); T = total utilizable area (ha); RS = road spacing (m); A = area of road coverage (ha); NC = total number of culverts in the APU; NB = total number of bridges in the APU; NCB = total number of culverts and bridges.

Table C.1. Calculated financial parameters by primary and secondary roads, as well as the total road network obtained from the optimized road planning (ORP) and the road built by traditional planning (RBTP) for APUs 06 and 14.

APU	Financial parameter	Primary road		Secondary road		Road network	
		RBTP	ORP	RBTP	ORP	RBTP	ORP
06	CR	101,097.01	99,394.54	105,477.60	102,144.51	206,574.61	201,539.04
	CH	64.31	63.23	67.10	64.98	131.41	128.21
	CC	27,769.95	27,769.95	0.00	0.00	27,769.95	27,769.95
	CB	15,055.56	7,527.78	0.00	0.00	15,055.56	7,527.78
	CCB	42,825.51	35,297.73	0.00	0.00	42,825.51	35,297.73
	CRI	143,922.52	134,692.27	105,477.60	102,144.51	249,400.12	236,836.77
14	CR	166,557.74	136,086.49	97,776.98	85,264.63	264,334.72	221,351.11
	CH	126.54	103.39	74.28	64.78	200.82	168.17
	CC	27,769.95	27,769.95	0.00	0.00	27,769.95	27,769.95
	CB	127,972.26	37,638.90	60,222.24	75,277.80	188,194.50	112,916.70
	CCB	155,742.21	65,408.85	60,222.24	75,277.80	215,964.45	140,686.65
	CRI	322,299.95	65,408.85	60,222.24	75,277.80	215,964.45	140,686.65

Where: CR = total cost of road construction (R$) per APU and per hectares (CH); CC = total cost of culvert (R$); CB = total cost of bridge (R$); CBC = total cost of culvert and bridge (R$); CRI = total cost of road infrastructure (R$).

References

Abdi, E., Majnounian, B., Darvishsefat, A., Mashayekhi, Z., Sessions, J., 2009. A GIS-MCE based model for forest road planning. J. For. Sci. 55, 171-176.

Acar, H.H., Dursun, E., Gulci, S., Gumus, S., 2017. Assessment of Road Network Planning By Using Gis-Based Multi-Criteria Evaluation for Conversion of Coppice Forest To High Forest. Fresenius Environ. Bull. 26, 2380-2388.

Acar, H.H., Dursun, E., Gulci, S., Gumus, S., 2017. Assessment of road network planning by using GIS-based multi-criteria evaluation for conversion of coppice forest to high forest. Fresenius Environ. Bull. 26, 2380-2388.

Aczél, J., Saaty, T. L.,1983. Procedures for synthesizing ratio judgements. Journal of mathematical Psychology, 27(1), 93-102.

Aguiar, M.O., da Silva, G.F., Mauri, G.R., de Mendonça, A.R., de Oliveira Santana, C.J., Marcatti, G.E., et al., 2021. Optimizing forest road planning in a sustainable forest management area in the Brazilian Amazon. Journal of Environmental Management, 288, 112332.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., De Moraes Gonçalves, J.L., Sparovek, G., 2013. Koppen's climate classification map for Brazil. Meteorol. Zeitschrift 22, 711-728. https://doi.org/10.1127/0941-2948/2013/0507

Andrade, d.; Ogliari, p., 2013. Estatística para as ciências agrárias e biológicas com noções de experimentação. Editora UFSC, Florianópolis, 478 pp.

Balieiro, M., Espada, A.L.V., Nogueira, O., Palmieri, R.; Lentini, M. As concessões de florestas públicas na Amazônia Brasileira: um manual para pequenos e médios produtores florestais. IMAFLORA, Piracicaba; IFT, Belém 204 pp. https://www.imaflora.org/public/media/biblioteca/manual_concessoes_ed2.pdf

Balieiro, M.R., Espada, A.L.V., Nogueira, O., Palmieri, R., Lentini, M., 2010. As concessões de florestas públicas na Amazônia Brasileira. Piracicaba, SP: Imaflora, Belém, 204 pp.

Barbosa, R.P., Rodriguez, L.C.E., Gorgens, E.B., 2017. Multi-criteria optimization for log extraction in Amazon based on airborne laser scanning data. Sci. For. Sci. 45.

Brasil, 2006. Instrução Normativa no 05 de 11 de dezembro de 2006. Ministério do Meio Ambiente.

Brasil, 2007. Norma de Execução nº 1, de 24 Abril de 2007 do Instituto Brasileiro do Meio Ambiente e Recursos Hídricos.

Brasil, 2009. Resolução nº 406, de 02 de fevereiro de 2009. Conselho Nacional do Meio Ambiente, CONAMA, Brasil.

Brasil, 2018. Resolução/CEMAAM N. 30 de 31 de outubro de 2018. Conselho Estadual do Meio Ambiente, CEMAAM, Brasil.

Brasil, 2018. Resolução/CEMAAM N. 30 de 31 de outubro de 2018. Conselho Estadual do Meio Ambiente, CEMAAM, Brasil.

Braz, E.M., 1997. Otimização da rede de estradas secundárias em projetos de manejo sustentável de floresta tropical. Embrapa Acre-Circular Técnica. 15. https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/492475/1/cirtec15.pdf

Braz, E.M., Basso, R.O., CURTO, R.D.A., de Mattos, P.P., Silva, J.P., 2018. Densidade ótima de estradas para a exploração em plano de manejo florestal. In Embrapa Florestas-Artigo em anais de congresso (ALICE). In: Seminário de colheita e transporte de madeira, 18., Ribeirão Preto.

Bugday, E., 2018. Application of artificial neural network system based on Anfis using GIS for predicting forest road network suitability mapping. Fresenius Environ. Bull. 27, 1656-1668.

Bugday, E., Akay, A.E., 2019. Evaluation of forest road network planning in landslide sensitive areas by GIS-based multi-criteria decision making approaches in Ihsangazi Watershed, Northern Turkey. Sumar. List 143, 325-336. https://doi.org/10.31298/sl.143.7-8.4

Bugday, E., Özel, H.B., 2019. Utilizing a fuzzy inference system (FIS) and modified analytical hierarchical analysis for forest road network planning in afforested lands. Polish J. Environ. Stud. 28, 1579-1589. https://doi.org/10.15244/pjoes/89611

Çalişkan, E., 2013. Planning of forest road network and analysis in mountainous area. Life Sci. J. 10, 2456-2465.

Çalişkan, E., Bediroglu, S., Yildirim, V., 2019. Determination forest road routes via GIS-based spatial multi-criterion decision methods. Appl. Ecol. Environ. Res. 17, 759-779. https://doi.org/10.15666/aeer/1701_759779

Ceddia, M.B., Villela, A.L.O., Pinheiro, É. F. M., Wendroth, O., 2015. Spatial variability of soil carbon stock in the Urucu river basin, Central Amazon-Brazil. Science of the Total Environment, 526, 58-69. https://doi.org/10.1016/j.scitotenv.2015.03.121

D’amours, S., Rönnqvist, M., Weintraub, A., 2008. Using Operational Research for supply chain planning in the forest products industry. INFOR 46, 265-281. https://doi.org/10.3138/infor.46.4.265

da Rocha, E. S., de barros, P.L.C., de Nazaré Maciel, M., 2007. Avaliação da densidade ótima de estradas florestais em dois sistemas de exploração florestal no estado do Para. Revista de Ciências Agrárias - Amazonian Journal of Agricultural and Environmental Sciences, 47(1), 49-58. http://periodicos.ufra.edu.br/index.php/ajaes/article/view/193.

da Silva Seabra, V., Cruz, C.M., 2014. Uso do sensoriamento remoto na avaliação de alterações dos estados dinâmicos da paisagem da bacia hidrográfica do Rio São João. Revista Brasileira de Cartografia, 66(2), 303-320.

de Carvalho, A.L., d'Oliveira, M.V.N., Putz, F.E., & de Oliveira, L.C. (2017). Natural regeneration of trees in selectively logged forest in western Amazonia. Forest Ecology and Management, 392, 36-44. http://dx.doi.org/10.1016/j.foreco.2017.02.049

de Morisson Valeriano, M., de Fátima Rossetti, D., 2012. Topodata: Brazilian full coverage refinement of SRTM data. Applied Geography, 32(2), 300-309. https://doi.org/10.1016/j.apgeog.2011.05.004

Demir, G., 2019. GIS-based landslide susceptibility mapping for a part of the North Anatolian Fault Zone between Reşadiye and Koyulhisar (Turkey). Catena, 183, 104211. https://doi.org/10.1016/j.catena.2019.104211

dos Santos, R.C., Lima, M., da Silva Junior, C.A., & Battirola, L.D. (2019). Disordered conversion of vegetation committees connectivity between forest fragments in the Brazilian Legal Amazon. Applied Geography, 111, 102082. https://doi.org/10.1016/j.apgeog.2019.102082

Eastman, J.R., 2003. IDRISI Kilimanjaro: guide to GIS and image processing. p.328

Emmert, F., 2014. Combinação de dados de campo e métodos computacionais para o planejamento da exploração florestal na Amazônia. Tese (Doutorado em Engenharia Florestal) - Universidade de Brasília.

Erdaş, O, 2008: Transport Tekniği. KSÜ Rektörlüğü, Kahramanmaraş, Yayın No: 130/20 554s.

Espada, A.; Pires, I.; Lentini, M.; Bittencourt, P. (2012). Manejo Florestal e Exploração de Impacto Reduzido em Florestas Naturais de Produção da Amazônia. IFT, Belém 31 pp. http://ift.org.br/wp-content/uploads/2014/11/Informativo-T%C3%A9cnico-1.pdf

Espírito-Santo, F.D.B., Santos, J.R.D., Silva, P.G.D., 2004. Técnicas de processamento de imagens e de análise espacial para estudo de áreas florestais sob a exploração madeireira. Revista Árvore, 28, 699-706.

FAO, 1974. logging and log transport in tropical high forest: a manual on production and costs. (FAO. Forestry Series, 5, FAO. Development Paper,18), Roma.

Figueiredo, E.O., 2008. MODEFLORA: Modelo Digital de Exploração Florestal. Embrapa Acre, Rio Branco.

Figueiredo, E.O., Braz, E.M., D'Oliveira, M.V.N., 2007. Manejo de precisão em florestas tropicais: Modelo digital de exploração florestal. EMBRAPA, Acre, Rio Branco, AC.

Figueiredo, E.O., Braz, E.M., Oliveira, M.V.N., 2007. Manejo de precisão em florestas tropicais: Modelo digital de exploração florestal. Embrapa Acre, Rio Branco, 183 pp.

Garcia, A.S., de FN Vilela, V.M., Rizzo, R., West, P., Gerber, J.S., Engstrom, P.M., Ballester, M.V.R., 2019. Assessing land use/cover dynamics and exploring drivers in the Amazon's arc of deforestation through a hierarchical, multi-scale and multi-temporal classification approach. Remote Sensing Applications: Society and Environment, 15, 100233. https://doi.org/10.1016/j.rsase.2019.05.002

Gromskaya, L.Y., Simonenkov, M.V., 2016. Current Status of Modeling and Optimization of Forest Roads. Lesnoy Zhurnal (Russian Forestry Journal) 108-122. https://doi.org/10.17238/issn0536-1036.2016.5.108

Guimaraes, A.F., de Souza, C.R., Rosa, C., dos Santos, J.P., Teixeira, L.A.F., Zanzini, L.P., 2021. Small-scale environmental variations drive vegetation structure and diversity in Amazon riverine forests. Flora, 283, 151916. https://doi.org/10.1016/j.flora.2021.151916

Haddad, N.M., Brudvig, L.A., Clobert, J., Davies, K.F., Gonzalez, A., Holt, R.D., et al., 2015. Habitat fragmentation and its lasting impact on Earth's ecosystems. Sci. Adv., 1(2), e1500052. https://*doi.org/*10.1126/sciadv.1500052

Hayati, E., Abdi, E., Majnounian, B., Makhdoum, M., 2013a. Application of sensitivity analysis in forest road networks planning and assessment. J. Agric. Sci. Technol. 15, 781-792.

Hayati, E., Majnounian, B., Abdi, E., 2012b. Qualitative evaluation and optimization of forest road network to minimize total costs and environmental impacts. iForest- Biogeosci. For. 5, 121-125. https://doi.org/10.3832/ifor0610-009

Heinrich R (1975) Problems of forest road construction in tropical high forests. Technical Report of FAO/Austria training course on forest roads and harvesting in mountainous forests. FAO, Rome

Heinrich, V.H., Dalagnol, R., Cassol, H.L., Rosan, T.M., de Almeida, C.T., Junior, C.H.S., et al., 2021. Large carbon sink potential of secondary forests in the Brazilian Amazon to mitigate climate change. Nature communications, 12(1), 1-11. https://doi.org/10.1038/s41467-021-22050-1

Holmes, T.P., Blate, D.M., Zweede, J.C., Pereira, R., Barreto, P., Boltz, F., Bauch, R., 2002. Financial and ecological indicators of reduced impact logging performance in the eastern Amazon. Forest Ecological Management 163: 93- 110.

Hosseini, S.A.O., Gorgandipur, M., Nikooy, M., 2018. Forest road network assessment using lookoutpoints orienting in Hyrcanian forest using GIS - Short communication. J. For. Sci. 64, 402-408. https://doi.org/10.17221/45/2018-JFS

IBAMA - Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, 2007. Norma de execução, nº 1 de 24 abril de 2007.

IBGE - Instituto Brasileiro de Geografia e Estatística, 2012. Manual Técnico da Vegetação Brasileira. 2º ed., p. 276. https://biblioteca.ibge.gov.br/visualizacao/livros/liv63011.pdf

International Tropical Timber Organization (ITTO), 2020. Biennial review and assessment of the world timber situation 2019-2020. https://www.itto.int/direct/topics/topics_pdf_download/topics_id=6783&no=1

Jaafari, A., Najafi, A., Rezaeian, J., Sattarian, A., Ghajar, I., 2015. Planning road networks in landslide-prone areas: A case study from the northern forests of Iran. Land use policy 47, 198-208. https://doi.org/10.1016/j.landusepol.2015.04.010

Kamarudin, N., Ismail, M.H., Jusoff, K., 2014. Quantification of least cost path analysis for best forest road planning. Malaysian For. 77, 101-110.

Kazama, V.S., Dalla Corte, A.P., Robert, R.C.G., Sanquetta, C.R., Arce, J.E., Oliveira-Nascimento, K.A., DeArmond, D., 2021. Global review on forest road optimization planning: Support for sustainable forest management in Amazonia. Forest Ecology and Management, 492, 119159. https://doi.org/10.1016/j.foreco.2021.119159

Keller, G., Sherar, J., Zweede, J., 2015. Overview of Amazon Basin Forest Roads Manual. Transp. Res. Rec. 2472 (1), 56-63. https://doi.org/10.3141/2472-07

Keller, G.; Sherar, J., 2003. Engenharia de estradas de baixo volume: manual de campo para as melhores práticas de gestão. USDA, Washington, 158 pp.

Lillesand, T., Kiefer, R. W., Chipman, J., 2015. Remote sensing and image interpretation. John Wiley & Sons, Hoboken, 736pp.

Lima, K.S., Meira Castro, A.C., Santos Baptista, J., Silva, U., 2020. Wood-Logging Process Management in Eastern Amazonia (Brazil). Sustainability, 12(18), 7571. https://doi.org/10.3390/su12187571

Lima, R.Y.M., Azevedo-Ramos, C., 2020. Compliance of Brazilian forest concession system with international guidelines for tropical forests. Forest Policy and Economics, 119, 102285.

Machado, C.C., Garcia, A.R., Silva, E., Fontes, A.M., 2003. Comparação de taxas de erosão em estradas florestais estimadas pelo modelo WEPP (Water Erosion Prediction Project) modificado em relção a medições experimentais. Revista Árvore, 27, 295-300.

Norizah, K., Mohd Hasmadi, I., 2012. Developing priorities and ranking for suitable forest road: Allocation using Analytic Hierarchy Process (AHP) in peninsular Malaysia. Sains Malaysiana 41, 1177-1185.

Pentek, T., Nevečerel, H., Ecimović, T., Lepoglavec, K., Papa, I., Tomašić, Ž., 2014. Strategic planning of forest road network in Croatia - Analysis of present situation as basis for future activities. Nov. Meh. Sumar. 35, 63-78.

Petković, V., Potočnik, I., 2018. Planning forest road network in natural forest areas: a case study in northern Bosnia and Herzegovina. Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering, 39(1), 45-56. https://hrcak.srce.hr/193550

Rogers, L.W., 2005. Automating contour-based route projection for preliminary forest road designs using GIS. University of Washington. 78 pp.

Saaty, T.L. The analytical hierarchy process: planning, priority setting, resource allocation. New York: McGraw-Hill, 1980. 287p.

Saaty, T.L., Vargas, L.G., 1991. Prediction, Projection and Forecasting. Kluwer Academic, Boston. 254 pp.

Saaty, T. L., 2005. Theory and applications of the analytic network process: decision making with benefits, opportunities, costs, and risks. RWS publications, Pittsburgh, 352 pp.

Sabogal, C., Pokorny, B., Silva, J.N.M., Carvalho, J.O.P., Zweede, J., Puerta, R., 2009. Diretrizes técnicas de manejo para produção madeireira mecanizada em florestas de terra firme na Amazônia brasileira. Embrapa Amazônia Oriental, Belém, 217 pp.

Santos, H.G. dos; Carvalho Junior, W. de; Dart, R. de O.; Aglio, M.L.D.; Sousa, J.S. de., et al., 2011. O novo mapa de solos do Brasil: legenda atualizada. Embrapa Solos, Rio de janeiro, 67 p. https://ainfo.cnptia.embrapa.br/digital/bitstream/item/123772/1/DOC-130-O-novo-mapa-de-solos-do-Brasil.pdf

Sarp, G., Duzgun, S., 2015. Morphometric evaluation of the Afşin-Elbistan lignite basin using kernel density estimation and Getis-Ord's statistics of DEM derived indices, SE Turkey. Journal of Asian Earth Sciences, 111, 819-826. https://doi.org/10.1016/j.jseaes.2015.07.022

Schietti, J., Emilio, T., Rennó, C.D., Drucker, D.P., Costa, F.R., Nogueira, A., et al., 2014. Vertical distance from drainage drives floristic composition changes in an Amazonian rainforest. Plant Ecology & Diversity, 7(1-2), 241-253.

Serviço Florestal Brasileiro (SFB), 2016. Relatório pós-exploratório: UMF III - Flona do Jamari - Upa 06 - 2016. AMATA, São Paulo, 26 pp.

Serviço Florestal Brasileiro (SFB), 2017. Plano operacional anual 07: UMF III - Flona do Jamari - Upa 14 - 2017/2018. AMATA, São Paulo, 159 pp.

Sessions J. 2007. Forest road operations in the Tropics. Springer, New York. pp. 170.

Silva, E.F., Silva, G.F., Figueiredo, E.O., Binoti, D.H.B., de Mendonça, A.R., Torres, C.M. M.E., Pezzopane, J.E.M., da Silva, G.F., 2018. Allocation of storage yards in management plans in the Amazon by means of mathematical programming. Forests 9, 127. https://doi.org/10.3390/f9030127

Silverman, B.W., 1986. Density Estimation for Statistics and Data Analysis. Chapman & Hall, London. http://dx.doi.org/10.1007/978-1-4899-3324-9

Souza A.L., Soares C.P.B., 2013. Florestas nativas: estrutura, dinâmica e manejo. Editora UFV, Viçosa, 322 pp.

Spadoni, G. L., Cavalli, A., Congedo, L., Munafò, M., 2020. Analysis of Normalized Difference Vegetation Index (NDVI) multi-temporal series for the production of forest cartography. Remote Sensing Applications: Society and Environment, 20, 100419. https://doi.org/10.1016/j.rsase.2020.100419

SUDAM - Superintendência do Desenvolvimento da Amazônia, 1978. Estudo de viabilidade técnico econômica da exploração mecanizada em floresta da terra firme, região de Curuá-Una. Belém, 1978. 133p.

Yilmaz, I., Keskin, I., 2009. GIS based statistical and physical approaches to landslide susceptibility mapping (Sebinkarahisar, Turkey). Bulletin of Engineering Geology and the Environment, 68(4), 459-471.

Zhao, M., Yang, J., Zhao, N., Liu, L., Ling, D. U., Xiao, X., Yue , T., Wilson, J.P., 2021. Spatially explicit changes in forest biomass carbon of China over the past 4 decades: Coupling long-term inventory and remote sensing data. Journal of Cleaner Production, 316, 128274. https://doi.org/10.1016/j.jclepro.2021.128274

GENERAL CONSIDERATIONS

According to the results obtained in this thesis, it is possible to point out that relevant information was found to promote advances in the science of forest road planning in management areas of Brazil forests and around the world. Specifically, in chapter I, the literature review demonstrated the relevance of research in Forest Road Planning (FRP) from the increasing trend of publications on the topic of FRP during the period 2009-2019. The results of this chapter are a tool to support decision-making on future FRP approaches to forest management for both natural and planted forests.

As a suggestion for future revisions on the subject, it is proposed to make a history of existing works on the FRP, that is, considering works prior to 2009, to evaluate the same parameters sought in chapter I or others. The roads studied in chapter I were only those that provide access to the transport of wood in the management area. Thus, another review study suggestion is the FRP for other purposes, such as recreation and forest fires, which also deserve further investigation into the methods of optimizing their planning to guide scientific advances in this area.

According to the results obtained in chapter II, it is possible to affirm that an important tool has been obtained to support the planning and evaluation of roads in the management area of a forest of great global relevance, which is the Amazon Rainforest. It is important to highlight that the methodological procedure proposed in this study considered one of the best methodological options for planning roads, as demonstrated in the review carried out in chapter I. This methodology was developed via programming code aiming to automate most of the road planning process and thus supporting the forest manager in decision making. This tool will be registered with the National Institute of Industrial Property of Brazil and will be made available to the public along with a user's manual.

The tool will allow the necessary adjustments and adaptations to other forest areas. In addition, it should be noted that the product of this tool consists of a first layout of the roads, at the level of strategic planning. Thus, the layout will need further adjustments at the tactical and operational level. That is, it requires improvements at a more local level with adjustments to the design of the road axis, such as its alignment in horizontal and vertical profile, such as curve radii, earthwork, etc. Moreover, adjustments in the form of detours for ecologically sensitive areas such as, nest sites or species of concern located in the path of the road alignment. Fauna information is difficult to include in strategic planning as many wild animals are always on the move.

In addition, it is noteworthy that the product of this tool consists of the spatial optimization of the density of roads, which does not replace the calculations of optimal or ideal density calculated through technical and financial parameters (SUDAM, 1978; Braz, 1997; Figueiredo et al. ., 2007; FAO, 1974). That is, it is intended to distribute the optimal density calculated in the best way throughout the forest according to the variables used.

Considering the extensive area of management units, located in areas of difficult logistics, to achieve the objective of the present study, the use of free access data with greater spatial accuracy obtained remotely today was maximized. However, for future studies, it is recommended to use other images with greater accuracy, such as those obtained with the support of technology such as LiDAR (Light Detection And Ranging) and/or ARP (Remotely Piloted Aircraft), so that the results of the road planning can be even more accurate. Although these images are expensive to obtain, they could be relevant for future research. Remote sensing data are strongly recommended for spatial FRP in Amazonia, but appropriate applications of pre-processing and post-processing techniques must be acquired.

In addition to the relative importance, the interviewed experts indicated other possibilities of relevant variables, which can be tested in future studies, such as access, accessibility level, presence of public roads, workforce training, earthworks, paving types, and soil structures. Moreover, the interviewees presented relevant information to pressure public policies that promote the use of more advanced technologies in the in the elaboration process the SFM plans in the Amazon. It was highlighted the lack of training of professionals in the area, as well as environmental analysts of Brazilian agencies that evaluate the SFMP. Therefore, support from the Brazilian government is needed to promote initiatives that help train professionals in the area to become aware of less impacting methodologies for effective sustainable management in this biome. As well as funding more research and development on optimizing forest infrastructure planning in the management area.

It is noteworthy that the cost values of roads and watercourse crossings are site-specific, established by a third-party company, for the study area that has the advantage of being relatively close to the state capital, Porto Velho, about 160 km, reducing the logistics costs of acquiring and maintaining equipment, machinery and raw material for road construction. In addition, to the smooth topography, there are paved federal roads near management area, facilitating the logistics of labor access. This situation is not very common for many forest management areas in the Brazilian Amazon, which means that gains in more critical areas may be in greater proportion and, therefore, should be tested with the methodology proposed in this study, at the level of strategic and tactical planning. Also, it is important to note that the costs are different when the road opening is carried out by the company that is harvesting the timber.

As operational gains were observed in the field, it is recommended that the maximum detailing of the information of the site at the time of forest inventory, for better detailing of the real environmental aspects and thus, more accurate results in planning. Furthermore, it is recommended to use the same work team in different sectors of management operations, such as inventory and harvesting, as the forest inventory is carried out in the rainy season and the harvest in the dry season. This helps harvesting operators move faster as they already know the field of work and helps to identify trees to be harvested more quickly as they have been trained to identify trees for inventory.

As a complement to the methodology proposed in the present study, it is recommended the simultaneous use of the methods of optimization for log landings and skid trails. Which have been efficiently studied by some recent studies for logging operations in Amazonia (Aguiar et al., 2020; Sales et al., 2019; Silva, 2019; Silva et al., 2020, 2018).

Finally, based on the results found, it can be considered that the main hypothesis of the present study was supported, and that the use of technical approaches used internationally in FRP can bring technical and scientific contributions to the SFM in the Amazon, which were demonstrated by the results discussed in the literature review in chapter I and by the methodological proposal presented in chapter II.

GERAL CONCLUSION

According to the literature review and the methodological proposal presented in the present study, it can be concluded that:

- The literature review allowed identifying recent advances achieved in the 2009-2019 decade in forest road planning, at different levels of planning and optimization, which can be applied to the area of forest management in the Amazon Basin;

- It was possible to identify the main factors: a) spatial variables (elevation, aspect, density of roads, proximity to the hydrographic network, slope, timber production, lithology or petrography, and distance from existing roads); b) spatial decision analysis methods (methods based on AHP and FL) and; c) methodologies for optimizing the layout of forest roads (methods based on Dijkstra algorithm and LCPA and Pegger tools);

- It was possible to find satisfactory results through modeling the spatial suitability of forest roads (FRSSM) using the AHP method, a Multicriteria Decision Making (MCDM), based on GIS, and the main spatial decision variables suitable for study areas, according to literary consultation, specialists, and visits to the field, for both studied UPAs;

- It was possible to obtain significant results in the methodological proposal for optimizing the planning and evaluation of the road layout, based on the FRSSM layer and the LCPA method according to technical and financial spatial (environmental) parameters, statistically proven for the APUs, at the strategic planning level;

- Expert opinion provided essential support for this work, promoting improvement initiatives not only specifically in the FRP but also at the level of operational infrastructure planning for SFM area in the Amazon.

GERAL REFERENCES

Abdi, E., Majnounian, B., Darvishsefat, A., Mashayekhi, Z., & Sessions, J. (2009). A GIS-MCE based model for forest road planning. *Journal of Forest Science*, 55(4), 171-176.

Acar, H. H., Dursun, E., Gulci, S., & Gumus, S. (2017). Assessment of road network planning by using GIS-based multi-criteria evaluation for conversion of coppice forest to high forest. *Fresenius Environmental Bulletin*, *26*(3), 2380-2388.

Aczél, J., & Saaty, T. L. (1983). Procedures for synthesizing ratio judgements. *Journal of mathematical Psychology*, *27*(1), 93-102.

Aguiar, M. O., da Silva, G. F., Mauri, G. R., de Mendonça, A. R., de Oliveira Santana, C. J., Marcatti, G. E., ... & Leite, C. C. C. (2021). Optimizing forest road planning in a sustainable forest management area in the Brazilian Amazon. *Journal of Environmental Management*, *288*, 112332. https://doi.org/10.1016/j.jenvman.2021.112332

Aguiar, M. O. (2019). *Otimização do planejamento integrado de infraestrutura na exploração florestal na Região Amazônica* (Tese de Doutorado) – Centro de Ciências Agrárias e Engenharias, Universidade Federal do Espírito Santo, Jerônimo Monteiro. Recuperado de: https://cienciasflorestais.ufes.br/pt-br/pos-graduacao/PPGCFL/detalhes-da-tese?id=13839.

Aguiar, M. O., da Silva, G. F., Mauri, G. R., da Silva, E. F., de Mendonca, A. R., Silva, J. P. M., ... & Figueiredo, E. O. (2020). Metaheuristics applied for storage yards allocation in an Amazonian sustainable forest management area. *Journal of Environmental Management*, *271*, 110926. https://doi.org/10.1016/j.jenvman.2020.110926

Akay, A. A. (2004). New methodology in designing forest roads. *Turkish J. Agricul. Forest*. 28, 273-279. Recuperado de: https://journals.tubitak.gov.tr/agriculture/issues/tar-04-28-4/tar-28-4-9-0311-6.pdf.

Akay, A. E., Wing, M. G., & Sessions, J. (2014). Estimating sediment reduction cost for low-volume forest roads using a LİDAR-derived high-resolution DEM. *The Baltic Journal of Road and Bridge Engineering*, *9*(1), 52-57. https://doi.org/10.3846/bjrbe.2014.07

Akgul, M., Demir, M., Ozturk, T., Topatan, H., & Budak, Y. E. (2016). Investigation of recreational vehicles maneuverability on forest roads by computer-aided driving analysis. *The Baltic Journal of Road and Bridge Engineering*, *11*(2), 111-119. https://doi.org/10.3846/bjrbe.2016.13

Akgul, M., Yurtseven, H., Gulci, S., & Akay, A. E. (2018). Evaluation of UAV-and GNSS-based DEMs for earthwork volume. *Arabian Journal for Science and Engineering*, *43*(4), 1893-1909. https://doi.org/10.1007/s10661-018-6948-0

Alvares, C. A., Stape, J. L., Sentelhas, P. C., Gonçalves, J. D. M., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, *22*(6), 711-728. https://doi.org/10.1127/0941-2948/2013/0507

Andersen, H. E., Reutebuch, S. E., McGaughey, R. J., d'Oliveira, M. V., & Keller, M. (2014). Monitoring selective logging in western Amazonia with repeat lidar flights. *Remote Sensing of Environment*, *151*, 157-165. https://doi.org/10.1016/j.rse.2013.08.049

Andrade, D. F., & Ogliari, P. J. (2007). *Estatística para as ciências agrárias e biológicas: com noções de experimentação*. Florianópolis: Editora da UFSC.

Arima, E. Y., Walker, R. T., Perz, S. G., & Caldas, M. (2005). Loggers and forest fragmentation: Behavioral models of road building in the Amazon basin. *Annals of the Association of American Geographers*, *95*(3), 525-541. https://doi.org/10.1111/j.1467-8306.2005.00473.x

Arima, E. Y., Walker, R. T., Sales, M., Souza Jr, C., & Perz, S. G. (2008). The fragmentation of space in the Amazon Basin. *Photogrammetric Engineering & Remote Sensing*, *74*(6), 699-709. https://doi.org/10.14358/PERS.74.6.699

Atalay, I., Efe, R., & Öztürk, M. (2014). Ecology and classification of forests in Turkey. *Procedia-Social and Behavioral Sciences*, *120*, 788-805. https://doi.org/10.1016/j.sbspro.2014.02.163

Babapour, R., Naghdi, R., Ghajar, I., & Ghodsi, R. (2015). Modeling the proportion of cut slopes rock on forest roads using artificial neural network and ordinal linear regression. *Environmental monitoring and assessment*, *187*(7), 1-14. 187. https://doi.org/10.1007/s10661-015-4688-y

Babapour, R., Naghdi, R., Ghajar, I., & Ghodsi, R. (2018). New strategies for estimation of cut and fill areas in road design with different ground cross-section offsets. *Scandinavian Journal of Forest Research*, *33*(2), 178-187. https://doi.org/10.1080/02827581.2017.1338748

Babapour, R., Naghdi, R., Ghajar, I., & Mortazavi, Z. (2018). Forest road profile optimization using meta-heuristic techniques. *Applied Soft Computing*, *64*, 126-137. https://doi.org/10.1016/j.asoc.2017.12.015

Babapour, R., Naghdi, R., Salehi, A., & Ghajar, I. (2014). A decision support system for allocation of mountain forest roads based on ground stability. *Arabian Journal for Science and Engineering*, *39*(1), 199-205. https://doi.org/10.1007/s13369-013-0833-5

Balieiro, M. R., Espada, A. L. V., Nogueira, O., Palmieri, R., Lentini, M. (2010). As concessões de florestas públicas na Amazônia Brasileira. Piracicaba: Imaflora, SP; Belém: IFT, PA.

Barbosa, R. P., Estraviz Rodriguez, L. C., & Gorgens, E. B. (2017). Otimização multicritério da extração madeireira na Amazônia com o uso de escaneamento laser aerotransportado. *Scientia Forestalis*, *45*(115), 541-550. dx.doi.org/10.18671/scifor.v45n115.11

Bont, L. G., Fraefel, M., & Fischer, C. (2018). A spatially explicit method to assess the economic suitability of a forest road network for timber harvest in steep terrain. *Forests*, *9*(4), 169. https://doi.org/10.3390/f9040169

Bont, L. G., Heinimann, H. R., & Church, R. L. (2015). Concurrent optimization of harvesting and road network layouts under steep terrain. *Annals of Operations Research*, *232*(1), 41-64. https://doi.org/10.1007/s10479-012-1273-4

Brasil. (2006). *Instrução Normativa no 05 de 11 de dezembro de 2006*. Ministério do Meio Ambiente.

Brasil. (2007). *Norma de Execução no 1, de 24 Abril de 2007 do Instituto Brasileiro do Meio Ambiente e Recursos Hídricos*.

Brasil. (2009). Resolução nº 406, de 02 de fevereiro de 2009. Conselho Nacional do Meio Ambiente, CONAMA, Brasil.

Brasil. (2012). *Lei no. 12.651 de 25 de Maio de 2012*. Dispõe sobre a proteção da vegetação nativa; altera as Leis nos 6.938, de 31 de agosto de 1981, 9.393, de 19 de dezembro de 1996, e 11.428, de 22 de dezembro de 2006; revoga as Leis nos 4.771, de 15 de setembro de 196. Brasília.

Brasil. (2018). *Resolução/CEMAAM N. 30 de 31 de outubro de 2018*. Conselho Estadual do Meio Ambiente, CEMAAM, Brasil.

Braz, E. M. (1997). Otimização da rede de estradas secundárias em projetos de manejo sustentável de floresta tropical. *Embrapa Acre-Circular Técnica (INFOTECA-E)*.

Braz, E. M. (2010). *Subsídios para o planejamento do manejo de florestas tropicais da Amazonia* (Tese de Doutorado) – Centro de Ciências Rurais, Universidade Federal de Santa Maria, Santa Maria. Recuperado de: http://coral.ufsm.br/ppgef/images/Teses2010/Evaldo-Munoz-Braz.pdf.

Braz, E. M., Basso, R. O., Curto, R. D. A., e Mattos, P. P., & Silva, J. P. (2018). Densidade ótima de estradas para a exploração em plano de manejo florestal. *Anais do Seminário De Colheita e Transporte de Madeira*. Ribeirão Preto, 18. pp. 45-49. Recuperado de: https://ainfo.cnptia.embrapa.br/digital/bitstream/item/178856/1/2018-AAC-Evaldo-SCTM-Densidade.pdf.

Bugday, E. (2018). Application of artificial neural network system based on ANFIS using GIS for predicting forest road network suitability mapping. *Fresenius Environmental Bulletin*, *27*(3), 1656-1668. Recuperado de: https://www.prt-parlar.de/download_feb_2018/.

Bugday, E., & Akay, A. E. (2019). Evaluation of forest road network planning in landslide sensitive areas by GIS-based multi-criteria decision making approaches in Ihsangazi watershed, Northern Turkey. *Šumarski list*, *143*(7-8), 325-336. https://doi.org/10.31298/sl.143.7-8.4. https://doi.org/10.31298/sl.143.7-8.4

Bugday, E., & Özel, H. B. (2019). Utilizing a fuzzy inference system (FIS) and modified analytical hierarchical analysis for forest road network planning in afforested lands. *Polish Journal of Environmental Studies*, *28*(3), 1579-1589. https://doi.org/10.15244/pjoes/89611

Çalışkan, E. (2013). Planning of forest road network and analysis in mountainous area. *Life science journal*, *10*(2), 2456-2465. Recuperado de: https://cjes.guilan.ac.ir/article_1049_3a105b3b8aa0dbd40d2e51f2ffef11c5.pdf

Çalişkan, E. (2017). Planning of environmentally sound forest road route using GIS & S-MCDM. *Šumarski list*, *141*(11-12), 583-591. https://doi.org/10.31298/sl.141.11-12.6

Caliskan, E., Bediroglu, S., & Yildirim, V. (2019). Determination forest road routes via GIS-based spatial multi-criterion decision methods. *Applied Ecology and Environmental Research*, *17*(1), 759-779. https://doi.org/10.15666/aeer/1701_759779

Çalişkan, E., & Karahalil, U. (2017). Evaluation of forest road network and determining timber extraction system using GIS: a case study in Anbardağ planning unit. *Šumarski list*, *141*(3-4), 163-171. https://doi.org/10.31298/sl.141.3-4.6

Castano-Villa, G. J., Estevez, J. V., Guevara, G., Bohada-Murillo, M., & Fonturbel, F. E. (2019). Differential effects of forestry plantations on bird diversity: a global assessment. *Forest Ecology and Management*, *440*, 202-207. https://doi.org/10.1016/j.foreco.2019.03.025

Cavalli, R., & Grigolato, S. (2010). Influence of characteristics and extension of a forest road network on the supply cost of forest woodchips. *Journal of Forest Research*, *15*(3), 202-209. https://doi.org/10.1007/s10310-009-0170-4

Ceddia, M. B., Villela, A. L. O., Pinheiro, É. F. M., & Wendroth, O. (2015). Spatial variability of soil carbon stock in the Urucu river basin, Central Amazon-Brazil. *Science of the Total Environment*, *526*, 58-69. https://doi.org/10.1016/j.scitotenv.2015.03.121

Chauvel, A., Lucas, Y., & Boulet, R. (1987). On the genesis of the soil mantle of the region of Manaus, Central Amazonia, Brazil. *Experientia*, *43*(3), 234-241. https://doi.org/10.1007/BF01945546

Contreras, M., Aracena, P., & Chung, W. (2012). Improving accuracy in earthwork volume estimation for proposed forest roads using a high-resolution digital elevation model. *Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering*, *33*(1), 125-142. Recuperado de: http://www.crojfe.com/site/assets/files/3760/12contreras.pdf.

Corvalan, C., Hales, S., McMichael, A. (2005). *Ecosystems and Human Well-being: Health Synthesis: A Report of the Millennium Ecosystem Assessment*. Geneva: World Health Organization.

Costa Filho, P. P., & da COSTA, H. B. (1980). Construção de estradas florestais e transporte florestal rodoviário na região amazônica. *Embrapa Amazônia Oriental-Circular Técnica, 6. Recuperado de: https://www.embrapa.br/busca-de-publicacoes/-/publicacao/376759/construcao-de-estradas-florestais-e-transporte-florestal-rodoviario-na-regiao-amazonica*.

Craven, M., & Wing, M. G. (2014). Applying airborne LiDAR for forested road geomatics. *Scandinavian Journal of Forest Research*, *29*(2), 174-182. https://doi.org/10.1080/02827581.2014.881546

D'amours, S., Rönnqvist, M., & Weintraub, A. (2008). Using operational research for supply chain planning in the forest products industry. *INFOR: information systems and operational research*, *46*(4), 265-281. https://doi.org/10.3138/infor.46.4.265

d'Oliveira, M. V., Reutebuch, S. E., McGaughey, R. J., & Andersen, H. E. (2012). Estimating forest biomass and identifying low-intensity logging areas using airborne scanning lidar in Antimary State Forest, Acre State, Western Brazilian Amazon. *Remote Sensing of Environment*, *124*, 479-491. https://doi.org/10.1016/j.rse.2012.05.014

da Rocha, E. S., de Barros, P. L. C., & de Nazaré Maciel, M. (2007). Avaliação da densidade ótima de estradas florestais em dois sistemas de exploração florestal no Estado do Pará. *Revista de Ciências Agrárias*, *47*(1), 49-58. Recuperado de: http://periodicos.ufra.edu.br/index.php/ajaes/article/view/193.

da Silva Seabra, V., Cruz, C.M. (2014). Uso do sensoriamento remoto na avaliação de alterações dos estados dinâmicos da paisagem da bacia hidrográfica do Rio São João. *Revista Brasileira de Cartografia*, 66(2), 303-320. Recuperado de: https://seer.ufu.br/index.php/revistabrasileiracartografia/article/view/43914/23178.

de Carvalho, A. L., d'Oliveira, M. V. N., Putz, F. E., & de Oliveira, L. C. (2017). Natural regeneration of trees in selectively logged forest in western Amazonia. *Forest Ecology and Management*, *392*, 36-44. https://doi.org/10.1016/j.foreco.2017.02.049

de Morisson Valeriano, M., & de Fátima Rossetti, D. (2012). Topodata: Brazilian full coverage refinement of SRTM data. *Applied Geography*, *32*(2), 300-309. https://doi.org/10.1016/j.apgeog.2011.05.004

Demir, G. (2019). GIS-based landslide susceptibility mapping for a part of the North Anatolian Fault Zone between Reşadiye and Koyulhisar (Turkey). *Catena*, *183*, 104211. https://doi.org/10.1016/j.catena.2019.104211

dos Santos, R. C., Lima, M., da Silva Junior, C. A., & Battirola, L. D. (2019). Disordered conversion of vegetation committees connectivity between forest fragments in the Brazilian Legal Amazon. *Applied Geography*, *111*, 102082. https://doi.org/10.1016/j.apgeog.2019.102082

Eastaugh, C. S., & Molina, D. (2011). Forest road networks: metrics for coverage, efficiency and convenience. *Australian Forestry*, *74*(1), 54-61. https://doi.org/10.1080/00049158.2011.10676346

Eastman, J. R. (2003). *IDRISI Kilimanjaro: guide to GIS and image processing*. Worcester: Clark Labs.

Edwards, F. A., Finan, J., Graham, L. K., Larsen, T. H., Wilcove, D. S., Hsu, W. W., ... & Hamer, K. C. (2017). The impact of logging roads on dung beetle assemblages in a tropical rainforest reserve. *Biological conservation*, *205*, 85-92. https://doi.org/10.1016/j.biocon.2016.11.011

Remzi, E. K. E. R., & Aydin, A. (2014). Assessment of forest road conditions in terms of landslide susceptibility: a case study in Yığılca Forest Directorate (Turkey). *Turkish Journal of Agriculture and Forestry*, *38*(2), 281-290. https://doi.org/10.3906/tar-1303-12

Emmert, F. (2014). *Combinação de dados de campo e métodos computacionais para o planejamento da exploração florestal na Amazônia* (Tese de Doutorado) – Departamento de

Engenharia Florestal, Universidade de Brasília, Brasília. Recuperado de: https://repositorio.unb.br/handle/10482/17341.

Enache, A., Ciobanu, V. D., Kühmaier, M., & Stampfer, K. (2013). An integrative decision support tool for assessing forest road options in a mountainous region in Romania. *Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering*, *34*(1), 43-60. Recuperado de: http://www.crojfe.com/site/assets/files/3942/enache_43-60.pdf.

Erdaş, O. (2008). Transport Tekniği. KSÜ Rektörlüğü, Kahramanmaraş, Yayın (130/20).

Eskandari, S., & Hosseini, S. A. (2013). Assessment of Drainage System Standards of Forest Roads in Iran Using GIS. *Polish Journal of Environmental Studies*, *22*(3), 675-682. http://www.pjoes.com/Assessment-of-Drainage-System-Standards-r-nof-Forest-Roads-in-Iran-Using-GIS,89021,0,2.html.

Espada, A., Pires, I., Lentini, M., & Bittencourt, P. (2013). *Manejo Florestal e Exploração de Impacto Reduzido em Florestas Naturais de Produção da Amazônia*. Belém: IFT. Recuperado de: http://ift.org.br/wp-content/uploads/2014/11/Informativo-T%C3%A9cnico-1.pdf.

Espírito-Santo, F. D. B., Santos, J. R. D., & Silva, P. G. D. (2004). Técnicas de processamento de imagens e de análise espacial para estudo de áreas florestais sob a exploração madeireira. *Revista Árvore*, *28*(5), 699-706. https://doi.org/10.1590/S0100-67622004000500009

Food and Agriculture Organization of the United Nations (FAO) (1974). *Logging and log transport in tropical high forest: a manual on production and costs*. Roma: FAO.

Figueiredo, E. O. (2008). *MODEFLORA: Modelo Digital de Exploração Florestal*. Rio Branco: Embrapa Acre. Recuperado de: https://www.embrapa.br/busca-de-publicacoes/-/publicacao/631386/modeflora-modelo-digital-de-exploracao-florestal.

Figueiredo, E.O., Braz, E.M., Oliveira, M.V.N. (2007). Manejo de precisão em florestas tropicais: Modelo digital de exploração florestal. Rio Branco: Embrapa Acre. Recuperado de: https://www.embrapa.br/busca-de-publicacoes/-/publicacao/501879/manejo-de-precisao-em-florestas-tropicais-modelo-digital-de-exploracao-florestal.

Garcia, A. S., de F. N. Vilela, V. M., Rizzo, R., West, P., Gerber, J. S., Engstrom, P. M., & Ballester, M. V. R. (2019). Assessing land use/cover dynamics and exploring drivers in the Amazon's arc of deforestation through a hierarchical, multi-scale and multi-temporal classification approach. *Remote Sensing Applications: Society and Environment*, *15*, 100233. https://doi.org/10.1016/j.rsase.2019.05.002

Ghaffariyan, M. R., Stampfer, K., & Sessions, J. (2009). Comparison of three methods to determine optimal road spacing for forwarder-type logging operations. *Journal of forest science*, *55*(9), 423-431. https://doi.org/10.17221/79/2008-JFS

Ghajar, I., Najafi, A., Karimimajd, A. M., Boston, K., & Ali Torabi, S. (2013). A program for cost estimation of forest road construction using engineer's method. *Forest science and technology*, *9*(3), 111-117. https://doi.org/10.1080/21580103.2012.759163

Grigolato, S., Mologni, O., & Cavalli, R. (2017). GIS applications in forest operations and road network planning: An overview over the last two decades. *Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering*, *38*(2), 175-186. Recuperado de: http://www.crojfe.com/site/assets/files/4078/grigolato.pdf.

Gromskaya, L. Y., & Simonenkov, M. V. (2016). Current status of modeling and optimization of forest roads. *Лесной журнал (Forestry journal),* 5(353), 108-122. https://doi.org/10.17238/issn0536-1036.2016.5.108

Guimaraes, A. F., de Souza, C. R., Rosa, C., dos Santos, J. P., Teixeira, L. A. F., Zanzini, L. P., ... & da Silva Zanzini, A. C. (2021). Small-scale environmental variations drive vegetation structure and diversity in Amazon riverine forests. *Flora*, *283*, 151916. https://doi.org/10.1016/j.flora.2021.151916

Haddad, N. M., Brudvig, L. A., Clobert, J., Davies, K. F., Gonzalez, A., Holt, R. D., ... & Townshend, J. R. (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science advances*, *1*(2), e1500052. https://doi.org/*10.1126/sciadv.1500052*

Havimo, M., Mönkönen, P., Lopatin, E., & Dahlin, B. (2017). Optimising forest road planning to maximise the mobilisation of wood biomass resources in Northwest Russia. *Biofuels*, *8*(4), 501-514. https://doi.org/10.1080/17597269.2017.1302664

Hayati, E., Abdi, E., Majnounian, B., & Makhdom, M. (2013a). Application of sensitivity analysis in forest road networks planning and assessment. *Journal of Agricultural Science and Technology*, *15*(4), 781-792. Recuperado de: https://jast.modares.ac.ir/article-23-3935-en.html.

Hayati, E., Majnounian, B., & Abdi, E. (2012). Qualitative evaluation and optimization of forest road network to minimize total costs and environmental impacts. *iForest-Biogeosciences and Forestry*, *5*(3), 121. https://doi.org/10.3832/ifor0610-009

Hayati, E., Majnounian, B., Abdi, E., Sessions, J., & Makhdoum, M. (2013b). An expert-based approach to forest road network planning by combining Delphi and spatial multi-criteria evaluation. *Environmental monitoring and assessment*, *185*(2), 1767-1776. https://doi.org/10.1007/s10661-012-2666-1

Heinrich, R. (1975). *Problems of forest road construction in tropical high forests.* Rome: FAO.

Holmes, T. P., Blate, G. M., Zweede, J. C., Pereira Jr, R., Barreto, P., Boltz, F., & Bauch, R. (2002). Financial and ecological indicators of reduced impact logging performance in the eastern Amazon. *Forest ecology and management*, *163*(1-3), 93-110. https://doi.org/10.1016/S0378-1127(01)00530-8

Hosseini, S. A., Mazrae, M. R., Lotfalian, M., & Parsakhoo, A. (2012). Designing an optimal forest road network by consideration of environmental impacts in GIS. *Journal of Environmental Engineering and Landscape Management*, *20*(1), 58-66. https://doi.org/10.3846/16486897.2012.662748

Hosseini, S. A. O., Gorgandipur, M., & Nikooy, M. (2018). Forest road network assessment using lookout points orienting in Hyrcanian forest using GIS-Short Communication. *Journal of Forest Science*, *64*(9), 402-408. https://doi.org/10.17221/45/2018-JFS

Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA) (2007). *Norma de execução, nº 1 de 24 abril de 2007*.

Instituto Brasileiro de Geografia e Estatística (IBGE). (2012). *Manual Técnico da Vegetação Brasileira*. 2º ed., p. 276. https://biblioteca.ibge.gov.br/visualizacao/livros/liv63011.pdf.

International Tropical Timber Organization (ITTO). (2019). *Biennial review and assessment of the world timber situation 2017-2018*.

International Tropical Timber Organization (ITTO). (2020). *Biennial review and assessment of the world timber situation 2019-2020*.

Irion, G. (1978). Soil infertility in the Amazonian rain forest. *Naturwissenschaften*, *65*(10), 515-519. https://doi.org/10.1007/BF00439791

Jaafari, A., Najafi, A., Rezaeian, J., Sattarian, A., & Ghajar, I. (2015). Planning road networks in landslide-prone areas: A case study from the northern forests of Iran. *Land Use Policy*, *47*, 198-208. https://doi.org/10.1016/j.landusepol.2015.04.010

Jourgholami, M., Abdi, E., & Chung, W. (2013). Decision making in forest road planning considering both skidding and road costs: a case study in the Hyrcanian Forest in Iran. *iForest-Biogeosciences and Forestry*, *6*(2), 59-64. https://doi.org/10.3832/efor0640-006

Jourgholami, M., & Majnounian, B. (2011). Harvesting systems in Hyrcanian forest, Iran; limitations and approaches. *Anais do International Symposium on Forestry Mechanisation (FORMEC)*, Graz, 44. pp. 1-9 Recuperado de: https://www.formec.org/images/proceedings/2011/formec2011_paper_jourgholami_majnounian.pdf.

Norizah, K., Mohd Hasmadi, I., & Kamaruzaman, J. K. (2014). Quantification of least cost path analysis for best forest road planning. *Malaysian Forester*, *77*(2), 101-110. Recuperado de: http://malaysianforester.my/forestry/journal.php.

Kazama, V. S., Dalla Corte, A. P., Robert, R. C. G., Sanquetta, C. R., Arce, J. E., Oliveira-Nascimento, K. A., & DeArmond, D. (2021). Global review on forest road optimization planning: Support for sustainable forest management in Amazonia. *Forest Ecology and Management*, *492*, 119159. https://doi.org/10.1016/j.foreco.2021.119159

Keller, G., Sherar, J., & Zweede, J. (2015). Overview of Amazon Basin Forest Roads Manual. *Transportation Research Record*, *2472*(1), 56-63. https://doi.org/10.3141/2472-07

Keller, G., & Sherar, J. (2003). *Engenharia de estradas de baixo volume: manual de campo para as melhores práticas de gestão*. Washington: USDA.

Kooch, Y., Moghimian, N., Wirth, S., & Haghverdi, K. (2020). Effects of shelterwood and single-tree cutting systems on topsoil quality and functions in northern Iranian forests. *Forest Ecology and Management*, *468*, 118188. https://doi.org/10.1016/j.foreco.2020.118188

Krč, J., & Beguš, J. (2013). Planning forest opening with forest roads. *Croatian Journal of Forest Engineering*, *34*(2), 217-228. Recuperado de: https://hrcak.srce.hr/116778.

Kühmaier, M., & Stampfer, K. (2010). Development of a multi-attribute spatial decision support system in selecting timber harvesting systems. *Croatian Journal of Forest Engineering*, *31*(2), 75-88. Recuperado de: https://hrcak.srce.hr/63719.

Lamprecht, H. (1990). *Silvicultura en los trópicos: los ecosistemas forestales en los bosques tropicales y sus especies arbóreas, posibilidades y métodos para un aprovechamiento sostenido*. Eschborn: GTZ.

Laschi, A., Foderi, C., Fabiano, F., Neri, F., Cambi, M., Mariotti, B., & Marchi, E. (2019). Forest road planning, construction and maintenance to improve forest fire fighting: a review. *Croatian Journal of Forest Engineering*, *40*(1), 207-219. Recuperado de: https://hrcak.srce.hr/217411.

Laschi, A., Neri, F., Brachetti Montorselli, N., & Marchi, E. (2016). A methodological approach exploiting modern techniques for forest road network planning. *Croatian Journal of Forest Engineering*, *37*(2), 319-331. Recuperado de: https://hrcak.srce.hr/173832.

Liampas, S. A., Stamatiou, C., & Drosos, V. (2019). Forest road network planning for biomass exploitation and fire preventions: a least cost path analysis. *Agricultural Engineering International: CIGR Journal*, *21*(4), 33-42. Recuperado de: https://cigrjournal.org/index.php/Ejounral/article/view/5385.

Lillesand, T., Kiefer, R. W., & Chipman, J. (2015). *Remote sensing and image interpretation*. John Wiley & Sons.

Lima, K. S., Meira Castro, A. C., Santos Baptista, J., & Silva, U. (2020). Wood-Logging Process Management in Eastern Amazonia (Brazil). *Sustainability*, *12*(18), 7571. https://doi.org/10.3390/su12187571

Lima, R. Y. M., & Azevedo-Ramos, C. (2020). Compliance of Brazilian forest concession system with international guidelines for tropical forests. *Forest Policy and Economics*, *119*, 102285. https://doi.org/10.1016/j.forpol.2020.102285

Ljubojević, D., Danilović, M., Marčeta, D., & Petković, V. (2018). Winching distance in function of the optimization of skid network. *South-east European forestry: SEEFOR*, *9*(2), 97-106. https://doi.org/10.15177/seefor.18-14

Machado, C. C., Garcia, A. R., Silva, E., & Fontes, A. M. (2003). Comparação de taxas de erosão em estradas florestais estimadas pelo modelo WEPP (Water Erosion Prediction Project) modificado em relação a medições experimentais. *Revista Árvore*, *27*, 295-300. https://doi.org/10.1590/S0100-67622003000300004

Martinhago, A. Z. (2012). *Otimização para alocação de pátios de estocagem para exploração de impacto reduzido na Amazônia brasileira* (Tese de Doutorado) – Departamento de Ciências Florestais, Universidade Federal de Lavras, Lavras. Recuperado de: http://repositorio.ufla.br/jspui/handle/1/422.

Jifroudi, H. R., Naghdi, R., Firozan, A., & Haghighi, M. (2009). The assigning of suitable model for valuation of effective factors in forest roads network planning (Shanderman Forest, Northern Iran). *Journal of Applied Sciences*, *9*(18), 3364-3370. https://doi.org/10.3923/jas.2009.3364.3370

Meignan, D., Frayret, J. M., Pesant, G., & Blouin, M. (2012). A heuristic approach to automated forest road location. *Canadian Journal of Forest Research*, *42*(12), 2130-2141. https://doi.org/10.1139/x2012-140

Hasmadi, I. M., Pakhriazad, H. Z., & Mohamad, F. S. (2010). Geographic information system-allocation model for forest path: a case study in Ayer Hitam Forest Reserve, Malaysia. *American Journal of applied sciences*, *7*(3), 376. https://doi.org/10.3844/ajassp.2010.376.380

Moher D., Liberati A., Tetzlaff J, Altman D. G., & The PRISMAGroup (2009) Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLoS Med* 6(7), e1000097. doi:10.1371/journal.pmed.1000097

Murray, A. T. (1998). Route planning for harvest site access. *Canadian Journal of Forest Research*, *28*(7), 1084-1087. https://doi.org/10.1139/x98-122

Najafi, A., & Richards, E. W. (2013). Designing a forest road network using mixed integer programming. *Croatian Journal of Forest Engineering*, *34*(1), 17-30. Recuperado de: https://hrcak.srce.hr/116726.

Nefeslioglu, H. A., Sezer, E. A., Gokceoglu, C., & Ayas, Z. (2013). A modified analytical hierarchy process (M-AHP) approach for decision support systems in natural hazard assessments. *Computers & Geosciences*, *59*, 1-8. https://doi.org/10.1016/j.cageo.2013.05.010

Nepstad, D., Schwartzman, S., Bamberger, B., Santilli, M., Ray, D., Schlesinger, P., ... & Rolla, A. (2006). Inhibition of Amazon deforestation and fire by parks and indigenous lands. *Conservation biology*, *20*(1), 65-73. https://doi.org/10.1111/j.1523-1739.2006.00351.x

Norizah, K., Mohd Hasmadi, I. (2012). Developing priorities and ranking for suitable forest road: Allocation using Analytic Hierarchy Process (AHP) in peninsular Malaysia. *Sains Malaysiana*, 41, 1177-1185. Recuperado de: https://www.ukm.my/jsm/pdf_files/SM-PDF-41-10-2012/01%20K.%20Norizah.pdf.

Parsakhoo, A. (2016). Metric measurements for optimization of forest road network alternatives in GIS-based programs. *Forest science and technology*, *12*(3), 153-161. https://doi.org/10.1080/21580103.2016.1141718

Parsakhoo, A., & Jajouzadeh, M. (2016). Determining an optimal path for forest road construction using Dijkstra's algorithm. *Journal of Forest Science*, *62*(6), 264-268. https://doi.org/10.17221/9/2016-JFS

Parsakhoo, A., & Lotfalian, M. (2017). Locating log depots and forest roads using a weighted-graph optimization algorithm. *Nova mehanizacija šumarstva: Časopis za teoriju i praksu šumarskoga inženjerstva*, *38*(1), 67-77. Recuperado de: https://hrcak.srce.hr/192256.

Pentek, T., Nevecerel, H., Ecimovic, T., Lepoglavec, K., Papa, I., & Tomasic, Z. (2014). Strategic planning of forest road network in Croatia - analysis of present situation as basis for future activities. *Nova mehanizacija sumarstva*, *35*, 63-79. Recuperado de: https://link.gale.com/apps/doc/A384209641/AONE?u=anon~c441485&sid=googleScholar&xid=bdfd86c7.

Petković, V., & Potočnik, I. (2018). Planning forest road network in natural forest areas: a case study in northern Bosnia and Herzegovina. *Croatian Journal of Forest Engineering*, *39*(1), 45-56. Recuperado de: https://hrcak.srce.hr/193550.

Picchio, R., Pignatti, G., Marchi, E., Latterini, F., Benanchi, M., Foderi, C., ... & Verani, S. (2018). The application of two approaches using GIS technology implementation in forest road network planning in an Italian mountain setting. *Forests*, *9*(5), 277. https://doi.org/10.3390/f9050277

Pourghasemi, H. R., Beheshtirad, M., & Pradhan, B. (2016). A comparative assessment of prediction capabilities of modified analytical hierarchy process (M-AHP) and Mamdani fuzzy logic models using Netcad-GIS for forest fire susceptibility mapping. *Geomatics, Natural Hazards and Risk*, *7*(2), 861-885. https://doi.org/10.1080/ 19475705.2014.984247

Rex, F. E., Dalla Corte, A. P., Debastiani, A. B., Kazama, V. S., & Sanquetta, C. R. (2018). Uso de dados LiDAR na estimativa de variáveis biofísica na Amazônia, sob diferentes resoluções espaciais. *Nativa*, *6*, 841-847. https://doi.org/10.31413/nativa.v6i0.6312

Rogers, L., & Schiess, P. (2001). Pegger & Roadview–a new GIS tool to assist engineers in operations planning. *Anais do The International Mountain Logging and Pacific Northwest Skyline Symposium.* Seattle, 11. pp. 177-182. Recuperado de: https://depts.washington.edu/sky2001/proceedings/papers/Rogers.pdf.

Rogers, L.W. (2005). *Automating contour-based route projection for preliminary forest road designs using GIS* (Dissertação de mestrado). University of Washington, Seattle. Recuperado de: http://www.ruraltech.org/pubs/theses/Lwrogers/lwrogers_ms_thesis.pdf.

Saaty, T. L. (1980). *The analytical hierarchy process: planning, priority setting, resource allocation*. New York, McGraw-Hill.

Santy, T. L. (1980). *The analytical hierarchy process: Planning, priority setting, resource allocation*. London: McGrawrHill International Book Co.

Saaty, T. L. (2005). *Theory and applications of the analytic network process: decision making with benefits, opportunities, costs, and risks*. Pittsburgh: RWS publications.

Sabogal, C., Pokorny, B., Silva, J.N.M., Carvalho, J.O.P., Zweede, J., Puerta, R. (2009). *Diretrizes técnicas de manejo para produção madeireira mecanizada em florestas de terra firme na Amazônia brasileira. Belém: Embrapa Amazônia Oriental*. Recuperado de: https://www.embrapa.br/busca-de-publicacoes/-/publicacao/853000/diretrizes-tecnicas-de-manejo-para-producao-madeireira-mecanizada-em-florestas-de-terra-firme-na-amazonia-brasileira.

Saito, M., Goshima, M., Aruga, K., Matsue, K., Shuin, Y., & Tasaka, T. (2013). Study of automatic forest road design model considering shallow landslides with LiDAR data of Funyu Experimental Forest. *Croatian Journal of Forest Engineering*, *34*(1), 1-15. Recuperado de: https://hrcak.srce.hr/116724.

Sales, A., Gonzáles, D. G. E., Martins, T. G. V., Silva, G. C. C., Spletozer, A. G., Telles, L. A. D. A., ... & Lorenzon, A. S. (2019). Optimization of Skid Trails and Log Yards on the Amazon Forest. *Forests*, *10*(3), 252. https://doi.org/10.3390/ f10030252

Santos, H. G., Carvalho Junior, W. D., Dart, R. D. O., Áglio, M. L. D., de Sousa, J. S., Pares, J. G., ... & de OLIVEIRA, A. P. (2011). *O novo mapa de solos do Brasil: legenda atualizada*. Rio de Janeiro: Embrapa Solos.

Sarp, G., & Duzgun, S. (2015). Morphometric evaluation of the Afşin-Elbistan lignite basin using kernel density estimation and Getis-Ord's statistics of DEM derived indices, SE Turkey. *Journal of Asian Earth Sciences*, *111*, 819-826. https://doi.org/10.1016/j.jseaes.2015.07.022

Schietti, J., Emilio, T., Rennó, C. D., Drucker, D. P., Costa, F. R., Nogueira, A., ... & Magnusson, W. E. (2014). Vertical distance from drainage drives floristic composition changes in an Amazonian rainforest. *Plant Ecology & Diversity*, *7*(1-2), 241-253. https://doi.org/10.1080/17550874.2013.783642

Schuh, M., Favarin, J. A. S., Marchesan, J., Alba, E., Berra, E. F., & Pereira, R. S. (2020). Machine learning and generalized linear model techniques to predict aboveground biomass in Amazon rainforest using LiDAR data. *Journal of Applied Remote Sensing*, *14*(3), 034518. https://doi.org/10.1117/1.jrs.14.034518

Serviço Florestal Brasileiro (SFB) (2016). *Relatório pós-exploratório: UMF III - Flona do Jamari - Upa 06 - 2016.* São Paulo: AMATA.

Serviço Florestal Brasileiro (SFB) (2017). *Plano Operacional Anual 07: UMF III - Flona do Jamari - Upa 14 - 2017/2018*. São Paulo: AMATA.

Sessions, J. (2007a). *Harvesting Operations in the Tropics*. New York: Springer.

Sessions, J. (2007b). *Forest road operations in the Tropics*. New York: Springer.

Sessions, J., Stewart, R., Anderson, P., & Tuor, B. (1986). Calculating the maximum grade a log truck can climb. *Western Journal of Applied Forestry*, *1*(2), 43-45. https://doi.org/10.1093/wjaf/1.2.43

Sessions, J., Wimer, J., Costales, F., & Wing, M. G. (2010). Engineering considerations in road assessment for biomass operations in steep terrain. *Western Journal of Applied Forestry*, *25*(3), 144-153. https://doi.org/10.1093/wjaf/25.3.144

Serviço Florestal Brasileiro (SFB). (2018*). Execução Técnica: Documentos*. Recuperado de: https://www.florestal.gov.br/documentos/concessoes-florestais/concessoes-florestais-florestas-sob-concessao/flona-do-jamari/.

Shirasawa, H., & Hasegawa, H. (2014). A comparative study of heuristic algorithms for the multiple target access problem. *Journal of forest research*, *19*(5), 437-449. https://doi.org/10.1007/s10310-013-0432-z

Silva, E. F. (2019). *Planejamento da exploração em florestas nativas manejadas da Amazônia por meio de pesquisa operacional* (Tese de Doutorado) – Centro de Ciências Agrárias e Engenharias, Universidade Federal do Espírito Santo, Jerônimo Monteiro. Recuperado de: https://cienciasflorestais.ufes.br/pt-br/pos-graduacao/PPGCFL/detalhes-da-tese?id=13691.

Silva, E. F., Da Silva, G. F., Orfanó Figueiredo, E., Breda Binoti, D. H., Ribeiro de Mendonça, A., Moreira Miquelino Eleto Torres, C., & Macedo Pezzopane, J. E. (2018). Allocation of storage yards in management plans in the Amazon by means of mathematical programming. *Forests*, *9*(3), 127. https://doi.org/10.3390/f9030127

Silva, E. F., da Silva, G. F., Figueiredo, E. O., de Mendonça, A. R., de Oliveira Santana, C. J., Fiedler, N. C., ... & Santos, J. S. (2020). Optimized forest planning: allocation of log storage yards in the Amazonian sustainable forest management area. *Forest Ecology and Management*, *472*, 118231. https://doi.org/10.1016/j.foreco.2020.118231

Silverman, B. W. (1986). *Density Estimation for Statistics and Data Analysis*. London: Chapman & Hall.

Siqueira-Gay, J., Sonter, L. J., & Sánchez, L. E. (2020). Exploring potential impacts of mining on forest loss and fragmentation within a biodiverse region of Brazil's northeastern Amazon. *Resources Policy*, *67*, 101662. https://doi.org/10.1016/j.resourpol.2020.101662

Sohrabi, H., Jourgholami, M., Jafari, M., Shabanian, N., Venanzi, R., Tavankar, F., & Picchio, R. (2020). Soil recovery assessment after timber harvesting based on the Sustainable Forest Operation (SFO) perspective in Iranian temperate forests. *Sustainability*, *12*(7), 2874. https://doi.org/10.3390/su12072874

Sombroek, W. (2000). Amazon landforms and soils in relation to biological diversity. *Acta Amazonica*, *30*, 81-100. https://doi.org/10.1590/1809-43922000301100

Souza A. L., Soares C. P. B. (2013). *Florestas nativas: estrutura, dinâmica e manejo*. Viçosa: Editora UFV.

Spadoni, G. L., Cavalli, A., Congedo, L., & Munafò, M. (2020). Analysis of Normalized Difference Vegetation Index (NDVI) multi-temporal series for the production of forest cartography. *Remote Sensing Applications: Society and Environment*, *20*, 100419. https://doi.org/10.1016/j.rsase.2020.100419

Superintendência do Desenvolvimento da Amazônia (SUDAM). (1978). *Estudo de viabilidade técnico econômica da exploração mecanizada em floresta da terra firme, região de Curuá-Una. Belém: SUDAM/IBDF/PRODEPEF.*

Tampekis, S., Sakellariou, S., Samara, F., Sfougaris, A., Jaeger, D., & Christopoulou, O. (2015). Mapping the optimal forest road network based on the multicriteria evaluation technique: the case study of Mediterranean Island of Thassos in Greece. *Environmental monitoring and assessment*, *187*(11), 1-17. https://doi.org/10.1007/s10661-015-4876-9

Tavankar, F., Bonyad, A. E., & Majnounian, B. (2015). Affective factors on residual tree damage during selection cutting and cable-skidder logging in the Caspian forests, Northern Iran. *Ecological Engineering*, *83*, 505-512. https://doi.org/10.1016/j.ecoleng.2015.07.018

ter Steege, H., Pitman, N. C., Sabatier, D., Baraloto, C., Salomão, R. P., Guevara, J. E., ... & Silman, M. R. (2013). Hyperdominance in the Amazonian tree flora. *Science*, *342*(6156), 1243092. https://doi.org/10.1126/science.1243092

Turk, Y. (2019). Forest Road Design with Cad Software: A Case Study in the Western Black Sea Region of Turkey. *Fresenius Environmental Bulletin*, *28*(3), 1743-1751.

Vale Júnior, J. F., de Souza, M. I. L., Nascimento, P. P. R., & de Souza Cruz, D. L. (2011). Solos da Amazônia: etnopedologia e desenvolvimento sustentável. *Revista Agro@mbiente On-line*, *5*(2), 158-165. https://doi.org/10.18227/1982-8470ragro.v5i2.562

Vieira, L. N., Rogalski, M., Faoro, H., Fraga, H. P. F., Anjos, K. G., Picchi, G. F. A., Nodari, R. O., Pedrosa, F. O., Souza, E. M., & Guerra, M. P. (2016). The plastome sequence of the endemic Amazonian conifer, Retrophyllum piresii (Silba) CN Page, reveals different recombination events and plastome isoforms. *Tree Genetics & Genomes*, *12*(1), 1-11. https://doi.org/10.1007/s11295-016-0968-0

Walker, R., Arima, E., Messina, J., Soares-Filho, B., Perz, S., Vergara, D., Sales, M., Pereira, R., & Castro, W. (2013). Modeling spatial decisions with graph theory: logging roads and forest fragmentation in the Brazilian Amazon. *Ecological applications*, *23*(1), 239-254. https://doi.org/10.1890/11-1800.1

Yilmaz, I., & Keskin, I. (2009). GIS based statistical and physical approaches to landslide susceptibility mapping (Sebinkarahisar, Turkey). *Bulletin of Engineering Geology and the Environment*, *68*(4), 459-471. https://doi.org/10.1007/s10064-009-0188-z

Yolasigmaz, H. A., & Güner, S. (2016). The process of silviculture planning in Turkey: Hisar case study. *Šumarski list*, *140*(9-10), 503-514. Recuperado de: https://hrcak.srce.hr/168141.

Yoshida, M., Sakurai, R., & Sakai, H. (2019). Forest road planning using precision geographic data under climate change. *International Journal of Forest Engineering*, *30*(3), 219-227. https://doi. org/10.1080/14942119.2018.1498687

Zakowska, L. (1999). Road curve evaluation based on road view perception study. *Transportation research record*, *1689*(1), 68-72. https://doi.org/10.3141/1689-10

Zhao, M., Yang, J., Zhao, N., Liu, L., Ling, D. U., Xiao, X., Yue, T., & Wilson, J. P. (2021). Spatially explicit changes in forest biomass carbon of China over the past 4 decades: Coupling long-term inventory and remote sensing data. *Journal of Cleaner Production*, *316*, 128274. https://doi.org/10.1016/j.jclepro.2021.128274

Zupic, I., & Čater, T. (2015). Bibliometric methods in management and organization. *Organizational research methods*, *18*(3), 429-472. https://doi.org/10.1177/1094428114562629