Optimization of forest harvest scheduling at the operational level

by

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Abstract

Forest harvesting consists of multiple sequential activities to convert trees into logs ready for delivery to mills: felling, processing, yarding and loading. The forest harvesting cost contributes significantly to the delivered cost of logs. Therefore, it is important to optimize the schedule of forest harvesting activities to minimize costs. Previous studies have developed mathematical programming models to optimize the forest harvesting scheduling at the operational level. However, these studies did not consider the precedence relationship between forest harvesting activities, multiple machine assignment decisions, and the use of multi-task machines. The goal of this dissertation is to optimize the scheduling of harvesting activities at the operational level considering the mentioned research gaps. To achieve this goal, three mathematical programming models are developed in this work.

In the first model, the precedence relationship between harvesting activities and the movement of individual machines is considered. In the second model, the multiple machine assignment decisions are incorporated in addition to those conditions considered in the first model. Also, the precedence relationship based on the slope of cut blocks is included in the second model. In the last model, the use of multi-task machines is incorporated in addition to other considerations in the second model. In this model, the scheduling of activities related to road construction within a cut block is also included.

All models determine the start time and end time of each harvesting activity at each cut block, and where the machine should move after completing its operation in one cut block. In addition, the second and third models also determine the number of machines to be assigned at each cut block for each activity. All the models are applied to the harvesting operations of a real case study in the coast of British Columbia. The results indicate that the harvesting cost from the models is (at most)

4.5% higher than that of the defined ideal cost benchmark. All the developed models can be easily applied to other cases and regions by modifying the sets of succeeding and preceding activities in the input data according to the requirement of the harvesting system.

Lay Summary

Forest harvesting consists of a sequence of activities that converts a stand of trees into logs. Forest harvesting costs impact the delivered cost of logs significantly. In this work, we develop mathematical programming models to optimize the scheduling of these activities, considering the sequential or precedence relationship between these activities, the movement of individual machines between cut blocks, and the use of machines that can perform multiple activities to minimize the total cost of forest harvesting. The models determine the start time and end time of each activity at each cut block, the number of machines to be assigned at each cut block for each activity, and where each machine should move after completing its operation in one cut block. The results are used to generate the schedule of each machine for each activity. The models are applied to the harvesting operations of a forest company in British Columbia, Canada.

Preface

All the research work presented in this dissertation including developing mathematical programming models, preparing data files, preparing graphs and analyzing the results were carried out by the author, Rohit Arora, during his PhD program. The work was conducted under the supervision of Dr. Taraneh Sowlati at the Industrial Engineering Research Group of the University of British Columbia, Vancouver, Canada.

The research gaps and methods to address those gaps were identified by me and Dr. Taraneh Sowlati. Dr. Sowlati also helped me in dissertation preparation with her feedback and valuable comments. Joel Mortyn provided comments and feedback to help us better understand the forest harvesting problem in the company, to obtain data and information, to develop more realistic models.

Parts of this dissertation are presented in the following publications.

- A version of Chapter 3 is published:
    - Arora R, Sowlati T, Mortyn J, Roeser D, Griess VC. 2022. Optimization of forest harvest scheduling at the operational level, considering precedence relationship among harvesting activities. International Journal of Forest Engineering.:1–12. https://doi.org/10.1080/14942119.2022.2085464

      I was the main author of this publication. I defined the problem, developed the mathematical model, analyzed the results and prepared the manuscript. Dr. Sowlati was the corresponding author; she helped with problem identification, developing the model, analyzing the results, and preparing and revising the manuscript. Joel

Mortyn helped with data collection, case study identification, model validation and manuscript revision. Dr. Roeser and Dr. Griess helped with manuscript revision.

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    I was the main author of this publication. I defined the problem, developed the mathematical model, analyzed the results and prepared the manuscript. Dr. Sowlati was the corresponding author; she helped with problem identification, developing the model, analyzing the results, and preparing and revising the manuscript. Joel Mortyn helped with data collection, case study identification, model validation and manuscript revision.
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  I was the main author of this publication. I defined the problem, developed the mathematical model, analyzed the results and prepared the manuscript. Dr. Sowlati was the corresponding author; she helped with problem identification, developing the model, analyzing the results, and preparing and revising the manuscript. Joel Mortyn helped with data collection, case study identification, model validation and manuscript revision.

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I want to specially thank my family for their immense love and support in all possible ways. My parents encouraged me to pursue my Ph.D. and supported me throughout my Ph.D. journey. I dedicate this dissertation to my parents.

To my parents

Chapter 1: Introduction

1.1 Background

The cost associated with providing sawmills with logs plays a significant role in the competitiveness of forest companies in the global market (Working Forest Staff 2020). The so called "delivered cost of logs" include the stumpage cost, harvesting cost, and transportation cost. The Global Timber and Sawmill Cost Benchmarking report released by Forest Economic Advisors (FEA) in 2019 highlighted the fact that regions with a low delivered cost of logs had a competitive advantage over regions with higher delivered cost of logs (Working Forest Staff 2020). At the global level, the delivered cost of logs has increased by 7% from 2016 to 2019. Meanwhile, for some countries such as Lithuania, Latvia, and some regions of Canada and Russia, the percentage of increase has been more than 20%. For instance, this cost has increased by almost 70% in the coastal region of British Columbia (BC), Canada, during the same period (Girvan and Taylor 2020). This increase in delivered cost has taken a toll on the export of industrial roundwood (saw logs, veneer logs, and pulpwood) from Canada. For instance, the export of coniferous industrial roundwood from Canada has decreased by almost 60% between 2016 and 2020, and the net export has decreased from 4 million m^3 to 1 million m^3 (UNECE/FAO 2021). Therefore, there is pressure on forest companies in the regions such as those in Canada to reduce the delivered cost of logs to remain competitive in the global market (Working Forest Staff 2020).

The harvesting cost is a main component of the delivered cost of logs. According to different studies (Visser 2010; Marques et al. 2014; Girvan and Taylor 2020), it accounts for 35-50% of the delivered cost of logs and has been identified as a factor that affects the competitiveness of the forest sector in BC (Competitiveness Agenda for British Columbia's Forest Sector 2016). Forest harvesting includes all the processes that are required to convert the stand of trees into industrial roundwood as per industrial requirements. The forest harvesting consists of following activities in British Columbia and the detailed description of activities is mentioned in the Appendix (MacDonald 1999; Schiess and Krogstad 2004):

- Felling – Trees are cut manually by a chain saw or mechanically by a machine such as a feller buncher or harvester.
- Processing – Cutting of trees into logs and removal of tops and branches as per the requirement of the industry.
- Yarding – Felled trees or logs are moved from the stump site to the landing zone or roadside using ground-based machines, cable-based machines, or aerial machines.
- Loading – Loading of logs to trucks by loaders for transportation to the mills or sort yards.

There is a precedence relationship between harvesting activities. For instance, processing cannot start before felling or loading cannot start before processing the felled trees. The precedence relationship or the sequence of activities depends on the harvesting system used in a region. There are two harvesting systems based on the form of timber during yarding: 1) full-tree and 2) manufactured log lengths (MacDonald 1999). In the full-tree system, no processing takes place at the felling site, and trees are yarded to the landing zone. In a manufactured log system, the processing of trees takes place at the stump site before being yarded to the landing zone. The manufactured log lengths system is divided into two sub-systems based on the length of logs. If the length of manufactured logs is between 12 and 25 m, then the system is known as the at-the-stump-processing system, and if the length of produced logs is between 5 and 8 m, then the system is known as cut to length system (MacDonald 1999). In both systems, logs are usually loaded into trucks using loaders at the landing zone or roadside (MacDonald 1999; Castro et al. 2016). In some cases, a road needs to be constructed within a cut block before starting the harvesting activities which results in extra activities such as felling of trees before the road construction in order to gain access to the cut block for road construction.

The forest harvesting has evolved from a low-productive manual labor system with basic tools to a highly productive mechanized operation with lower labor input (Visser 2010). As a result, in modern harvesting operations, the contribution of labor cost is less than 30% of the total cost of harvesting, and the remaining is machine-related costs (Visser 2010; Murray et al. 2022). One major component of the harvesting cost is the machine ownership cost, as machines for harvesting have high purchase costs. For instance, in a contractor survey done in 2018, about 80% of the harvesting contractors identified the cost of harvesting machinery as their highest challenge (Church 2018). In their study, Murray et al. (2022) reported that the machine ownership cost for different activities varied between 35 to 40% of the total cost. Therefore, some forest companies acquire multi-task machines to increase the productivity and utilization of machines to offset this high capital cost and consequently increase profitability. Also, most forest companies have a limited number of machines that need to be moved from one harvesting cut block to another during harvesting. This movement cost accounts for 6-10% of harvesting costs depending on the size of harvest areas and the distance between them (Väätäinen et al. 2006; Conrad 2014; Santos et al. 2019). To improve the utilization of machines, while considering the movement of machines between cut blocks and the assignment of harvesting crews, operational level plans are modeled and optimized (Karlsson et al. 2003; Victor and Cancela 2018; Santos et al. 2019).

Forest harvest planning problems at the operational level determine how harvesting activities should take place at each cut block and how resources should be allocated to achieve the goals of higher-level plans. In the literature, mathematical programming models where the objective function minimized the harvesting cost (Epstein et al. 2006; Santos et al. 2019), maximized the revenue (Vera et al. 2003; Legües et al. 2007), or minimized the movement cost of machines (Victor and Cancela 2018) have been developed to tackle this problem. Models have been developed for both single period (Vera et al. 2003; Epstein et al. 2006) and multi-period plans (Karlsson et al. 2003; Santos et al. 2019). The planning horizon of multi-period models varied from days (Epstein et al. 1999) to weeks (Santos et al. 2019). The main decisions involved in these studies were related to detailed scheduling (Corner and Foulds 2005; Santos et al. 2019), machine location (Vera et al. 2003; Epstein et al. 2006), machine sequencing (Karlsson et al. 2003; Victor and Cancela 2018), and bucking decisions (Epstein et al. 1999; Dems et al. 2017).

In some studies, a limited number of machines was assumed to be available for harvesting, and the movement of a group of machines (rather than individual ones) from one cut block to another was considered (Karlsson et al. 2003; Victor and Cancela 2018; Santos et al. 2019). The main decision in these studies was related to cut block sequencing for harvesting to reduce the movement cost. However, in a few studies, no movement of machines was considered at all and their aim was to determine where to locate machines to minimize the harvesting cost (Vera et al. 2003; Epstein et al. 2006; Legües et al. 2007). Similarly, some studies focused on a single harvesting activity (e.g., yarding or felling) (Epstein et al. 1999; Vera et al. 2003; Epstein et al. 2006), while in other studies the term harvesting was used without considering any particular activity (Karlsson et al. 2003; Santos et al. 2019). The proposed models were applied to real-world case studies (Santos et al. 2019) or on data sets (Vera et al. 2003; Victor and Cancela 2018). For solving these models, exact methods were used for small problems (Victor and Cancela 2018; Santos et al. 2019), while inexact methods such as heuristics and metaheuristics were used for large-sized and complex problems (Epstein et al. 2006; Legües et al. 2007). In all these studies, it was assumed that each machine was exclusively used for one harvesting activity.

A similar scheduling problem is faced by agricultural contractors, who move their machines between agricultural farms to perform harvesting. In the agricultural literature, mathematical models have been developed to optimize the scheduling, machine assignment, and machine movement decisions to minimize the total duration of harvesting (Basnet et al. 2006; Orfanou et al. 2013; Edwards et al. 2015; Guan et al. 2018). Similar to the studies in forestry, in all these studies, it was assumed that each machine was exclusively used for one harvesting activity.

Although many previous studies focused on operational level planning, some aspects of forest harvesting problems have not been addressed in the literature. Harvesting at the operational level includes many activities, and there is a precedence relationship between these activities. To the best of my knowledge, no study has considered this precedence relationship in the scheduling of harvesting activities for multiple cut blocks as these studies either focused on only one activity, such as yarding (Epstein et al. 2006), or used the general term harvesting (Santos et al. 2019). Studies at the operational level in forestry that involved the movement of machines (Karlsson et al. 2003; Victor and Cancela 2018; Santos et al. 2019) assumed that machines of all activities moved as a team from one cut block to another, therefore the movement of individual machines was not considered. Moreover, studies on machine assignment in forestry (Vera et al. 2003; Epstein et al. 2006) assumed that the number of machines to be allocated to each cut block was pre-defined, and the model did not prescribe the number of machines to be allocated to each cut block. In studies involving more than one harvest activity, e.g., Santos et al. (2019), it was assumed that each activity had an exclusive set of machines, but in reality, some machines, can be used for more than one activity. These multi-task machines were not considered in the literature. To overcome these challenges, models are developed in this research to minimize the harvesting cost for a real case study by considering the precedence relationship between harvesting activities, the movement of individual machines between cut blocks, the possibility of assigning multiple machines for each activity, and the use of multi-task machines.

1.2 Research Objectives

The overall goal of this work is to optimize the scheduling of forest harvesting at the operational level to minimize the total cost of harvesting The overall goal is achieved gradually through following objectives:

1. Optimize the forest harvest scheduling considering the precedence relationship between harvesting activities and movement of individual machines between the cut block.
    - To achieve this objective a mathematical programming model is developed for scheduling of harvesting activities taken into consideration the precedence relationship between activities and individual machine movement.
2. Evaluate the impact of multiple machine assignment to each cut block and the precedence relationship between activities based on the slope of the cut block on the forest harvest scheduling.
    - To achieve this objective the previous mathematical programming model is extended, and the results are compared with those from the single machine assignment model.
3. Evaluate the impact of using multi-task machines on forest harvest scheduling
    - To achieve this objective the previous mathematical programming model is extended to incorporate the use of multi-task machines and results are compared with those from the exclusive machines model.

1.3 Case Study

The case study for this work is a large integrated forest company that operates in the coast of British Columbia, Canada, and Washington State, United States. The forest company owns six sawmills, typically harvests 500–700 cut blocks annually and is licensed to harvest 6 million m^3 of timber annually. Out of these cut blocks, almost 50% are completely contracted out, and contractors are responsible for all harvesting operations from stump to dump. For the rest of the cut blocks, the forest company either performs the harvesting activities using its own machines or contracts out some of the harvesting activities. For this work, we are focusing on just over 100 cut blocks of the forest company in the Port Alberni region of British Columbia. The availability of cut blocks for harvesting depends on the time of year. For instance, higher elevation blocks are available only during the summer season.

In the forest company's cut blocks, both manual and mechanical felling takes place. Due to steep slopes and the large size of trees in the coastal region, the majority of felling (80%) is performed manually using chainsaws, with the remainder performed by a feller buncher. Trees that are felled manually are first processed at the stump site before being transported to the roadside. Trees that are felled mechanically are first ground yarded to the roadside and then processed using loaders with processor heads. In cut blocks with a slope ≤50%, the majority of felled trees are yarded by ground-based machines, mostly hoe chuckers (also known as shovel loggers in other regions). Around 30-40% of yarding in the case study area is performed by a ground-based system. In cut blocks with a slope>50%, most of the yarding is performed by cable yarders. Around 50-60% of yarding in the case study area is done by a cable-based system. If a cut block is not connected to the road network, a helicopter performs the yarding. Aerial-based systems are used for 5-10% of yarding in the case study area. Lastly, all logs are loaded into trucks at the roadside using hydraulic loaders and are sent to the sort yards for additional processing and sorting. In some cut blocks, the road has to be built before the start of all other harvesting activities. This results in some extra activities in those cut blocks which includes: manual or mechanical felling to gain access to the cut block, processing of felled trees, construction of the road and loading of the felled trees on the trucks.

The forest company has a limited number of machines for harvesting, and machines for each harvesting activity move from one cut block to another after the activity is done. Ground-based machines move on their own between cut blocks if the distance is less than one km. Otherwise a low-bed trailer is used for the movement of machines between the cut blocks. Some machines are used for multiple harvesting activities to improve the utilization of machines. For instance, when a hoe chucker moves to a cut block for ground yarding, after finishing ground yarding, it performs loading in the same cut block. This multi-activity use of machines also helps reduce the movement cost of machines. The other aspects of the harvesting operations in the forest company are mentioned below:

- At each cut block, multiple machines can be assigned for each harvesting activity. However, once a machine enters a cut block to start its operation, it typically does not leave until the activity is finished. As a result, all assigned machines for a harvesting activity at a cut block have the same end time for operations.
- The start time of operations of all machines used for a harvesting activity at a cut block may not be the same. Machines that arrive earlier can start their operations, and other machines can join them later. However, due to operational requirements for cable yarding, the start time of all assigned machines for cable yarding has to be the same.

- If an activity has two preceding activities, and the start time of the activity depends on the start time of the preceding activities, then the activity can start when either of the preceding activities starts. For instance, if in a cut block, both manual and mechanical felling take place for the road construction, then the road construction can start when either of the felling has started.
- The slope of cut blocks dictates the precedence relationship between harvesting activities. Some harvesting activities can co-occur in safe slope (=<50%) cut blocks. However, in an unsafe slope (>50%) cut blocks, an activity can only start after completing the preceding activity.
- Thirty nine out of 106 cut blocks in this study have a safe slope, and the rest have an unsafe slope.

The forest company uses different tools and systems for planning and decision making at different planning levels. Patchworks is used for strategic-level decisions. The forest company has also developed an optimization software for a planning horizon of 12-18 months. The software provides monthly decisions such as which cut blocks to harvest and what cutting program to run at each mill. However, there is a lack of integration between tools at different planning levels such as tactical and operational level. Furthermore, there is a lack of analytical models for some operational-level activities such as scheduling of harvesting activities. One of the most important short-term decisions that forest company faces is the scheduling of harvest activities. At present, decision-makers use their own knowledge and experience for scheduling of these activities and no other tool is used for planning of harvest scheduling. The forest company requires a tool that can support managers' decisions related to the scheduling of harvest activities taking into consideration the precedence relationship between activities, the availability of cut blocks and availability of machines.

This research aims to address this problem by developing an optimization model for scheduling the harvesting activities at the operational level. The model can provide a guideline to managers for scheduling of forest harvesting. The planning horizon of this model is 12 weeks, with weekly decisions. The model is developed based on a rolling horizon approach i.e., it can be executed for two consecutive planning horizons and the output of the current planning horizon will be used as the input for the next planning horizon.

1.4 Outline of the thesis

In addition to the current chapter, this dissertation consists of the following chapters:

- The studies on forest harvest scheduling at the tactical and operational levels and similar scheduling related studies in other fields are reviewed in Chapter 2.
- In chapter 3, a mathematical model is developed for detailed scheduling of harvesting considering precedence relationship between activities and the movement of individual machine between cut blocks. The model is applied to a real case study, results are analyzed and compared with ideal cases, and conclusions are derived.
- In Chapter 4, the model developed in Chapter 3 is modified to consider a precedence relationship based on the slope of cut blocks and multiple machine assignment for each activity in the detailed scheduling. The model is applied to a real case study, results are analyzed and compared with those of the previous model, and conclusions are derived.
- In Chapter 5, the model developed in Chapter 4 is modified to take into consideration multi-task machines and the construction of road within a cut block. The model is applied to a

real case study, results are analyzed and compared with those of pervious models, and conclusions are derived.

- Finally, Chapter 6 concludes the dissertation with a note on the strengths and limitations of this work and the direction for future research.

Chapter 2: Literature Review

2.1 Synopsis

This chapter reviews the previous studies that developed models to optimize forest harvest planning. The studies in forest harvest planning are divided based on the planning horizon. At the tactical level, forest harvesting decisions were integrated with wood flow and road construction decisions. At the operational level, detailed scheduling decisions were combined with machine movement and location decisions. Furthermore, similar optimization studies in other fields, such as agriculture and mining, are reviewed in this chapter. In forestry, the studies focused on economic objectives like minimizing the total cost or maximizing the revenue. In contrast, most studies in other sectors focused on minimizing the total time. For small-sized problems, exact methods were used, whereas for large-sized problems, meta-heuristics were used. In forestry, no study considered the precedence relationship between harvesting activities, multiple machine assignment decisions, and the use of multi-task machines. In the agricultural literature, the precedence relationship between activities and machine assignment decisions were included, however these studies did not consider any planning horizon and did not consider multi-task machines. In the mining literature, precedence relationships were included, but multiple machine assignment decisions and the use of multi-task machines were not considered.

2.2 Optimization models for forest harvest planning

In forest harvesting, hierarchical planning is used to simplify the planning process, and the problem is broken down into strategic, tactical, and operational planning levels (Diaz-balteiro and Mcdill 2014). Strategic plans are made for large-scale resource allocation and long terms. Production levels and broad objective targets set by strategic plans are implemented by lower-level plans (Boyland 2003). Tactical plans are medium-term plans and focus on intermediate-term goals. The planning horizon of tactical plans is between one to ten years (Boyland 2003). The lowest level of planning is the operational level, which details exactly how each activity will be carried out at each harvesting area (Boyland 2003). The studies at the tactical and operational levels are more relevant to this work and are reviewed in the following sections.

2.2.1 Optimization models at the tactical level

The main problem faced at the tactical level is to decide where to harvest and how much to cut in each planning period considering the minimum demand level for each product from the mills to minimize the total cost of harvesting and transportation. Other tactical level problems in forest harvesting consist of decisions related to which roads to construct and when to construct them. Traditionally forest harvest scheduling and road building were solved sequentially. However, few studies suggested that integrated models resulted in a lower cost than sequential ones (Diaz-balteiro and Mcdill 2014). This model formulation is also known as an integrated harvest road model.

Richards and Gunn (2000) and Naderializadeh and Crowe (2020) developed integrated harvest road model in their work. Richards and Gunn (2000) developed the model for a forest area in Nova Scotia, and their objective function was minimization of the volume loss cost due to suboptimal harvesting timing and road construction cost. The two decision variables in their work were: 1) which stands to harvest in each time period, and 2) which roads to construct in each time period. They included log flow, accessibility, adjacency, and green-up constraints. They solved this model using the Tabu search heuristic. They also analyzed the trade-off between the road construction cost and the cost of volume loss due to suboptimal timing of harvesting. In the trade-off results showed that spending in road construction decreased the cost of volume loss. However, after a certain value for road construction cost, the marginal improvement in the cost of volume loss became nearly zero. In this way, this analysis helped managers in decisions regarding the expenditure on road construction. Naderializadeh and Crowe (2020) developed a mathematical model to maximize the net profit, i.e., the difference between total revenues and total costs. The total cost included road construction cost and transportation cost. The authors included binary decision variables for harvesting and road construction, i.e., whether a stand was harvested in a time period or not and whether a road was constructed in a time period. The continuous decision variables were added for the flow of timber. Constraints were added to ensure stands were harvested only once during the planning horizon, the volume of timber harvested was lower than an upper bound, the flow balance between nodes, and that the road was built only once during the planning horizon. They also added adjacency constraints to prevent the harvesting of two adjacent stands. Additional logical constraints were added to ensure a road was built in periods prior to the flow of timber through that road. The model was executed using two data sets of Kenogami forests located in Canada. The model was solved using the CPLEX (CPLEX 2021) solver. The data sets included 707 and 900 stands, respectively. Naderializadeh et al. (2022) solved the same model using a metaheuristic algorithm.

Inventory decisions were combined with road construction decisions in the optimization model by Andalaft et al. (2003) . The planning horizon of the integrated model was 2 to 5 years with seasonal time steps. The authors defined the objective function as the maximization of the net profit. The total cost included the costs of harvesting, transportation, storage, and road building and upgrading. The authors added the inventory balance constraint, capacity constraint, and logical constraint (for example, flow-through an arc was not possible until the road was constructed for that arc). They used a Lagrangian relaxation approach to solve this problem. Henningsson et al. (2007) presented a similar model for the Swedish forest company Holmen, but they only considered road upgradation decisions in their work.

The characteristics of the harvesting crew and machines affect the performance and duration of harvesting operations at a cut block (Diaz-balteiro and Mcdill 2014). Therefore, the crew and machine assignment to each cut block is an important decision at the tactical level. In their work, crew assignment decisions were integrated with inventory and road maintenance decisions by Karlsson et al. (2004). The authors defined the objective function as the minimization of the total cost, including harvesting, transportation, road opening, and storage costs. The additional constraints added to the model were the storage balance constraint, storage capacity constraint, and logical constraint to make sure that at least one road was connected to the harvest area. The planning horizon of the model was one year with monthly time steps. They applied their model to a case study in Sweden. The model was solved with the help of CPLEX software (CPLEX 2021).

For integrated forest companies that own sawmills, significant gains can be achieved through an increase in fiber freshness because the old fiber is detrimental to sawmill performance (Beaudoin et al. 2007). Therefore, decreasing the time between harvesting and processing at the mill is important. To tackle this problem, a mathematical model was developed by Beaudoin et al. (2007) to integrate harvesting decisions and the mill anticipated production decisions, i.e., the volume of products made at the mill in each period of the study. In addition, the authors added additional constraints for the mill processing capacity such as how much processing could be done at the mill. They also considered uncertainty in their model and performed scenario analysis using the rule-based simulation. They developed a case based on data from a firm in Quebec, Canada, and used the CPLEX software for the solution (CPLEX 2021). The planning horizon of the problem was one year with monthly time steps, and their approach resulted in 8.8% more profit than that of the deterministic approach.

During harvesting, machines are moved between cut blocks. The machine movement is not a value-added activity and increases the harvesting costs (Diaz-balteiro and Mcdill 2014). Bredström et al. (2010) considered the movement of machines in their work. The authors combined harvest sequencing decisions with harvest scheduling decisions. The model assigned each machine to harvest areas and scheduled the movement of the machine between those harvest areas. The authors defined the objective function as the minimization of the total cost. The total cost included the cost of harvesting, the cost of movement, the daily travel time of the machine operator to the harvest area, and the penalty for not harvesting a harvest area. They had additional constraints related to the movement of machines such as a machine could not leave a node unless it had visited the node in the past. They solved this model using a two-phase approach. In the first phase, they assigned areas to each machine, and in the second phase, they generated a sequence for each machine according to the assignment in the first phase. They applied the model to a Swedish forestry company.

Frisk et al. (2016) addressed the tactical level harvest scheduling slightly differently. The authors divided the entire planning horizon of one year into two periods: 1) business periods, and 2) anticipation periods. They used daily time steps for the business period and monthly time steps for the anticipation period. They performed detailed scheduling for the business period only. They used the rolling horizon approach to solve this problem. The main decisions involved in their work were to determine the start time and the harvesting team for each harvest area, flow amount, and inventory levels. They defined the objective function as the maximization of revenues minus total cost. The main constraints in the model were the availability, capacity, demand, and flow constraints. They solved the full model using a solution approach based on the decomposition and aggregation techniques. They applied their model to two Swedish companies, and the results showed an 8.8% and 1.5% cost savings for each company, respectively. The summary of papers in forest harvesting at the tactical level is shown in Table 2-1.

Table 2-1 Summary of forest harvesting optimization studies at the tactical level

Reference	**Modelling approach and solution**	**Key decisions**	**Planning horizon**	**Volume availability**	**Assignment constraints**	**Flow balance constraints**	**Capacity constraints**	**Demand constraints**	**Logical constraints**	**Cost objective**	**Country**
Richards & Gunn (2000)	IP, metaheuristics	Road construction and harvesting	Not clearly mentioned	*	*					*	Canada
Andalaft et al. (2003)	MILP, exact	Road construction, harvesting, flow and inventory	2-5 years	*	*	*	*	*	*	*	Chile
Karlsson et al. (2004)	MILP, exact	Crew assignment, road maintenance, and harvesting	1 year	*	*	*	*	*	*	*	Sweden
Henningsson et al. (2007)	MILP, exact	Road upgradation, harvesting, and flow	10 years	*	*	*	*	*	*	*	Sweden
Beaudoin et al. (2007)	MILP, exact	Harvesting, flow, production, and inventory	1 year	*		*	*	*		*	Canada
Bredström et al. (2010)	IP, heuristics	Harvesting and harvest sequencing	1 year	*	*		*		*	*	Sweden
Frisk et al. (2016)	MILP, heuristics	Harvest scheduling, flow, and inventory	1 year	*	*	*	*	*		*	Sweden

Reference	Modelling approach and solution	Key decisions	Planning horizon	Volume availability	Assignment constraints	Flow balance constraints	Capacity constraints	Demand constraints	Logical constraints	Cost objective	Country
Naderializadeh and Crowe (2020)	MILP, exact	Road construction, harvesting and flow	Not clearly mentioned	*	*	*			*	*	Canada
Naderializadeh and Crowe (2022)	MILP, heuristics	Road construction, harvesting and flow	Not clearly mentioned	*	*	*			*	*	Canada

IP: Integer Programming MILP: Mix Integer Linear Programming

2.2.2 Optimization models at the operational level

At the operational level, forest harvest planning problems determine the specific courses of action and allocation of resources to achieve the tactical level goals, as tactical level models decide when and where harvesting activities should occur, but they do not prescribe how harvesting activities should take place. Operational-level planning models incorporate decisions on where to locate harvesting machinery, when and where the machine should move from one cut block, how to buck (or cross-cut) trees to obtain the required products by length and diameter, and detailed scheduling of harvesting activities.

The location of the harvesting machine is one of the most critical decisions in forest harvesting as it determines the landing zones. A set of stands can be harvested from each landing zone depending on the type of stand and type of machine. To address this issue, single-period mathematical models were developed by Epstein et al. (2006) and Vera et al. (2003). The common decisions involved in these papers were the selection of machine location, the amount of timber harvested from each stand, the amount of timber harvested by each location, road construction decisions, and timber flow decisions. The main constraints in these studies were timber flow constraints, availability constraints, machine assignment constraints to guarantee that only one type of machine can be assigned to a selected location, and logical constraints (for example, timber flow was possible between two nodes if roads linking those nodes were built).

Epstein et al. (2006) defined the objective function as minimizing the total cost. The total cost included machine fixed cost, and road construction, transportation, and harvesting costs. The authors added an additional constraint to ensure the entire forest was harvested. They used a heuristic approach to solve this model. Vera et al. (2003) defined the objective function as maximizing net revenues. The authors included demand constraints in their work. They used the Lagrangian relaxation and strengthening of the LP formulation approach for solving this model. They applied their model to two data sets. Legües et al. (2007) solved the same model using a Tabu search algorithm, which significantly reduced the computation time to get the similar results.

Previous studies on machine location assumed that there were enough machines and that each cut block could have its own machine. However, in most forest companies, the number of machines is limited, and the machine is moved from one cut block to another. In their work, machine movement decisions were integrated with crew assignment decisions by Karlsson et al. (2003). The authors defined the set of schedules for all harvesting crews. A harvesting crew comprised of a harvester, a forwarder, and two working groups. A schedule described areas to be harvested and the harvesting sequence during the planning period. The model selected the optimum schedule for each harvesting crew. The planning horizon of the model was 4 to 6 weeks with weekly time steps. The main decisions involved in their work included the selection of a schedule for each harvesting crew, flow decisions, and storage decisions. They defined the objective function as the minimization of the total cost. The total cost included the cost of schedules (cost of operations and cost of movements), road opening cost, transportation cost, and storage cost. They solved this model using CPLEX (CPLEX 2021). They applied their model to the case of a Swedish company, and the results indicated savings of about 2%. Victor and Cancela (2018) considered only machine movement costs in their work. The authors defined the objective function as the minimization of total machine movement cost. They developed the mathematical model based on Multi Depot Multiple Traveling Salesman Problem. The model was solved using the CPLEX software (CPLEX 2021). Both studies (Karlsson et al. 2003; Victor and Cancela 2018) assumed that the machines of all harvesting operations would move together from one cut block to another.

Another important decision at the operational level is the selection of bucking patterns. Bucking patterns define how a felled tree should be processed to obtain a set of products. The OPTICORT system has been used in the Chilean forest industry for harvesting and bucking decisions. The mathematical model embedded in the OPTICORT system was described by Epstein et al. (1999). The primary decision of the model was to determine the volume of timber harvested using each bucking pattern. Demand constraints, timber availability constraints, and machine availability constraints were included in the model. However, bucking patterns were generated manually for the system, which was not an easy task. To simplify this problem, Epstein et al. (1999) developed a column-generation approach to generate bucking patterns. The bucking patterns generation implemented within the LP formulation improved the solution. Also, they mentioned that the implementation of the OPTICORT system resulted in savings of about 5-8% in harvesting costs compared to traditional manual approach of scheduling. In their work, bucking decisions were combined with storage decisions by Dems et al. (2017). The main decisions involved in their work were related to the amount of harvesting that should be done using each bucking pattern and the amount of products that should be stored at the mill in each period. The time period of this model was one year with monthly time steps. The authors also included inventory capacity constraints in their model. The model was solved using the CPLEX software (CPLEX 2021).

Another area of research in forest planning at the operational level is the detailed scheduling of harvesting activities, i.e., determining the start time and end time of harvesting activities at each cut block. A mathematical model for the detailed scheduling of a single forest cut block was developed by Corner and Foulds (2005). The authors considered the precedence relationship between different harvesting activities and resource constraints in terms of the number of available workers in their study. They developed an integer programming model to solve the problem. The main objective of this study was to minimize the duration of harvesting the entire block. The model's key decisions were to determine the start time and end time of each harvesting activity in the cut block and the activity performed by each worker. The author added precedence relationship constraints in their work. They scheduled the harvesting activities in a 50-ha cut block in New Zealand involving nine workers and four harvesting operations.

The detailed scheduling problem for multiple cut blocks was tackled by Santos et al. (2019). Their mathematical models provided the start time and end time of harvesting at each cutting block. In their work, the authors integrated machine movement and detailed scheduling decisions. They assumed that machines of all harvesting activities would move together. They defined the set of machines as harvesting fronts, which included a feller buncher, a skidder, a forwarder, a loader, and a processor. The planning horizon of the model was 7-15 days with daily time steps. The primary decisions involved in their work were related to the start time of the harvesting front at a stand and the sequence of movement of the harvesting front from one stand to another. They added additional constraints to ensure that once a harvesting front started harvesting in a stand, it would operate on this same stand until the stand was completely harvested. To test their model, they constructed 13 problem instances with increasing levels of complexity. The number of cut blocks varied from 12 to 50, and the number of variables varied from 4,248 to 178,350 in those problem instances. They solved this model using GUROBI (GUROBI 2023). The processing time varied from 10 seconds to 16 hours. One of the findings of their work was that the transportation cost contributed more than 75% to the objective function, whereas the harvesting and movement costs contributed 12% and 11% to the objective function, respectively. The summary of papers in forest harvesting at the operational level is shown in Table 2-2.

Table 2-2 Summary of forest harvesting optimization studies at the operational level

Key Decisions	**Reference**	**Modelling approach and solution**	**Planning horizon**	**No partial harvesting**	**Volume availability**	**Inventory balance**	**Bucking constraints**	**Demand**	**Capacity constraint**	**Flow balance**	**Accessory constraint**	**Movement constraint**	**Assignment constraint**	**Precedence relationship**	**Cost objective**	**Minimize time objective**	**Country**
Bucking decisions	Epstein et al. (1999)	MILP, exact	3 months		*		*	*	*	*					*		Chile
	Dems et al., (2017)	MILP, exact	1 year	*	*	*	*		*						*		Canada
Machine location	Vera et al. (2003)	MILP, exact	Single period		*					*	*		*		*		NA
	Epstein et al. (2006)	MILP, heuristics	Single period	*	*					*	*		*		*		Chile
	Legües et al. (2007)	MILP, metaheuristics	Single period		*					*	*		*		*		NA
Machine movement	Karlsson et al. (2003)	MILP, exact	6 weeks		*	*		*	*		*		*		*		Sweden
Machine movement	Victor & Cancela, (2018)	IP, exact	Not clear					*				*	*		*		NA
Detailed scheduling	Corner & Foulds, (2005)	IP, exact	Not clear						*				*	*		*	New Zealand
	Santos et al. (2019)	IP, exact	6 weeks	*	*			*	*			*	*		*		Brazil

IP: Integer Programming MILP: Mix Integer Linear Programming

2.3 Optimization models for scheduling in other sectors

Agricultural contractors perform crop harvesting activities for farmers who do not have enough labor or machines (Guan et al. 2018). These contractors move their machines from farm to farm to perform crop harvesting activities. The most common problem these contractors encounter is the scheduling of machines for executing multiple activities in multiple farms (Edwards et al. 2015). To address this issue, a mathematical model was developed by Basnet et al. (2006) to schedule activities that were carried out by contractors at various farms. The authors assumed a precedence relationship between all activities with some time lags. Each activity could be performed with only one type of machine, but more than one machine could be used. As a result, duration of each activity depended on the number of machines assigned to it. The key decisions involved in their work were: 1) when to start and end each activity at each farm, 2) how many pieces of machines to be assigned to each farm for each activity, and 3) where each machine should move from the current farm. They defined the objective function as minimizing the time of the entire harvesting process. The main constraints included in their work were: precedence relationship constraints, machine movement constraints, and constraints for the start time and end time for each activity at each farm. They developed a heuristic solution based on Greedy and Tabu Search approaches to solve the model of relatively large dimensions. They tested their model on numerical data sets. A similar model was used by Orfanou et al. (2013) for scheduling the harvesting activities of biomass crops with the cost as an additional feature of the individual schedules which provided the decision maker the ability to assess the relationship and trade-off between cost and time. The authors applied this model to a real-life case study in Denmark which involved five farms and three activities. They created different scenarios with different combinations of available machines for each activity and compared their make-span time and costs.

One of the limitations of the mentioned studies was that they assumed any activity would not start on the farm until all assigned machines for that activity had arrived on that farm. This issue was addressed by Edwards et al. (2015). In their model, the authors assumed that a machine could start its operation on a farm without waiting for additional machines, but all machines would finish the operations together at a farm, i.e., the end time for all machines would be the same. They also considered the agricultural field readiness in their model and added constraints to ensure that a field was ready when an activity started on it. To solve this problem, the authors developed an algorithm known as the look-forward algorithm (LFA). They applied their model to a real-life case study involving five farms and three activities in England-Wales. They also tested their model on 18 numerical datasets ranging from 3 farms to 20 farms with 2 to 5 activities. They compared their results with the those of the Tabu Search algorithm and concluded that LFA could find the most optimal solution to the problem, while the Tabu search algorithm found a near-optimal solution. Guan et al. (2018) used a similar model in sugarcane farm scheduling with additional soft time window constraints, i.e., there was a penalty if an activity was not finished within time windows. The authors defined the objective function as a combination of minimization of the make-span, movement time, and delay time. They applied this model to a real-life case study in Japan involving 5 farms and 3 activities. To solve this model, they developed a solution approach by integrating the Simulated Annealing algorithm with the MIP solver of the GLPK (GLPK 2023).

The open-pit mine production scheduling at the operational level is similar to the forest harvest scheduling problem. The open-pit mine production involves processes such as drilling, blasting, and excavating with a precedence relationship between them. Kozan and Liu (2016) developed a mathematical model to optimize the schedule of these operations for an iron core mine in Australia. The objective function of this model was to minimize the total duration of all these operations at all mining jobs. The authors included constraints for precedence relationships and machine assignment in their model. The model was solved using the CPLEX (CPLEX 2021) solver. Kozan and Liu (2017) developed a heuristic approach to solve the same problem for large-sized problems.

2.4 Conclusions

Mathematical programming and optimization techniques have been used in scheduling of forest harvesting activities. At the tactical level, the planning horizon of forest harvesting studies varied from 1 year to 10 years with monthly or seasonal time steps. Most of the studies at the tactical level integrated harvesting decisions with the flow of timber decisions. Other studies at the tactical level included decisions on machine and crew assignment (Bredström et al. 2010; Frisk et al. 2016), inventory decisions (Andalaft et al. 2003), road construction decisions (Richards and Gunn 2000; Naderializadeh and Crowe 2020; Naderializadeh et al. 2022) and production decisions (Beaudoin et al. 2007) in their work.

At the operational level, the planning horizon of previous studies varied from few weeks to few months with daily or weekly time steps. Some studies did not consider the movement of machines in their work, and they integrated machine location decisions with harvesting decisions (Vera et al. 2003; Epstein et al. 2006; Legües et al. 2007). On the contrary, other studies included machine movement and harvesting decisions in their work (Karlsson et al. 2003; Victor and Cancela 2018; Santos et al. 2019). These studies assumed that machines of all harvesting activities move together as a team between cut blocks. Few studies included detailed scheduling decisions, i.e., determining the start time and end time of harvesting at each cut block in their work for single or multiple cut blocks (Corner and Foulds 2005; Santos et al. 2019). In most of these studies, 'harvesting' was used as a general term, and individual harvesting activities and their precedence relationship were not considered. Corner and Foulds (2005) considered individual activities, but they focused on harvest scheduling of a single cut block. In all the studies at the operational level, the decision on the number of machines or teams that should be assigned at each harvest area was not included. It was assumed that only one team or machine could be assigned. In all these studies, the utilization of machines that can perform multiple activities was not considered.

Similar optimization models have been developed for detailed scheduling in agriculture (Basnet et al. 2006; Orfanou et al. 2013; Edwards et al. 2015; Guan et al. 2018) and open-pit mining (Kozan and Liu 2016; Kozan and Liu 2017). All these studies considered the precedence relationship between activities, exclusive machines for each activity, and the movement of individual machines. The objective function of all these studies was to minimize the total time of completing harvesting, so they did not consider any planning horizon. In studies related to agricultural harvesting, decisions on multiple machine assignment were included, on the contrary, in open pit mining, it was assumed that only one machine could be assigned for each activity.

So far, no study in forestry has considered the movement of individual machines, the precedence relationship between harvesting activities for multiple cut blocks, the assignment of multiple machines for the same activity at each cut block, and the utilization of machines that can perform multiple activities for multiple cut blocks and multi periods. However, all these aspects apply to the practical operations of forest companies. Therefore, an optimization model should be developed considering these aspects of harvesting operations.

Chapter 3: Optimization of forest harvest scheduling at the operational level, considering precedence relationship among harvesting activities

3.1 Synopsis

The competitiveness of forest companies is strongly affected by the costs associated with getting the logs to the mills. As harvesting costs contribute significantly to this cost, mathematical programming models were developed to optimize the scheduling of harvest activities within and between cut blocks to reduce the overall cost. However, the precedence relationship between harvesting activities occurring concurrently across multiple cut blocks has not been considered in the existing literature. In this chapter, a mixed-integer linear programming model is developed to optimize the scheduling of harvesting activities, considering the precedence relationship among harvesting activities. The objective function of the model is to minimize the total cost. The total cost includes operating cost, idle time cost and movement cost of machines. The model determines the start time and end time of each harvesting activity at each cut block, considering the movement time of machines between cut blocks. The model is applied to the case of a large forest company in British Columbia, Canada. The model's harvesting cost is only 1.37% higher than the lowest possible harvesting cost. According to the results, 47 out of 134 machines are used for harvesting and only 3 assigned machines have an idle time. The detailed harvesting schedule is generated for each cut block and each machine based on the start time, the end time, and the operating time for each activity at each cut block.

3.2 Problem Formulation

A precedence relationship exists between the forest harvesting activities, i.e., some activities cannot start before starting and ending of some other activities. These relationships were not considered in the existing studies on the optimization of forest harvesting for multiple cut blocks. Also, in the operational-level studies, it was assumed that machines of all harvesting activities move together as a team between different cut blocks to complete harvesting. However, in many forest companies, machines for each harvesting activity move individually between different cut blocks. To address these gaps, a mathematical model is developed for the optimization of forest harvest scheduling, considering the precedence relationship between harvesting activities and the movement of the individual machine between cut blocks to minimize the total cost of harvesting. The developed model is applied to the harvesting operations of the forest company, which is introduced in section 1.3, to optimize the scheduling of the harvesting activities at the operational level for a planning horizon of 12 weeks.

3.3 Mathematical formulation

The problem is formulated as a mixed-integer linear programming model as it involves both continuous and integer decision variables. The model is developed based on a rolling horizon approach, which means it is executed after each planning horizon and the output of one planning horizon will be used as the input for next planning horizon.

Assumptions of the mathematical model are as follows:

- Roads are already constructed in all cut blocks.
- There are seven harvesting activities, and each activity uses exclusive machines. The list of activities and the number of machines are shown in Table 3-1.
- Cut block 0 is the virtual depot from where machines can move to any cut block and the travel time between the depot and cut blocks is zero.

- Manual felling and manual processing are conducted by the same person with the same chainsaw.
- A set of cut blocks is created for each harvesting activity because all activities may not be performed in all cut blocks. This set is further subdivided into two subsets. The first subset is the set of cut blocks in which the harvesting activity started in the previous planning horizon, but required some extra time after the previous planning horizon to be completely done. The second subset is the set of cut blocks in which harvesting activity will start in this planning horizon.
- For cable yarding, a machine refers to a team of a cable yarder and a loader for stacking.
- For ground yarding, stacking is performed by the hoe chucker itself.
- For aerial yarding, both yarding and loading take place simultaneously, so no separate loader is required for stacking.
- Only one machine can be assigned to each activity at each cut block.
- The precedence relationship for an activity is the same for all cut blocks irrespective of their slope. For instance, in all cut blocks, loading cannot start before the completion of ground yarding and cable yarding.

Table 3-1 Machines available for harvesting activities (Source: Oral communication with company)

Activity number	**Harvesting activity**	**Number of Machines**	**Number of cut blocks in which activity takes place**
1	Manual felling and processing	60	30
2	Mechanical felling	1	5
3	Ground yarding	21	23
4	Cable yarding	23	20
5	Aerial yarding	2	5
6	Mechanical processing	6	5
7	Loading	21	30

The following sections explain the different components of the mathematical programming model.

The sets, parameters and decision variables in the mathematical model are shown in Table 3-2.

Table 3-2 Model sets, indices, parameters, and decision variables

Sets	Description
I	Set of cut blocks
K	Set of harvesting activities
J	Set of machines
$I_k \subset I$	Set of cut blocks for activity *k*
$I_{kp} \subset I$	Set of cut blocks where activity *k* was started in the previous planning horizon
$I_{kn} \subset I$	Set of cut blocks where activity *k* can start in the current planning horizon
$J_k \subset J$	Set of machines for activity *k*
Indices	**Description**
$i \in I$	Represents current cut block
$i' \in I$	Represents previous cut block
$i^* \in I$	Represents next cut block
$k \in K$	Represents harvesting activity performed at the current cut block
$k^p \in K$	Represents preceding harvesting activity at the current cut block
$j \in J$	Represents machines
$j^p \in J$	Represents machine of preceding harvesting activity in cut block
Parameters	**Description**
α_{jik}	Time needed by machine *j* to perform activity *k* at cut block *i* (in weeks)
β_{jik}	Operating cost for machine *j* to perform activity *k* at cut block *i* (Can$/week)
$\gamma_{i'i}$	Distance between cut block *i'* and *i* (in km)
δ_k	Speed of movement of machines of activity *k* (km/week)
λ	Movement cost (Can$/km)
τ_{ik}	Penalty cost if activity *k* has not started during the planning horizon in cut block *i*
θ_{jik}	Cost for the extra time required after the planning horizon by machine *j* to perform activity *k* at cut block *i* (Can$/week)
η_j	Idle time cost for machine *j* (Can$/week)
π_j	Fixed cost if machine *j* is moved from the depot (Can$)
σ	Planning horizon (in weeks)
μ_{ik}	Minimum time lag required between activity *k* and the activity preceding activity *k* for cut block *i* (in weeks)
ϕ_{jik}	Binary parameter, equals 1 if machine *j* required extra time after the previous planning horizon to complete activity *k* at cut block *i*

ω_{jik}	Extra time required by machine j after the previous planning horizon to complete activity k at cut block i
M	A large number used in constraints involving binary decision variables
Decision Variables	**Description**
X_{jik}	Start time of machine j to perform activity k at cut block i
Y_{jik}	End time of machine j to perform activity k at cut block i
$Z_{ji'ik}$	Binary variable will take value 1 if machine j moves from cut block i' to i to perform harvesting activity k, otherwise it will be 0
U_{ik}	Binary variable will take value 1 if activity k has not started at cut block i during the planning horizon, otherwise it will be 0
V_{jik}	Extra time required after the planning horizon by machine j to perform activity k at cut block i
P_{jik}	Binary variable will take value 1 if machine j requires extra time after the planning horizon to perform activity k at cut block i
S_j	Start time of operation for machine j
E_j	End time of operation for machine j
IT_j	Idle time for machine j

3.3.1 Objective function

The objective function of the model is to minimize the total cost and is shown in equation (3.1). The components of the total cost are presented in equations (3.2) to (3.7).

Minimize (Total costs) = Minimize (Operating cost of machines + Movement cost of machines + Penalty cost for not performing an activity + Cost of operating after planning horizon + Cost of idle time of machines + Fixed cost of using machines) (3.1)

$$Operating\ cost\ of\ machines = \sum_{k\in K}\sum_{i\in I_k}\sum_{j\in J_k}\left(Y_{jik} - X_{jik} - V_{jik}\right) * \beta_{jik} \tag{3.2}$$

$$Movement\ cost\ of\ machines = \sum_{k\in K}\sum_{i,i'\in I_k, i'\neq i}\sum_{j\in J_k} Z_{ji'ik} * \gamma_{i'i} * \lambda \tag{3.3}$$

$$Penalty\ cost\ for\ not\ performing\ an\ activity = \sum_{k\in K}\sum_{i\in I_k} U_{ik} * \tau_{ik} \tag{3.4}$$

$$Cost\ of\ operating\ after\ planning\ horizon = \sum_{k\in K}\sum_{i\in I_k}\sum_{j\in J_k}(V_{jik}) * \theta_{jik} \tag{3.5}$$

$$Cost\ of\ idle\ time\ of\ machines = \sum_{j\in J} IT_j * \eta_j \tag{3.6}$$

$$Fixed\ cost\ of\ using\ machines = \sum_{k\in K}\sum_{j\in J_k}\sum_{i\in I_k} Z_{j0ik} * \pi_j \tag{3.7}$$

3.3.2 Constraints

In this section, constraints of the model are explained. They are presented by equations (3.8) - (3.25).

Constraint set (3.8) ensures that machine *j* can move from the depot to only one cut block to perform harvest activity *k*. In case machine *j* is not moved to any cut block during the entire planning horizon, then $\sum_{i \in I_k} Z_{j0ik}$ will remain 0.

$$\sum_{i \in I_k} Z_{j0ik} \leq 1, \ \forall \ j \in J_k, k \in K \tag{3.8}$$

Constraint set (3.9) is added to ensure that only one machine can arrive at cut block *i,* to perform activity *k*. In case activity *k* is not performed at cut block *i* during the entire planning horizon, then $\sum_{i' \in I_k+0, i' \neq i} \sum_{j \in J_k} Z_{ji'ik}$ will remain 0.

$$\sum_{i' \in I_k+0, i' \neq i} \sum_{j \in J_k} Z_{ji'ik} \leq 1, \forall \ i \in I_k, k \in K \tag{3.9}$$

Constraint set (3.10) ensures that machine *j* can only move from cut block *i* to cut block i^* to perform activity *k*, if it had already moved from cut block i' to cut block *i* before.

$$\sum_{i' \in I_k+0, i' \neq i} Z_{ji'ik} \ \geq \ \sum_{i^* \in I_k, i^* \neq i} Z_{jii^*k} \ , \forall \ j \in J_k, i \in I_k, k \in K \tag{3.10}$$

Constraint set (3.11) guarantees that machine *j* performing activity *k* at cut block *i* at the end of the previous planning horizon will move from depot to the same cut block at the start of the current planning horizon. In case machine *j* is working at a cut block at the end of the previous planning horizon, then ϕ_{jik} will be 1 and will force Z_{j0ik} to be 1 and X_{jik} to be zero.

$$X_{jik} \leq -M * \left(\phi_{jik} - Z_{j0ik}\right), \forall \ j \ \in J_k, i \in I_{kp}, k \in k \tag{3.11}$$

Constraint set (3.12) specifies that the start time of machine *j* for harvest activity *k* at cut block *i* is zero, if machine *j* has not moved to cut block *i*.

$$X_{jik} \leq M * \sum_{i' \in I_k+0, i' \neq i} Z_{ji'ik} \quad , \forall j \in J_k, i \in I_k, k \in K \qquad (3.12)$$

Constraint set (3.13) states that the start time of machine *j* at cut block *i* for activity *k* is greater than the end time of machine *j* for activity *k* at cut block i' plus the machine movement time between cut blocks *i* and i'. In case machine *j* does not move to cut block *i* then the right-hand side value will become negative and X_{jik} will become zero due to constraint set (3.12).

$$X_{jik} \geq \left(Y_{ji'k} + (\gamma_{i'i}/\delta_k)\right) - M(1 - Z_{ji'ik}) , \forall j \in J_k , i \in I_k, i' \in I_k + 0 , i' \neq i, k \in K \quad (3.13)$$

Constraint set (3.14) makes sure that if machine *j* requires extra time after the previous planning horizon to complete activity *k* at cut block *i*, then its end time is equal to the extra time required by machine *j* after the previous planning horizon to complete activity *k* at cut block *i*.

$$Y_{jik} = \omega_{jik} , \forall j \in J_k , \; k \in K , i \in \; I_{kp} \qquad (3.14)$$

Constraint set (3.15) ensures that in case machine *j* moves to cut block *i* to perform activity *k* during the planning horizon, then its end time is equal to the start time of machine *j* at cut block *i* plus the time needed by machine *j* to perform activity *k* at cut block *i*.

$$Y_{jik} = X_{jik} + \; \sum_{i' \in I_k+0, i' \neq i} Z_{ji'ik} \alpha_{jik} , \forall j \in J_k, k \in K , i \in I_{kn} \qquad (3.15)$$

Constraint set (3.16) indicates that the start time of machine *j* for activity *k* at cut block *i* is greater than the end time of activity k^p which precedes activity *k* at cut block *i* plus the minimum time required between activity *k* and k^p. In case two activities can start simultaneously then $Y_{j^p ik^p}$ can be replaced by $X_{j^p ik^p}$.

$X_{jik} \geq \left(\sum_{j^p \in J_{k^p}} Y_{j^p ik^p} + \mu_{ik}\right) - M * \left(1 - \sum_{i' \in I_k + 0, i' \neq i} Z_{ji'ik}\right) \quad , \forall\, i \in I_{kn}\, , k \in (3,4, \dots ,7), j \in J_k, k^p \in (K\ preceding\ k)$ (3.16)

Constraint set (3.17) guarantees that machine *j* can move to cut block *i* to perform activity *k* only if machine j^p moved to cut block *i* to perform activity k^p in the past. In case no machine j^p has moved to cut block *i* to perform activity k^p, then $\sum_{i' \in I_{k^p} + 0, i' \neq I} \sum_{j^p \in J_{k^p}} Z_{j^p i' ik^p}$ will become 0 and it will force $\sum_{i' \in I_k + 0, i' \neq i} Z_{ji'ik}$ to remain 0.

$\sum_{i' \in I_k + 0, i' \neq i} Z_{ji'ik} \leq \sum_{i' \in I_{k^p} + 0, i' \neq i} \sum_{j^p \in J_{k^p}} Z_{j^p i' ik^p} \quad , \forall\, j \in J_k, i \in I_{kn}, k \in (3,4, \dots ,7), k^p \in (K\ preceding\ k)$ (3.17)

Constraint set (3.18) states that the start time of machine *j* at cut block *i* to perform activity *k* is less than or equal to the planning horizon of the problem. In case an activity does not start in this planning horizon, then its start time will be zero as per constraint (3.12).

$X_{jik} \leq \sigma \quad , \forall\, j \in J_k, i \in I_k, k \in K$ (3.18)

Constraint set (3.19) ensures that if machine *j* has not moved to cut block *i* to perform activity *k* during the planning horizon, then the binary variable associated with the penalty of not starting activity *k* at cut block *i* will become 1.

$U_{ik} = 1 - \sum_{i' \in I_k + 0, i' \neq i} \sum_{j \in J_k} Z_{ji'ik} \quad , \forall\, i \in I_k, k \in K$ (3.19)

Constraint set (3.20) calculates the extra time required by machine *j* to perform activity *k* at cut block *i* after the planning horizon σ. In case the end time of machine *j* to perform activity *k* at cut block *i* is less than the planning horizon, then $(Y_{jik} - \sigma)$ will become negative, and V_{jik} will take the value of 0.

$V_{jik} \geq Y_{jik} - \sigma \quad , \forall\, j \in J_k, i \in I_k, k \in K$ (3.20)

Constraint set (3.21) and (3.22) calculates the value of P_{jik} which will take the value of one, if machine *j* requires extra time after the planning horizon to perform activity k at cut block i. . In case the value of V_{jik} is 0, then equation (3.22) will force P_{jik} to be 0.

$$V_{jik} \leq M * P_{jik} \quad , \forall\, j \in J_k, i \in I_k, k \in K \tag{3.21}$$

$$M * V_{jik} \geq P_{jik} \quad , \forall\, j \in J_k, i \in I_k, k \in K \tag{3.22}$$

Constraint set (3.23) determines the start time of operations of machine *j*. In case machine *j* moves from the depot to cut block *i* to perform activity *k*, then the value of S_j will be less than or equal to the start time of machine *j* to perform activity *k* at cut block *i*.

$$S_j \leq X_{jik} + M * \left(1 - Z_{j0ik}\right), \forall\, i \in I_k, k \in K, j \in J_k \tag{3.23}$$

Constraint set (3.24) determines the end time of operations of machine *j*. The end time of operations of machine *j* will be greater than or equal to the ending time of machine *j* to perform activity *k* at the last cut block it performed its operation in. In case the machine has not moved to any cut block, then the right-hand side value will become 0, and although E_j can take any value, the objective function of minimizing cost will force it to be 0.

$$E_j \geq Y_{jik}, \forall\, i \in I_k, k \in K, j \in J_k \tag{3.24}$$

Constraint set (3.25) will ensure the start time of machine *j* remains zero if it has not moved from the depot.

$$S_j \leq M * \sum_{i \in I_k} Z_{j0ik} \quad , \forall\; k \in K, j \in J_k \tag{3.25}$$

Constraint set (3.26) calculates the idle time of machine *j*. For machine *j*, idle time IT_j will be equal to the difference between the total time when the machine was in operation given by $\left(E_j - S_j\right)$ and the actual operating time of the machine given by $\sum_{k\in K}\sum_{i\in I_k}(Y_{jik}-X_{jik})$ plus the total machine movement time given by $\sum_{k\in K}\sum_{i'\in I_k+0}\sum_{i\in I_k}Z_{ji'ik}*\left(\frac{\gamma_{i'i}}{\delta_k}\right)$

$$IT_j=(E_j-S_j)-\sum_{k\in K}\sum_{i\in I_k}(Y_{jik}-X_{jik})-\sum_{k\in K}\sum_{i'\in I_k+0}\sum_{i\in I_k}Z_{ji'ik}*\left(\frac{\gamma_{i'i}}{\delta_k}\right),\ j\in J \tag{3.26}$$

Equations (3.26) and (3.27) show the range of decision variables.

$$X_{jik},Y_{jik},V_{jik},S_j,E_j,IT_j\in R^+ \tag{3.27}$$

$$U_{ik},Z_{ji'ik},P_{jik}\in\{0,1\} \tag{3.28}$$

3.3.3 Input parameters

The information related to the machines' operating cost and productivity, the size of cut blocks, the volume of standing timber at each cut block, and distances between the cut blocks were obtained from the forest company. Cut blocks range in size from 0.9 ha to 54 ha. The data regarding the cost and productivity of machines for different harvesting activities were provided in Can$/hr and m^3/hr, respectively. The productivity and cost of machines were converted into Can$/week and m^3/week using the weekly productive hours of each machine. The productivity of each machine varies based on the type of cut block, i.e., old growth and second growth. The operating cost of machines includes labour cost, fuel cost and maintenance cost. The capital cost of machines is not included in the operating cost as it is considered in strategic and tactical level planning tools used by the forest company for harvest scheduling. The operating time for each machine in a cut block is calculated based on the cut block's volume and the machine's productivity.

For the case study, no data were provided regarding the demand of logs by the forest company. Hence, to ensure that the maximum harvesting will occur, a penalty cost is added to the mathematical model. The penalty cost occurs when a harvesting activity at a cut block did not start within the planning horizon. The value of the penalty cost of an activity at a cut block is assumed to be higher than the cost of performing that activity by the highest operating cost machine to ensure that, if feasible, the model always opts for harvesting. For instance, in cut block C5, the cost of cable yarding by the highest operating cost machine is 40,000 Can$. Therefore, the penalty cost of not starting the cable yarding in this cut block is assumed to be 52,000 Can$. A harvesting activity can either finish in the current planning horizon or continue in the next planning horizon. However, to ensure that maximum activities are finished within the current planning horizon, we assumed that the cost of extra time of performing harvesting in the next planning horizon is 100 Can$/week higher than the operating cost of the machine in the current planning horizon.

Additionally, the forest company would like an estimate of the number of machines sufficient to perform harvesting. Therefore, a fixed operating cost is added to the model. This cost occurs whenever a machine leaves the depot and starts its operations. Therefore, the model will strive to use fewer machines to complete harvesting due to this fixed operating cost and can provide a good estimation of the number of machines sufficient for harvesting. The nominal fixed cost of machines that were applied for each harvesting activity is shown in Table 3-3. The idle time cost for a machine is assumed to be 50% of the operating cost. The cost of moving machines between cut blocks on low bed trailers is 20 Can$/km.

Table 3-3 Fixed operating cost of using machines for each harvesting activity

Harvesting activity	**Fixed operating cost (Can$/machine)**
Manual felling and processing	10
Mechanical felling	5,000
Ground yarding	5,000
Cable yarding	5,000
Aerial yarding	10,000

Mechanical processing	5,000
Loading	5,000

3.3.4 Execution of the model

The mixed-integer linear programming (MILP) model was built and executed using the AIMMS 4.77 software (AIMMS 2022). The model was executed on a desktop computer with Intel ® core ™ i7-6700 CPU @ 3.41 GHz processor and 16.0 GB RAM. The model was solved using the CPLEX solver (CPLEX 2021). CPLEX uses a branch and bound algorithm to solve the MILP model. The model run involved 30 cut blocks and 134 machines. The model included 8,423 non-negative continuous decision variables, 76,538 integer decision variables, and 99,581 constraints.

Three different cases are considered to assess the results of the model in terms of operating cost and penalty cost as there is no information regarding these costs or any similar study in the past to compare the results. The three cases are explained below:

The ideal operating cost case: The forest company has a number of machines for each harvesting activity, as shown in Table 3-1. However, the machines are not identical and have different operating costs (Can\$/m^3). In the ideal case, it is assumed that the operating cost (Can\$/m^3) of all the machines for each harvesting activity is equal to the lowest operating cost (Can\$/m^3) of the machines for that harvesting activity. This case provides the lowest possible operating cost of harvesting performed during the planning horizon, if all the machines had the lowest cost. It can be a good benchmark for comparing the results.

The average operating cost case: In this case, it is assumed that operating costs (Can\$/m^3) of all the machines for each harvesting activity is equal to the average operating cost (Can\$/m^3) of machines that are available for that harvesting activity. This case provides the average operating cost of harvesting performed during the planning horizon, if all the machines had the average cost.

The ideal penalty cost case: In this case, it is assumed that each activity can start at the earliest time at each cut block. In other words, machines with the highest productivity are always available at the cut blocks, and there is no delay in harvesting due to unavailability of machines. This case provides the maximum number of harvesting activities that can start in the planning horizon or the lowest value of penalty cost.

3.4 Results

The AIMMS software found the integer solution after about 4 million iterations in 3.5 hours with an optimality gap of 2.97%. In the best integer solution, only 47 out of 134 machines are used for harvesting. Only 3 out of 47 assigned machines have an idle time. The total cost for the best integer solution calculated by AIMMS is 9,024,876 Can$. All components of the objective function are shown in Table 3-4.

Table 3-4 Components of the objective function in Can$

Cost component	**Value (Can$)**	**Percentage of total (%)**
Operating cost of machines	2,292,247	25.40
Movement cost of machines	26,642	0.30
Penalty cost for not performing an activity	5,772,478	63.96
Cost of operating after the planning horizon	832,018	9.22
Cost of idle time of machines	1,211	0.01
Fixed cost of using machines	100,280	1.11
Total cost	**9,024,876**	**100**

Table 3-5 shows the total operating cost, volume, and the operating cost per volume for each harvesting activity. The manual felling and processing have the highest operating cost because they have started in all cut blocks within the planning horizon. The volume of trees that are felled and processed manually in the planning horizon is 78,923 m^3. The total operating cost of aerial yarding is the second highest even though its volume is lower than other harvesting activities such as ground yarding and loading. This high cost is due to the operating cost per m^3 (71.54 Can$) of aerial yarding being significantly higher than that of other harvesting activities. The total operating cost for other harvesting activities is significantly lower than that for the manual felling and aerial yarding, because in many cut blocks these activities have not started within the planning horizon. The mechanical processing has the lowest total operating cost because the volume of trees that are mechanically processed in the planning horizon is only 4,104 m^3.

Table 3-5 Operating cost for each harvesting activity for a 12-week planning horizon

Activity	**Operating cost (Can$)**	**Volume (m^3)**	**Operating cost per volume (Can$/$m^3$)**
Manual felling and processing	966,318	78,923	12.24
Mechanical felling	108,533	20,594	5.27
Ground yarding	118,635	23,240	5.10
Cable yarding	295,212	12,228	24.17
Aerial yarding	715,385	10,000	71.54
Mechanical processing	21,630	4,104	5.27
Loading	66,537	23,466	2.84

All assigned harvesting activities are completed within the planning horizon for 13 cut blocks. Activities that have started but not completed during the planning horizon include manual felling and processing in 11 cut blocks, mechanical felling in one cut block, cable yarding in 1 cut block, mechanical processing in 2 cut blocks and, loading in 3 cut blocks as shown in the Figure 3-1.

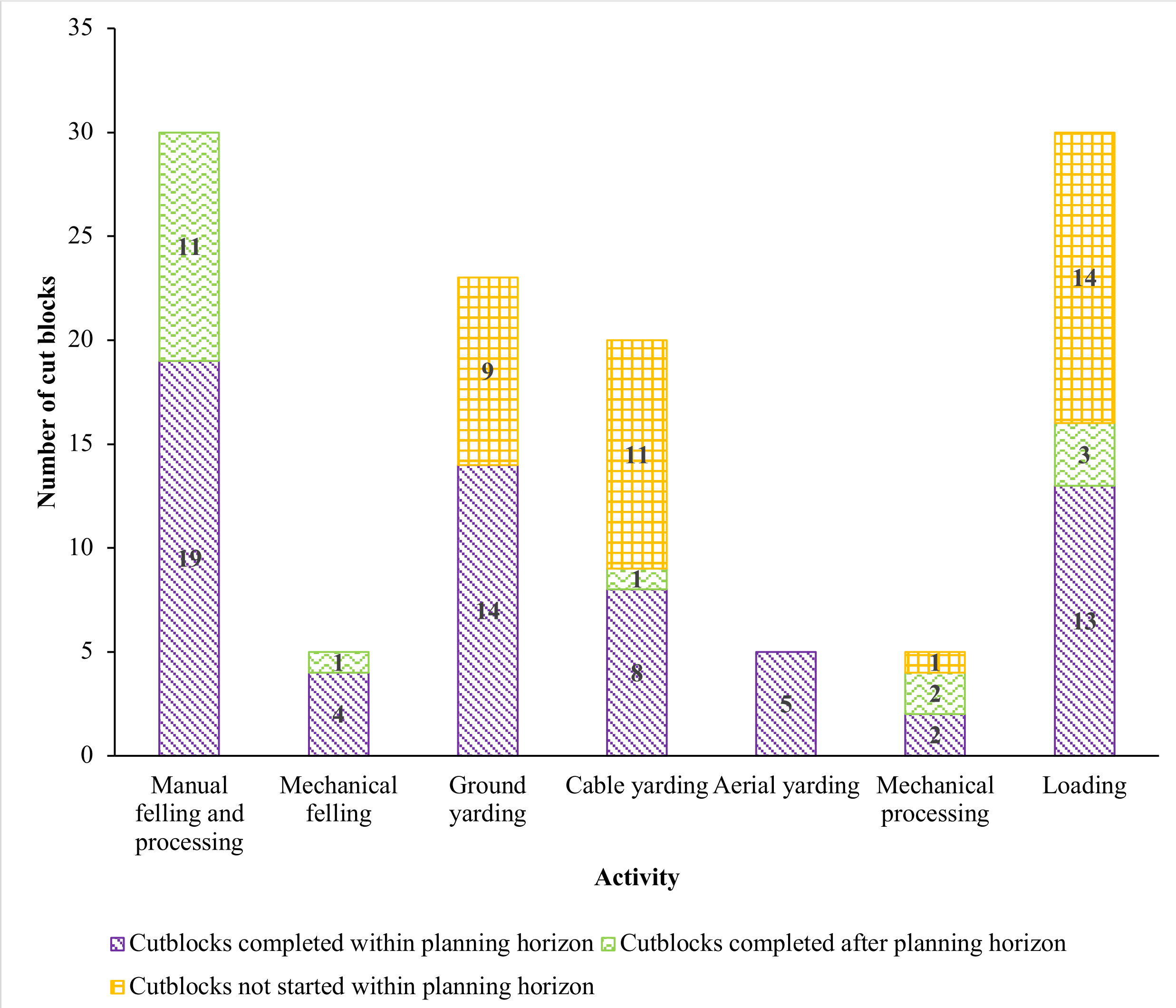


Figure 3-1 Harvesting details in 12-week planning horizon

The operating cost of machines from the model's output is compared with the ideal operating cost case and average operating cost case for the same amount of harvesting (Figure 3-2). The cost based on the model's output is 1.37% (31,596 Can$) higher than that of the ideal operating cost case because the machines with the lowest operating cost are limited and it is not possible to achieve the ideal operating cost. For instance, for cable yarding only two out of 22 machines have the lowest operating cost. Therefore, to complete these activities at the assigned cut blocks within the planning horizon, machines with higher operating cost must be used. In comparison with the average operating cost case, the model's output is 10.24% lower.

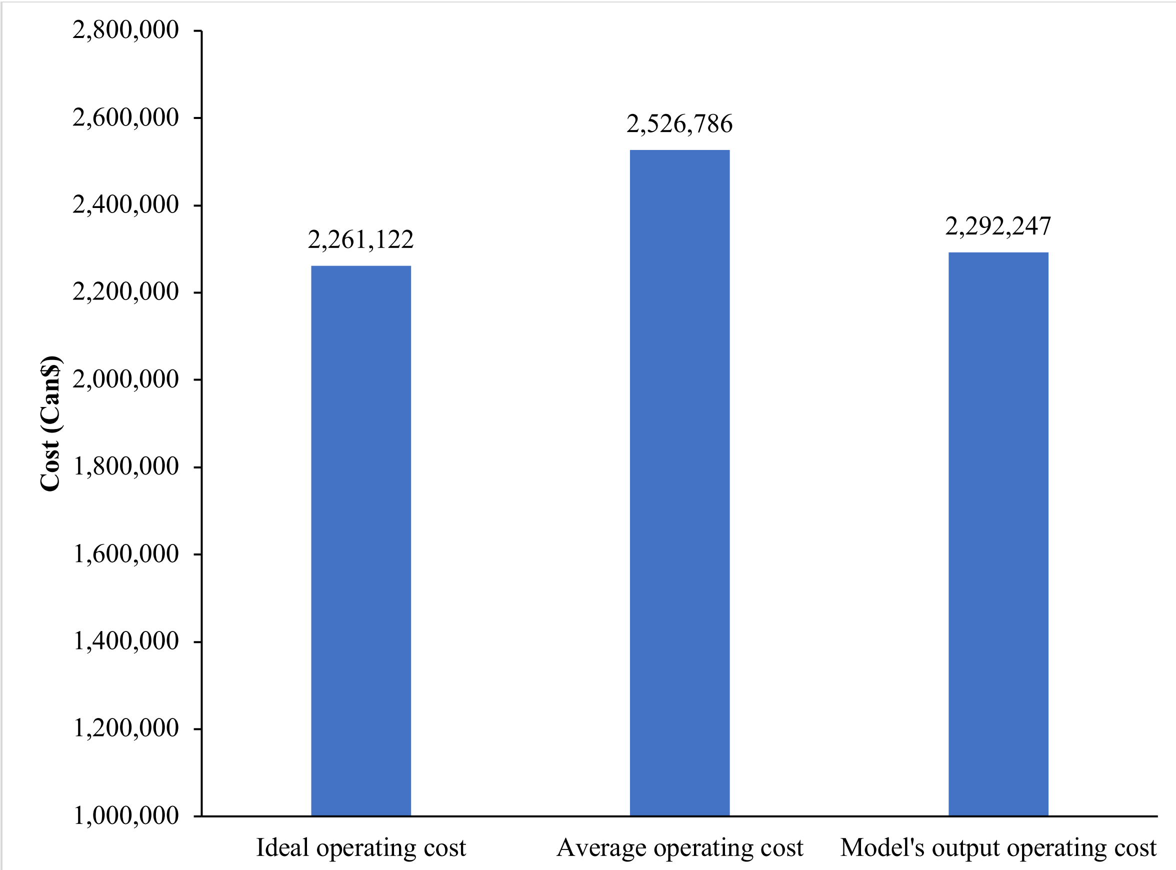


Figure 3-2 Comparison of operating costs for harvesting performed during the planning horizon

The harvesting activities that started during the planning horizon as per the best integer solution are compared with the harvesting activities started in the ideal penalty cost case (Figure 3-3). The harvesting activities started in the model is equal to the harvesting activities started in the ideal penalty cost case for all harvesting activities except the ground yarding. The number of cut blocks in which ground yarding started as per model's output is lower than that in the ideal penalty cost case because in one of the cut blocks, i.e., C14, the preceding activity for ground yarding, i.e., mechanical felling, is completed within the planning horizon in the ideal penalty cost case. In contrast, according to the model's output, extra time is required after the planning horizon to complete the mechanical felling in cut block C14. This disparity occurs because in the ideal penalty cost case, we assume that each activity can start at the earliest time, i.e., zero in the case of mechanical felling. As a result, mechanical felling is finished in all cut blocks within the planning horizon in the ideal penalty cost case. However, it is practically not possible to mechanically fell all cut blocks, i.e., 27,935 m^3, within the planning horizon with only one feller buncher. Therefore, it can be concluded that the penalty cost (PC) calculated by the model is optimum and cannot be decreased any further with available machines.

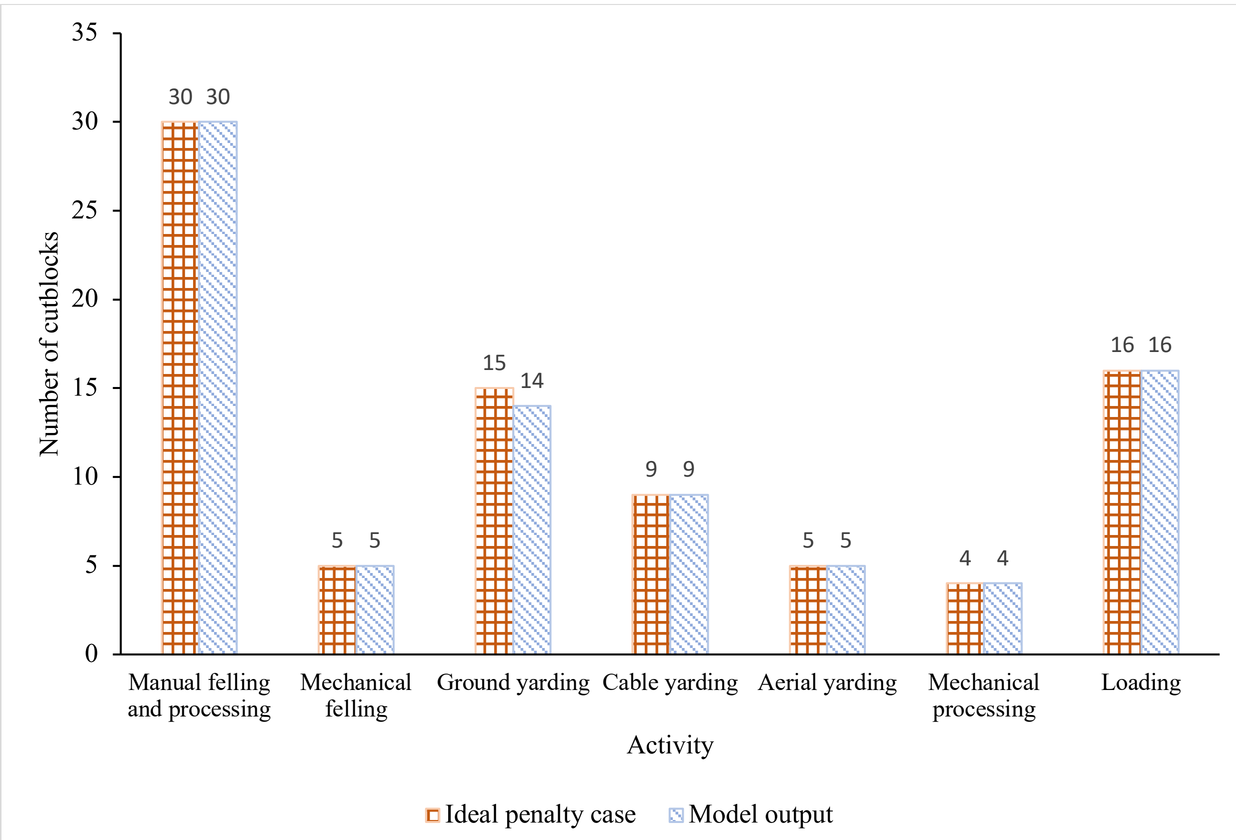


Figure 3-3 Comparison of the amount of harvesting started during the planning horizon

The detailed schedule for each cut block is generated based on the output of the optimization model. The values of the start time, the end time, and the operating time for each activity at each cut block is used to generate a detailed schedule for each cut block. The following paragraphs show the detailed schedule derived for 2 cut blocks: cut block C12 and cut block C24. Similar schedules are generated for all cut blocks but are not shown here for sake of brevity.

The detailed schedule of cut block C12, in which both manual and mechanical felling take place, is shown in Figure 3-4. The trees that are felled manually are processed at the stump site and then they are moved to the landing zone using cable yarding, whereas the trees that are felled mechanically are first moved to the landing zone using ground yarding machines and then they are mechanically processed at the landing zone. The scheduling result for this cut block is in accordance with these precedence relationships. In this cut block, loading is preceded by mechanical processing and cable yarding. As a result, loading does not start until both preceding activities are completed in the cut block.

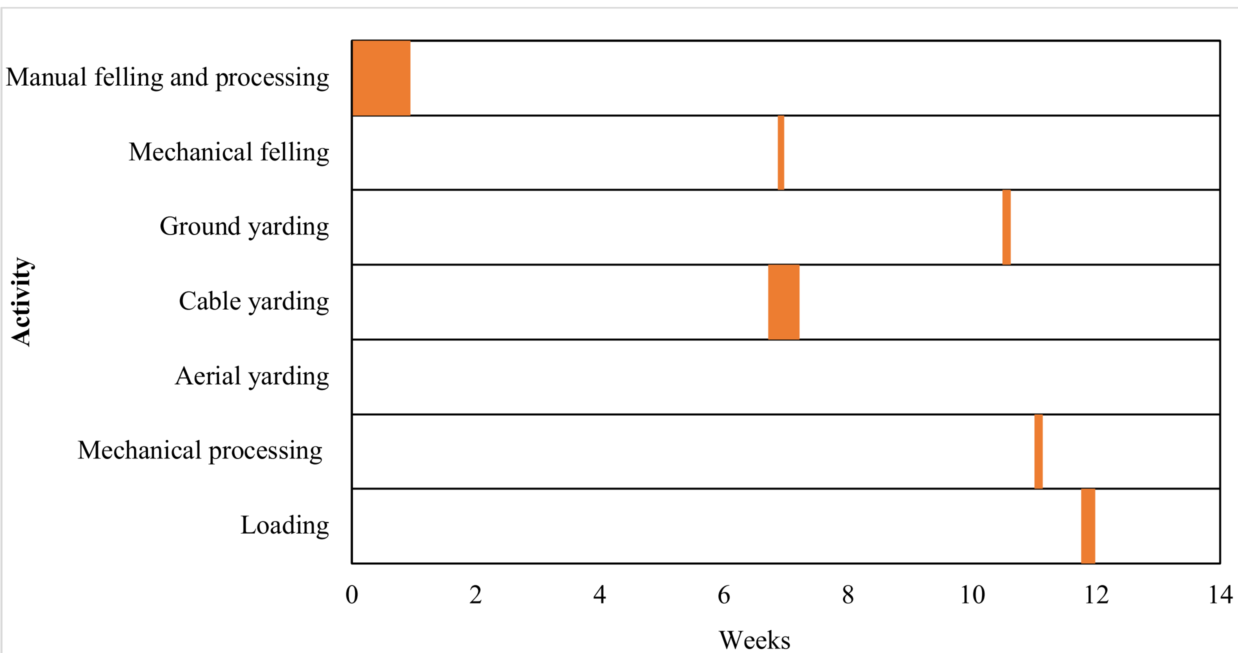


Figure 3-4 Detailed schedule of cut block C12

In cut block C24, all harvesting activities cannot be completed within one planning horizon (Figure 3-5). It requires 1.15 weeks after the current planning horizon to complete the loading activity. In the next planning horizon, loading starts from time 0 in the cut block and finishes in 1.55 weeks.

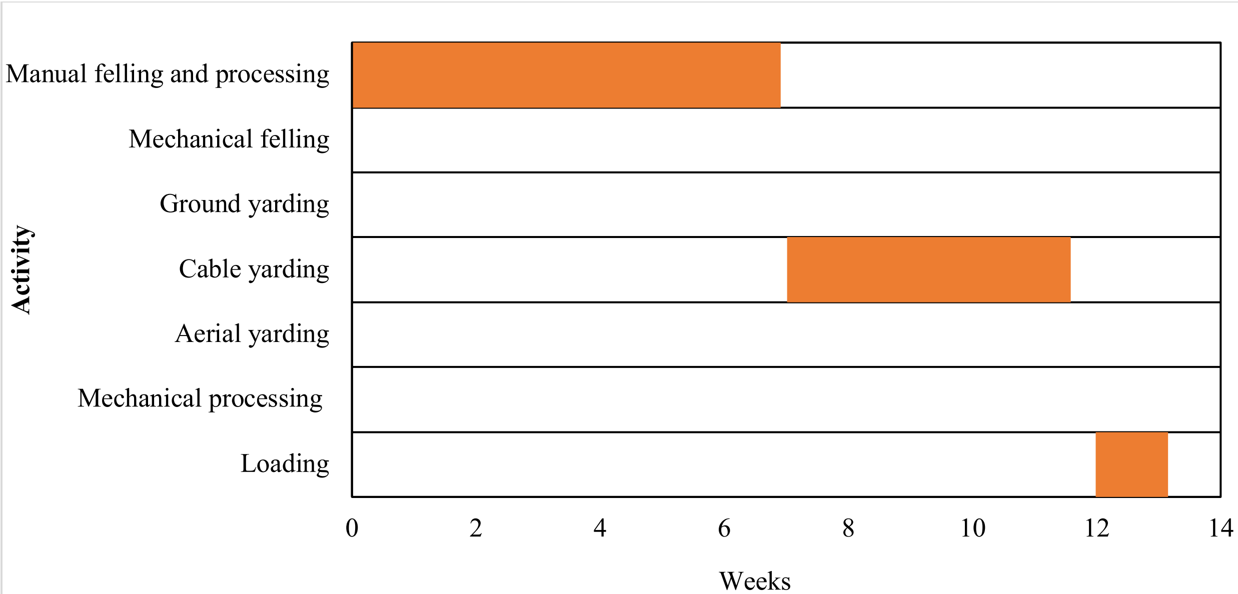


Figure 3-5 Detailed schedule of cut block C24 in current planning horizon

The detailed schedule for each machine is generated based on the output of the optimization model. The values of the start time, the end time, the operating time at each cut block, and the movement time between cut blocks are used to generate the detailed schedule for each machine. For instance, the detailed schedule of machine M61 is depicted in Figure 3-6. This machine finishes its operation in the assigned five cut blocks within the planning horizon with zero idle time. Similar detailed schedules are generated for all machines but are not shown here for the sake of brevity.

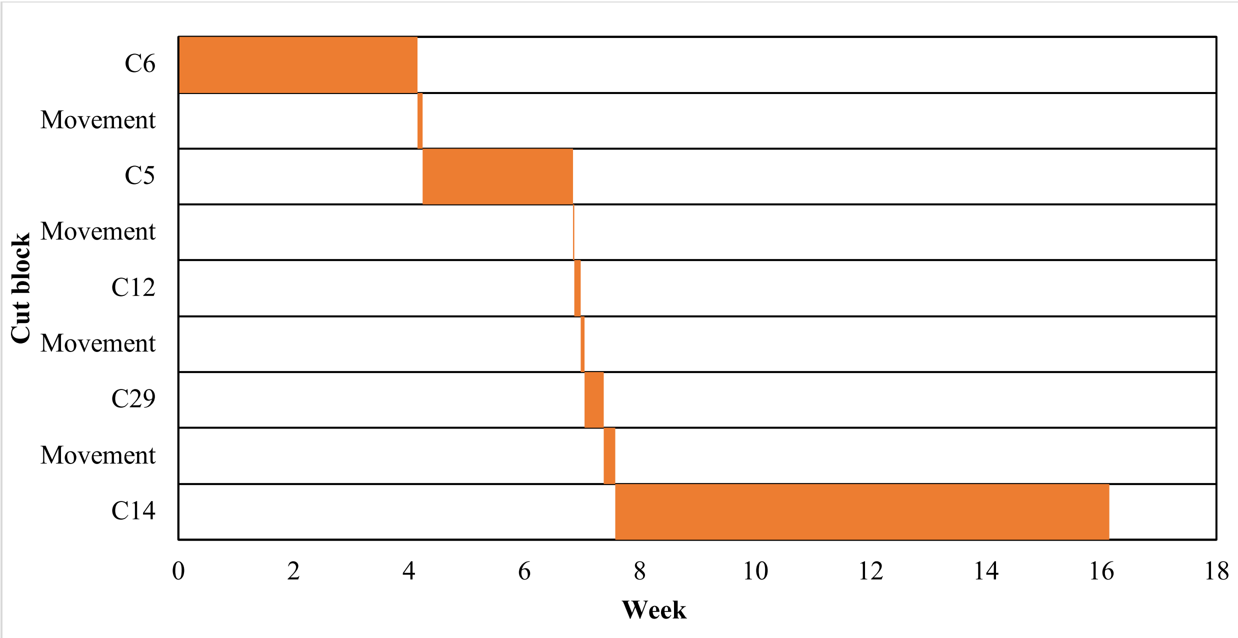


Figure 3-6 Detailed schedule of machine M61 (mechanical feller)

3.5 Discussion

In this chapter, a mixed-integer linear programming model is developed for the detailed scheduling of harvesting activities at the operational level. Unlike previous studies in forest harvest scheduling, the precedence relationship between harvesting activities for multiple cut blocks and the movement of individual machines between cut blocks are considered in this model. Similar to the models for agriculture harvest scheduling (e.g., Basnet et al. (2006)), all the precedence relationships between different harvesting activities are met in our study as shown in the detailed scheduling of cut blocks (Figures 3-4 and 3-5). However, in the agriculture harvest scheduling studies, no planning horizon was considered, and the model was run only once for detailed scheduling to minimize the duration of harvesting. In contrast, the planning horizon is considered in the model developed in this study, and constraints are added to the model to make sure that the outputs of the model implemented for the current planning horizon can be used as the inputs for the next planning horizon, which is an important aspect of the planning and one of the contributions of the proposed model. This aspect of the model ensures the continuity of operations of the machines. Therefore, if a machine requires some extra time after the current planning horizon to complete its operation in a cut block, then the same machine will be assigned to the same cut block in the next planning horizon, and it will start its operation from time zero in the next planning horizon. For instance, machine M83 (cable yarder + loader) requires 4.34 weeks after current planning horizon to complete its operation in cut block C6 (Figure 3-7), and it starts its operation in cut block C6 from time 0 in the next planning horizon (Figure 3-8).

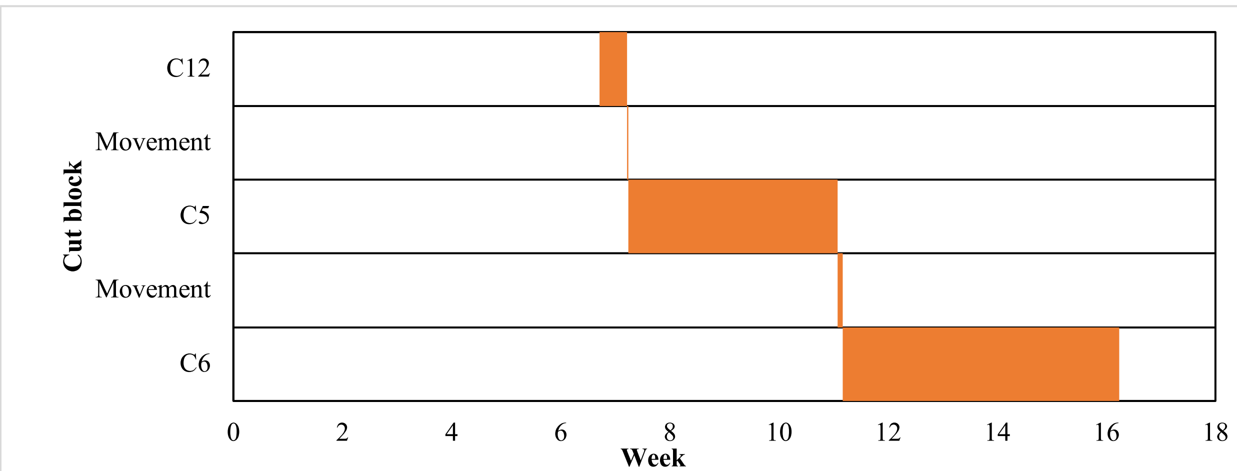


Figure 3-7 Detailed schedule of machine M83 (cable yarder + loader) in current planning horizon

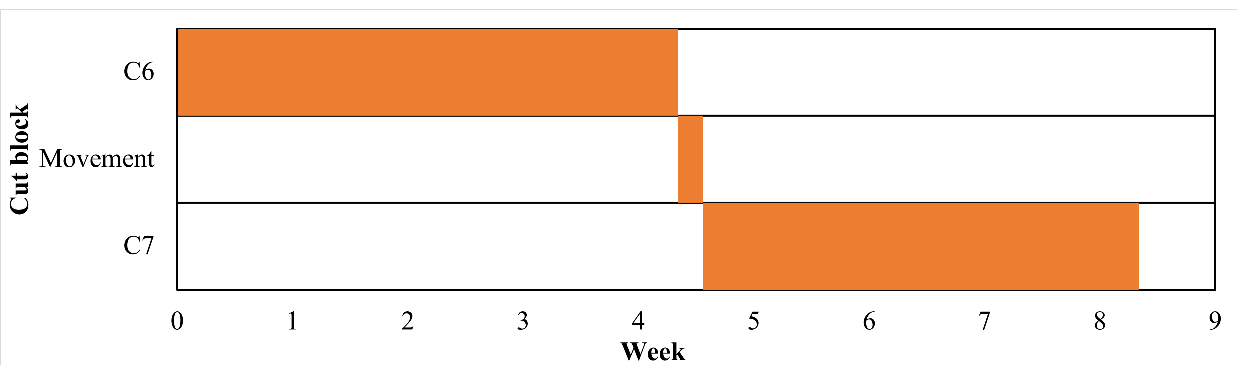


Figure 3-8 Detailed schedule of machine M83 (cable yarder + loader) in next planning horizon

The developed model can be used by forest companies for better utilization of machines in the harvesting of cut blocks, as the model can prescribe delaying the start of some of the harvesting activities to minimize the idle time of machines. For instance, Tables 3-6 compares the schedule of Machine M83 (cable yarder + loader) based on the earliest start time and the model's output to perform the loading at assigned cut blocks. Machine M83 could start its operation at the earliest start time in all the assigned cut blocks, however, it would result in a total idle time of 5.66 weeks for its operation (Table 3-6). Therefore, by delaying the start time of the machine in cut block C12 from week 1.05 to week 6.71 the idle time of machine M83 is reduced from 5.66 weeks to zero. As a result of this approach, only 3 assigned machines have idle time. Additionally, the model ensures that this delay does not result in any extra penalty cost.

Table 3-6 Comparison of schedule of machine M83 (cable yarder + loader) based on the earliest time and the model's output

Cut block	Start time (in weeks)		End time (in weeks)		Idle time (in weeks)		Movement time (in weeks)
	Earliest start time	Model output	Earliest start time	Model output	Earliest start time	Model output	
C12	1.05	6.71	1.56	7.22	0	0	0
C5	7.24	7.24	11.07	11.07	5.66	0	0.02
C6	11.16	11.16	16.24	16.24	0	0	0.09

In this work, different harvesting systems are considered for different types of felling activities. The trees are felled either manually using a chainsaw or mechanically using a feller-buncher. After manual felling, trees are processed at the stump site or in woods, then they are yarded to the landing zone, where loading takes place. So, the precedence relationship for the manual felled part is: 1) manual felling and processing, 2) yarding, and 3) loading. However, after mechanical felling, the trees are yarded to the landing zone, where mechanical processing takes place, then they are loaded to the trucks. Therefore, the precedence relationship for the mechanical felled part is: 1) mechanical felling, 2) yarding, 3) mechanical processing, and 4) loading. In case there is any other different harvesting system, then the precedence relationship constraints (constraint set 3.16) and machine movement constraints (constraint set 3.17) can easily be modified to accommodate this change, and the preceding activities have to be updated only in the input data. Furthermore, the developed model can be modified to accommodate other precedence relationships, such as a harvesting activity starting a few weeks after the start of the previous harvesting activity, or two harvesting activities starting simultaneously in the cut block.

Another approach for solving this problem could be to use a heuristic or metaheuristics method. However, the operating cost obtained by the model was very close to the lowest possible operating cost, and the penalty cost calculated could not be improved any further, as discussed earlier. Also, the solver found the best integer solution with an optimality gap of 2.97% in 3.5 hours which is acceptable for a model with a planning horizon of three months, as the model has to be run once per quarter. Therefore, heuristics were not used for solving the problem.

3.6 Conclusions

In this chapter, an optimization model was developed to minimize the total costs of harvesting, considering the precedence relationship among harvesting activities and the movement of individual machines between the cut blocks.

The model determined the start and the end times for each harvesting activity at each cut block and where machines should move after completing their operation in one cut block. The model was applied to a real case study of a large forest company in Coastal British Columbia for a three-month planning horizon. The case study included 30 cut blocks and 103 machines. The solver found the integer solution after 3.5 hours with an optimality gap of 2.97%. The value of the objective function was 9,024,876 Can$. The penalty cost of not starting a harvesting activity during the planning accounted for more than 63% of the objection function value because manual felling was not finished within the planning horizon in 11 large cut blocks. As a result, succeeding activities could not start in those cut blocks during the planning horizon.

The results indicated that all the assigned harvesting activities were completed in 13 cut blocks within the planning horizon, while 17 cut blocks required extra time after the planning horizon. The operating cost from the model's output was 1.37% higher than that of the ideal operating cost case. The penalty cost from the model was optimum, and it could not be improved any further with available machines. Out of 134 machines, 47 machines were assigned for harvesting and only three machines had an idle time.

Chapter 4: Detailed scheduling of forest harvesting at the operational level incorporating decisions on multiple machine assignment

4.1 Synopsis

It is crucial to efficiently schedule harvesting activities in order to reduce the delivered cost of logs. Mathematical models have been used to optimize the harvest scheduling at the operational level. However, in the existing literature, the number of machines assigned for each activity at each cut block was not considered as a decision variable. Also, the impact of the slope of cut blocks on the precedence relationship between harvesting activities was not considered in the previous studies. In this chapter, a mathematical programming model is developed with the possibility of assigning multiple machines for the same harvest activity at each cut block, considering the precedence relationship between activities based on the slope of cut blocks in order to minimize the total cost of harvesting. This model is an extension of our previous work in Chapter 3 on detailed scheduling of harvesting. The model is applied to the harvesting operations of a large forest company in Coastal British Columbia, Canada. The model's result for operating cost is only 3.3% higher than that of the lowest possible operating cost. Out of 134 machines, 91 machines are used for harvesting and only one machine has an idle time. For the same case study, the total cost of the developed model is about 34% lower than that of the previous model developed in Chapter 3 due to the possibility of assigning multiple machines for each harvesting activity at each cut block.

4.2 Problem Formulation

The precedence relationship between harvesting activities in many regions is based on the slope of cut blocks. In cut blocks with a specific value of slopes depending on the region of harvesting, it is safe to start succeeding harvesting activity before the completion of the preceding harvesting activity. Moreover, many forest companies assign multiple machines to perform harvest activities in each cut block to ensure that the maximum harvesting can be done during the planning horizon. This is especially done for harvest activities with low productivity like manual felling and processing. Therefore, the developed model in Chapter 3 with the assumption that only one machine could be assigned to perform each harvesting activity and the same precedence relationship for all cut blocks, cannot be used in these cases. To address these two gaps, the model developed in Chapter 3 is modified and the modified model is applied to the same case discussed in Chapter 1.3.

4.3 Mathematical Model

Since the problem includes both continuous and integer decision variables, it is formulated as a mixed-integer linear programming (MILP) model. The model has a planning horizon of three months (12 weeks) with weekly time steps and will be run based on a rolling horizon approach, and the outputs of the current planning horizon are used as the inputs for the next planning horizon. The mathematical model for detailed harvest scheduling in Chapter 3 is modified by altering 7 constraint sets and adding 9 new constraint sets to the model in order to account for the possibility of assigning multiple machines for each activity and considering the slope condition of cut blocks in precedence relationship of harvest activities. The objective function of the modified model is the same as that in Chapter 3 and is represented by equations (3.1) to (3.7). Input parameters which were discussed in Section 3.4 are used in this model, too.

All assumptions of the mathematical programming model mentioned in Chapter 3.3 are used except the following two assumptions:

- Only one machine can be assigned to each activity at each cut block.

- Precedence relationship for an activity is same for all cut blocks irrespective of their slope. For instance, in all cut blocks loading cannot start before finishing of ground and cable yarding.

In addition, the following considerations about the case study are added in the modified model:

- At each cut block, multiple machines can be assigned for each harvesting activity. However, once a machine enters a cut block to start its operation, it cannot leave until the activity is finished. As a result, all assigned machines for a harvesting activity at a cut block have the same end time for operations.
- The start time of operations of all machines used for a harvesting activity at a cut block may not be the same. Machines that arrive earlier can start their operations, and other machines can join them later. However, due to operational requirements for cable yarding, the start time of all assigned machines for cable yarding must be the same.
- The precedence relationship between activities varies depending on the slope of the cut blocks. In cut blocks with a slope=<50%, some activities such as loading and yarding take place simultaneously. In cut blocks with a slope >50%, an activity can only start after the completion of the preceding harvesting activity due to safety reasons.

All sets, parameters and notations which are used from previous model are represented in Table 3-2. Table 4-1 depicts the new sets, parameters and variables used in the modified mathematical programming model.

Table 4-1 Model sets, parameters, and decision variables

Sets	Description
$I_{kng} \subset I$	Set of cut blocks with safe slope where activity *k* will start in current planning horizon
$I_{kns} \subset I$	Set of cut blocks with unsafe slope where activity *k* will start in current planning horizon
Parameters	**Description**
ψ_{ik}	Volume available at cut block *i* for harvesting activity *k* (m^3)
Q_{jik}	Productivity of machine *j* to perform harvesting activity k at cut block *i* (m^3/week)
ξ_i	Size of cut block *i* (ha)
ρ_k	Number of machines that can be assigned per hectare for harvesting activity *k* (machines/ha)
ς_{ik}	Volume available at cut block *i* for harvesting activity *k* after previous planning horizon (m^3)
Decision Variables	**Description**
ET_{ik}	End time of activity *k* at cut block *i*
ST_{ik}	Start time of activity *k* at cut block *i*
R_{ik}	Volume remained at cut block *i* for harvesting activity *k* at the end of planning horizon
N_{ik}	Number of machines assigned at cut block *i* for harvesting activity *k*

4.3.1 Constraints

The constraint sets which are directly adopted from the previous model are represented by equations (3.8), (3.10), (3.11), (3.13), (3.17), (3.18), (3.20) to (3.26).

Constraint sets (4.1) to (4.7) represent the constraints which are modified from those in the previous model in order to include multiple machine assignment and precedence relationship dependent upon the slope.

Constraint set (4.1) defines the maximum number of machines that can be assigned to a cut block for a harvesting activity. In previous model, it was assumed that only one machine could be assigned for each activity.

$$\sum_{i' \in I_k+0, i' \neq i} \sum_{j \in J_k} Z_{ji'ik} \leq 1 + (\xi_i * \rho_k), \forall \ i \in I_k, k \in K \quad (4.1)$$

Constraint sets (4.2) and (4.3) make sure that the start time and end time of operation of a machine which is not moving to a cut block is zero.

$$Y_{jik} \leq M * \sum_{i' \in I_k+0, i' \neq i} Z_{ji'ik} \quad , \forall\, j \in J_k, i \in I_k, k \in K \tag{4.2}$$

$$Y_{jik} \;\geq\; X_{jik} \quad , \forall\, j \in J_k, i \in I_k, k \in K \tag{4.3}$$

Constraint set (4.4) states that for cut blocks with a slope>50%, the start time of operation of a machine at a cut block is always greater than the end time of the previous harvesting activity plus the minimum lag required between the two activities. In previous model, $\sum_{j^p \in J_{k^p}} Y_{j^p ik^p}$ was used instead of ET_{ik^p} because it was assumed that only one machine could be used.

$$X_{jik} \geq (ET_{ik^p} + \mu_{ik}) - M * \left(1 - \sum_{i' \in I_k+0, i' \neq i} Z_{ji'ik}\right) \quad , \forall\, i \in I_{kns}\,, k \in (3,4,\ldots,7), j \in J_k, k^p \in (K\ preceding\ k) \tag{4.4}$$

Constraint set (4.5) states that for cut block with a slope=<50%, the start time of operation of a machine at a cut block is always greater than the start time of the previous harvesting activity plus the minimum lag required between the two activities. This constraint was not required in the previous model because it was assumed that all cut blocks had the same precedence relationship independent of the slope of cut blocks.

$$X_{jik} \geq (ST_{ik^p} + \mu_{ik}) - M * \left(1 - \sum_{i' \in I_k+0, i' \neq i} Z_{ji'ik}\right) \quad , \forall\, i \in I_{kng}\,, k \in (3,4,\ldots,7), j \in J_k, k^p \in (K\ preceding\ k) \tag{4.5}$$

Constraint sets (4.6) and (4.7) calculate the penalty variable. In case no machine moves to a cut block to perform a harvesting activity (the activity did not start in the planning horizon), then the penalty variable associated with that harvesting activity becomes one for that cut block. In the previous model, the penalty cost was calculated by only one constraint set (3.19) because it was assumed that only one machine could be assigned for each activity.

$$\sum_{i' \in I_k+0, i' \neq i} \sum_{j \in J_k} Z_{ji'ik} \;\geq (1 - U_{ik}), \forall\, i \in I_k, k \in K \tag{4.6}$$

$$M * (1 - U_{ik}) \geq \sum_{i' \in I_k + 0, i' \neq i} \sum_{j \in J_k} Z_{ji'ik}, \forall\, i \in I_k, k \in K \tag{4.7}$$

Equations (4.8) to (4.16) represent the constraints that are added to the model developed in Chapter 3.

Constraint sets (4.8) and (4.9) determine the start time and end time of a harvesting activity at a cut block. In case multiple machines enter the cut block to perform a harvesting, then start time value for the precedence relationship will be consider as the start time of the machine which came in the last.

$$\mathrm{ST}_{ik} \geq \mathrm{X}_{jik} \quad , \forall\, j \in \mathrm{J_k}, i \in I_k, k \in \mathrm{K} \tag{4.8}$$

$$\mathrm{ET}_{ik} \geq \mathrm{Y}_{jik} \quad , \forall\, j \in \mathrm{J_k}, i \in I_k, k \in \mathrm{K} \tag{4.9}$$

Constraint set (4.10) works with constraint set (4.9) to ensure that the end time of all machines at a cut block is the same if they move to the cut block. In case the machine does not operate at the cut block, then the end time of the machine will become zero for that cut block as per constraint set (4.2).

$$Y_{jik} \geq \mathrm{ET}_{ik} - M * (1 - \textstyle\sum_{i' \in I_k + 0, i' \neq i} Z_{ji'ik}), \forall\, i \in I_k, k \in K, j \in J_k \tag{4.10}$$

Constraint set (4.11) ensures that for cable yarding, the start time of all machines assigned at a cut block is the same. This constraint is added because the setup of all assigned machines for cable yarding at a cut block is done at the same time by the forest company.

$$X_{ji4} \geq \mathrm{ST}_{i4} - M * (1 - \textstyle\sum_{i' \in I_4 + 0, i' \neq i} Z_{ji'i4}), \forall\, i \in I_4, j \in J_4 \tag{4.11}$$

Constraint set (4.12) guarantees that in case two harvesting activities can be performed simultaneously in the planning horizon, then the end time of the succeeding activity is always greater than the preceding activity.

$$ET_{ik} \geq ET_{ik^p} \; \forall \, i \in I_{kng}, k \in K, k^p \in (K \; preceding \; k) \tag{4.12}$$

Constraint sets (4.13) and (4.14) ensure that the summation of harvested volume by all machines of a harvesting activity at a cut block is equal to the volume available for that harvesting activity at that cut block. In case no machine moves to the cut block, then $(1 - U_{ik})$ will become zero and it will force the left-hand side of equation set (4.14) to be zero. As a result, the start time and end time variables of that activity will become zero for the cut block.

$$\sum_{j \in J_k} (Y_{jik} - X_{jik}) * \text{♀}_{jik} = \varsigma_{ik} \,, \forall \; k \in K \,, i \in \; I_{kp} \tag{4.13}$$

$$\sum_{j \in J_k} \left(Y_{jik} - X_{jik}\right) * \text{♀}_{ijk} = \; \psi_{ik} * (1 - U_{ik}) \; \forall \, k \in K \,, i \in I_{kn} \tag{4.14}$$

Constraint set (4.15) calculates the number of machines assigned at each cut block for each harvesting activity.

$$N_{ik} = \sum_{i' \in I_k + 0, i' \neq i} \sum_{j \in J_k} Z_{ji'ik} \quad , \forall \; i \in I_k, k \in K \tag{4.15}$$

Constraint set (4.16) calculates the volume left at the end of the planning horizon for cut blocks in which harvesting started during the planning horizon.

$$R_{ik} = \sum_{j \in J_k} V_{jik} * \; \text{♀}_{jik} \,, \forall \; i \in I_k, k \in K \tag{4.16}$$

Equations (4.17), (4.18), and (4.19) depict the range of decision variables.

$$X_{jik}, Y_{jik}, V_{jik}, \mathrm{S_j}, \mathrm{E_j}, R_{ik} \in \mathrm{R}^+ \tag{4.17}$$

$$N_{ik} \in \text{Integers} \tag{4.18}$$

$U_{ik}, P_{jik}\ Z_{ji'ik} \in \{0,1\}$ (4.19)

4.3.2 Model execution

The developed mathematical programming model is executed using AIMMS (AIMMS 2022) on a computer with Intel ® core ™ i7-6700 CPU @ 3.41 GHz processor and 16.0 GB RAM. The CPLEX 20.1 (CPLEX 2021) solver is used by AIMMS to solve this mathematical programming model. All data files are created using Excel and are fed to the AIMMS software. The size of the case study and the mathematical programming model are shown in Table 4-2.

Table 4-2 Size of the developed model

Size of the case study	
Number of cut blocks	30
Number of machines	134
Planning horizon	12 weeks
Size of the mathematical programming model	
Number of constraints	134,264
Number of continuous decision variables	14,372
Number of binary decision variables	97,654

Similar to the previous model in Chapter 3, three benchmarks are used in this paper for comparison and validation of the results driven from the model because no data were available for comparison of results. These benchmarks are: 1) the ideal operating cost case, 2) the average operating cost case, and 3) the penalty cost case. The operating cost and the penalty cost of harvesting activities performed during the planning horizon derived from the developed model are compared with those from the three benchmarks.

4.4 Results

AIMMS determined the solution after about 250 million iterations in 20 hrs. Ninety one out of 134 machines are used in the best integer solution. Only 1 machine has an idle time. The value of the objective function is 5,962,082 Can$. The operating cost during and after the planning horizon account for more than 92.5% of the total cost. All components of the objective function costs are represented in Figure 4-1.

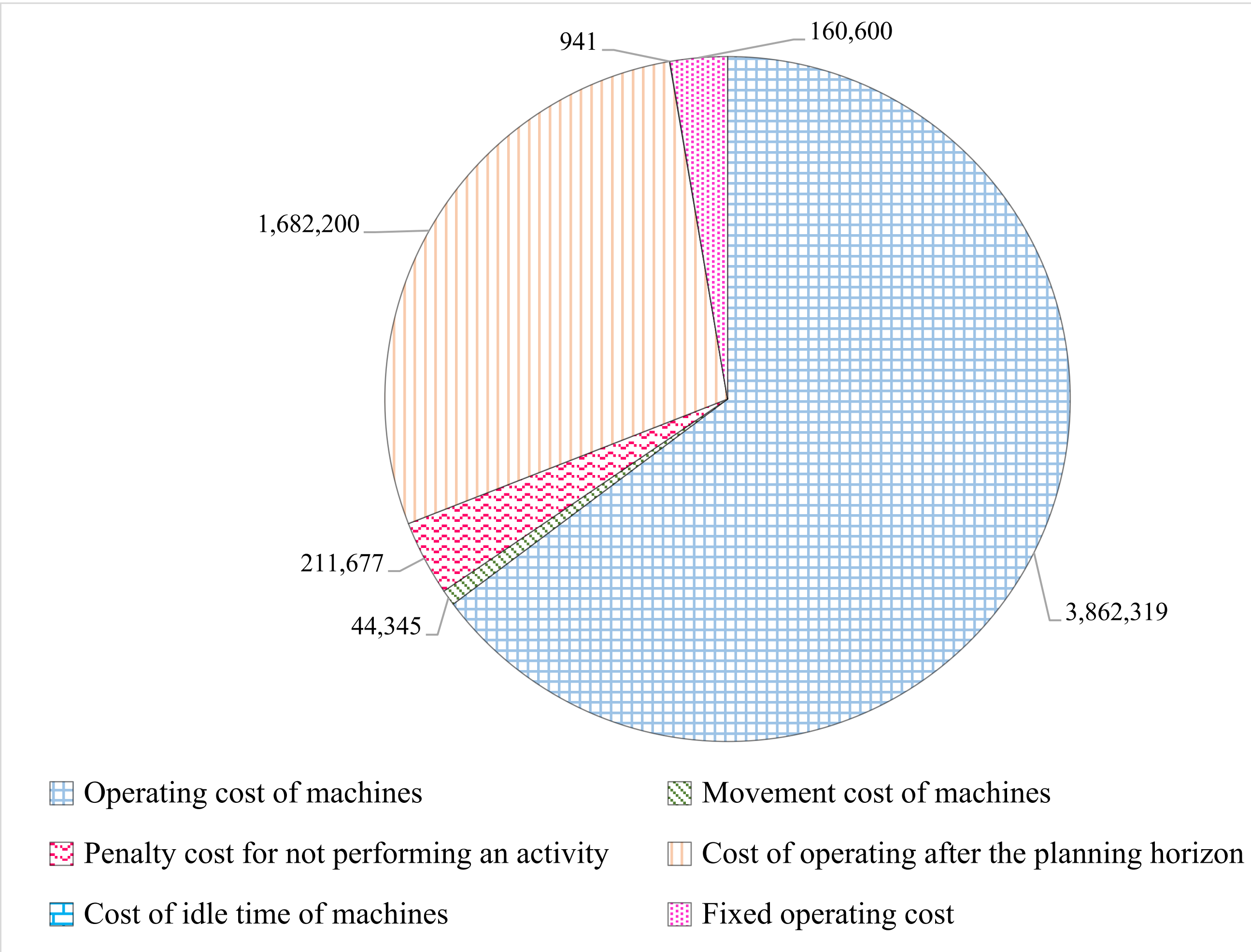


Figure 4-1 Components of the objective function

Table 4-3 shows the total operating cost, volume, and the operating cost per volume for each harvesting activity.

Table 4-3 Operating cost for each harvesting activity for a 12-week planning horizon

Activity	**Operating cost (Can$)**	**Volume (m^3)**	**Operating cost per volume (Can$/$m^3$)**
Manual felling and processing	1,643,578	134,565	12.21

Mechanical felling	147,640	27,935	5.29
Ground yarding	118,635	23,240	5.10
Cable yarding	346,657	14,860	23.32
Aerial yarding	715,385	10,000	71.54
Mechanical processing	67,268	12,755	5.27
Loading	85,102	30,000	2.84

Figure 4-2 displays how much harvesting is done during the planning horizon. All harvesting activities in all cut blocks, except for loading, start within the planning horizon. Loading did not start in 5 cut blocks because the preceding activity did not finish with the planning horizon. Out of 30 cut blocks, all assigned harvesting activities are completed in 17 cut blocks within the planning horizon, and in 13 cut blocks some activities require some extra time after the planning horizon. Activities that started within the planning horizon but did not finish include mechanical felling in 1 cut block, ground yarding in 3 cut blocks, cable yarding in 9 cut blocks, mechanical processing in 2 cut blocks, and loading in 8 cut blocks. Activities in these 13 cut blocks will be completed in the next planning horizon.

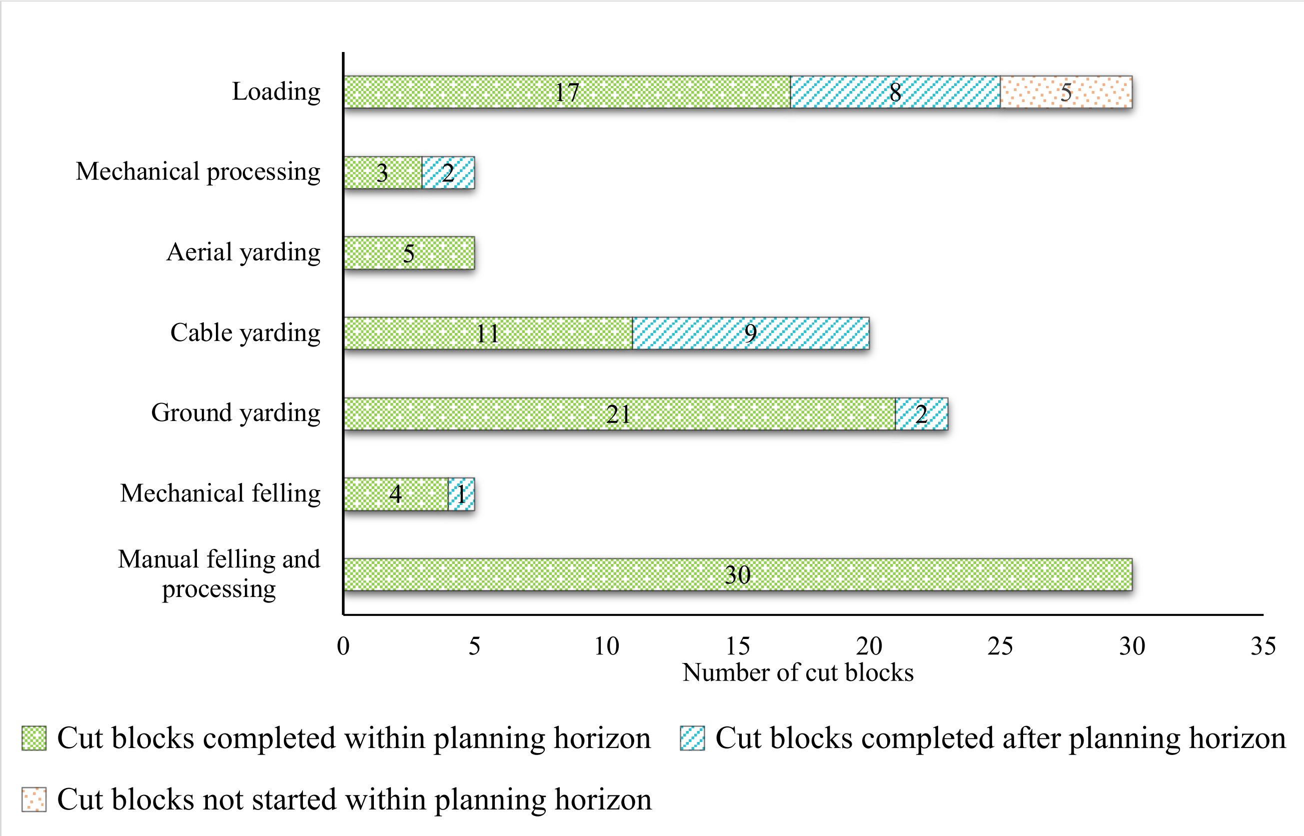


Figure 4-2 Harvesting activities completed, not completed and not started on cut blocks during the planning horizon

For the same amount of harvesting performed during the planning horizon, the operating cost of the model is compared with those of the ideal operating cost case and the average operating cost case (Figure 4-3). The model's solution operating cost is 3.84% (148,650 Can$) higher than that of the ideal operating cost case. For manual felling and processing, mechanical felling, and aerial yarding all machines are identical, therefore, all three costs are the same. However, for other activities, the operating cost from the model is significantly lower than that of the average cost case and is comparable to that of the ideal cost. Practically, it is not possible to achieve the ideal operating cost because the number of machines with the lowest operating cost are limited. For instance, for cable yarding, only 2 out of 22 machines have the lowest operating cost. Therefore, some high operating costs machines have to be used to ensure that maximum harvesting takes place during the planning horizon.

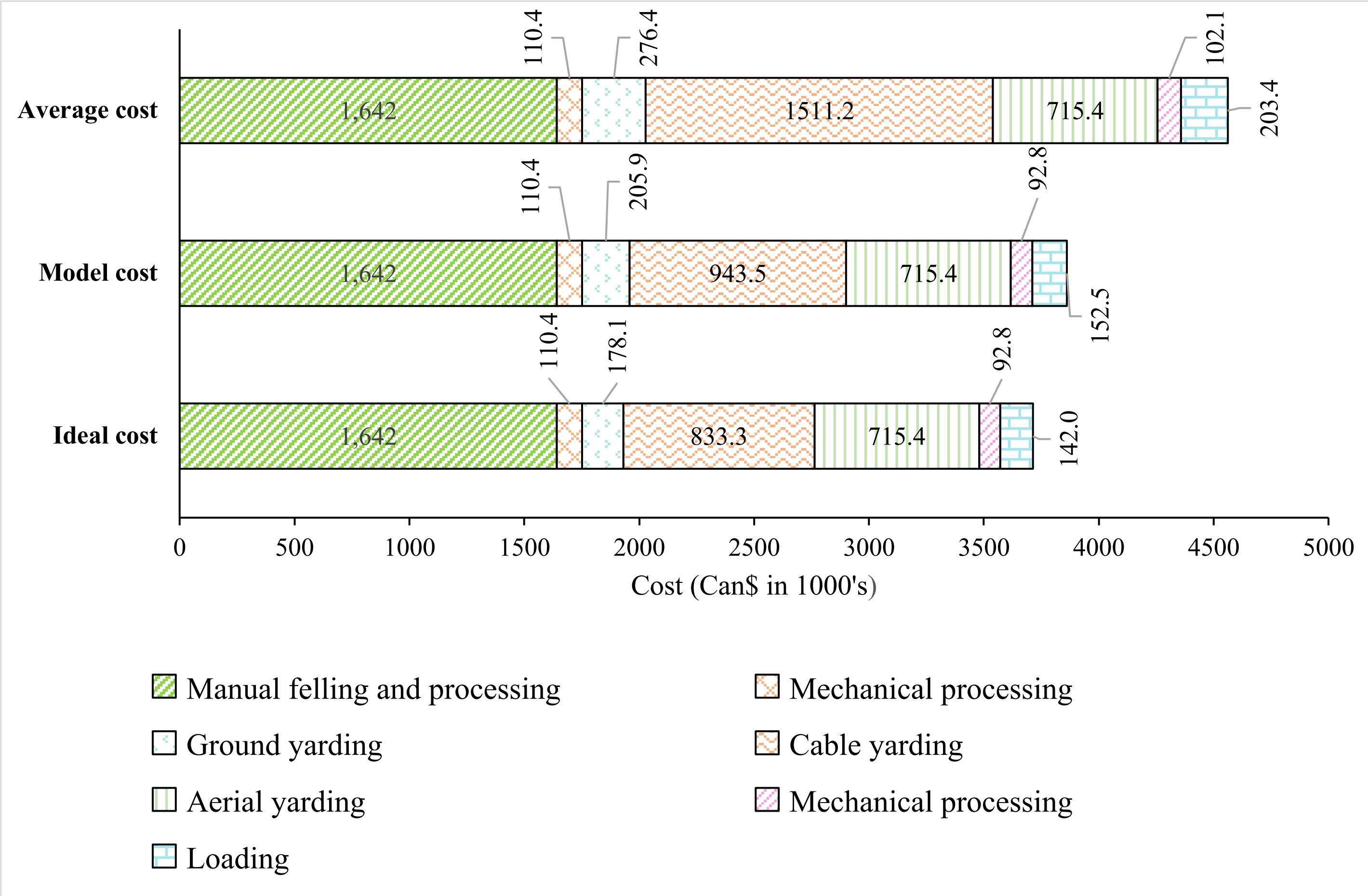


Figure 4-3 Comparison of operating cost for the three cases with the same amount of harvesting

The number of cut blocks in which harvesting activities started during the planning horizon for the model was identical to that from the ideal penalty cost case (Figure 4-4), and they are identical. In 5 cut blocks with a slope>50%, loading did not start during the planning horizon in both cases. This happens because in these cut blocks, cable yarding can not finish within the planning horizon even if the maximum number of cable yarders of highest productivity started at their earliest start time. So, it can be concluded that the penalty cost of the model can not be improved further and is optimum.

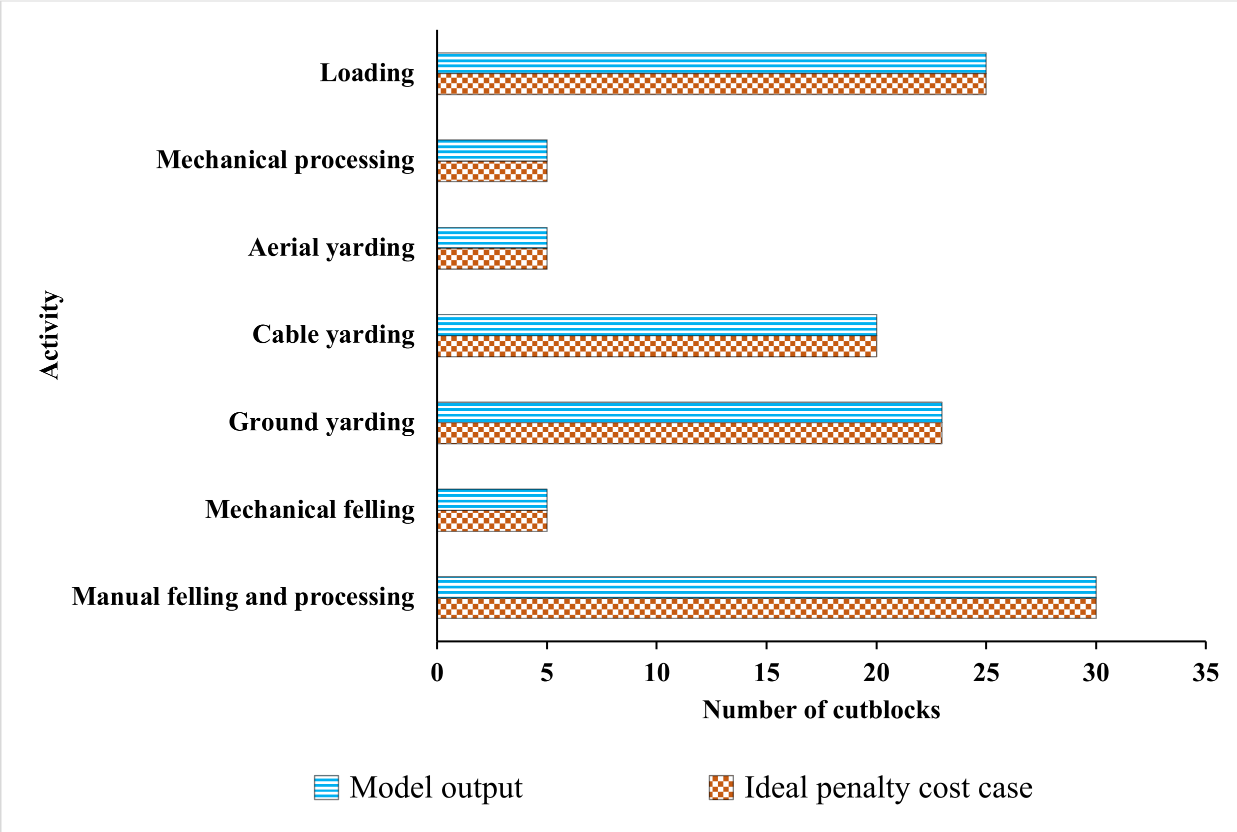


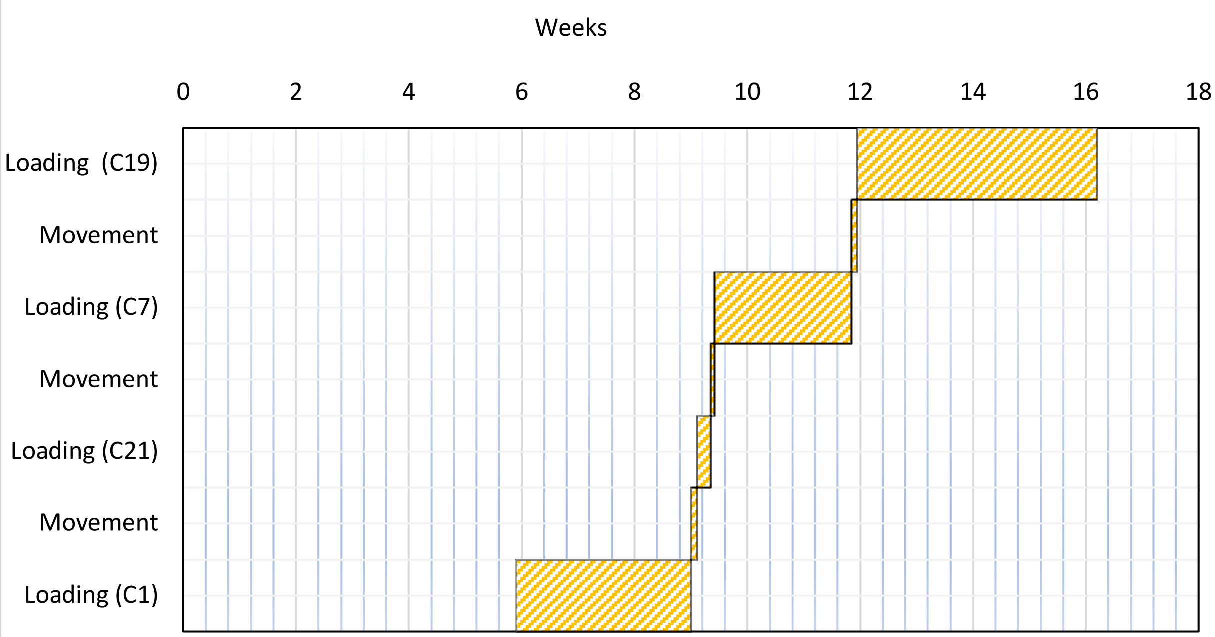
Figure 4-4 Comparison of harvesting activities started during the planning horizon

The detailed schedule of manual felling and processing for cut block C25 is shown in Table 4-4 to demonstrate that the start time of machines can vary, but the end time will remain the same. In this cut block, 4 fellers are assigned for manual felling and processing. The manual fellers using machines M20, M27, and M54 directly move from the depot to cut block and start their operations at time 0. However, the feller using machine M34 first performed its operations at cut block C10 and then joined the other three fellers at 0.96 weeks. All four manual fellers finish their operations simultaneously at 2.026 weeks. Similar schedules are prepared for all activities at all cut blocks, but for brevity they are not all shown here.

Table 4-4 Schedule of manual felling at cut block C25

Machine	Start time (week)	End time (week)
M20	0	2.026
M27	0	2.026
M54	0	2.026
M34	0.96	2.026

The detailed schedule of machine M104 during the planning horizon is shown in Figure 4-5. As shown in this figure, the machine moves from one cut block to another cut block to perform the loading activity and it moves individually between cut blocks. The machine leaves the depot in week 5.94 and performs loading in 4 cut blocks during the planning horizon with zero idle time.



	Loading (C1)	Movement	Loading (C21)	Movement	Loading (C7)	Movement	Loading (C19)
Start time	5.9	8.995	9.117	9.345	9.413	11.843	11.95
Duration	3.095	0.122	0.228	0.068	2.43	0.107	4.25

Figure 4-5 Detailed schedule of machine M104

The detailed schedule of cut block C14 is presented in Table 4-5 to show that in a cut block having a slope ≤ 50%, multiple activities can occur simultaneously. It is a cut block in which both manual and mechanical felling occur. Both felling activities take place at separate portions of the cut block. Manually felled trees are processed at the stump site before being cable yarded to the roadside. Mechanically felled trees are first ground yarded to the stump site before being mechanically processed by the processor at the roadside. Therefore, in this cut block, the loading of trucks is preceded by mechanical processing and cable yarding. Since this is a cut block with a slope ≤ 50%, all activities can take place at the same time with a small gap between their start time except for yarding and manual felling and processing. Due to technical reasons, cable yarding cannot start in the part of the cut block where manual felling and processing are going on. In the detailed schedule of this cut block, ground yarding starts at 8.71 weeks before finishing the mechanical felling at 15.94 weeks (the next planning horizon) to ensure no penalty cost is incurred. Similarly, mechanical processing starts before finishing the ground yarding, and loading starts before finishing of cable yarding and mechanical processing to make sure that the penalty cost due to not starting a harvesting activity does not occur.

Table 4-5 Detailed schedule of harvesting at cut block C14

Activity	Start time (week)	End time (week)
Manual felling and processing	0	7.32
Mechanical felling	7.37	15.94
Ground yarding	8.71	16.14
Cable yarding	8.51	21.11
Mechanical processing	9.11	19.72
Loading	11.95	22.44

The detailed schedule of the cut block C23 is shown in Table 4-6 to demonstrate that in an unsafe slope (>50%) cut block, an activity cannot start before the completion of the previous harvesting activity. It is a cut block in which only manual felling occurs. All trees are manually processed at the stump site. Some portions of the trees are ground yarded to the roadside, and the rest is cable yarded to the roadside. Therefore, the preceding activities for loading in this cut block are ground yarding and cable yarding. Since it is a cut block with a slope>50%, the loading of trucks cannot start unless both cable yarding and ground yarding are finished due to safety reasons. Hence, in the detailed schedule, loading started at 9.62 weeks after finishing both cable yarding and ground yarding at 9.22 weeks.

Table 4-6 Detailed schedule of harvesting at cut block C23

Activity	Start time (week)	End time (week)
Manual felling and processing	0	5.53
Ground yarding	8.97	9.22
Cable yarding	6.06	9.22
Loading	9.62	10.55

4.5 Discussion

In this research, a mathematical programming model is developed for optimizing the forest harvest scheduling at the operational level. A similar model was developed in Chapter 3, in which the precedence relationship among harvesting activities for detailed scheduling at the operational level was considered. However, in that chapter and previous studies for scheduling at the operational level (Karlsson et al. 2003; Vera et al. 2003; Epstein et al. 2006; Santos et al. 2019), it was assumed that only one machine could be assigned for each harvesting activity. On the contrary, in this newly developed model, the number of machines to be assigned at each cut block for each harvesting activity is considered as a decision variable rather than a predefined parameter. Also, in the model developed in Chapter 3, it was assumed that for any harvesting activity, all cut blocks had the same precedence relationship. However, the precedence relationship may vary depending upon the slope of the cut block. In this chapter, it is assumed that in cut blocks with a slope ≤50%, succeeding activities can start before the completion of the preceding activities with a small-time gap between the start time of these activities, while in cut blocks with a slope>50%, succeeding activities cannot start before the completion of preceding activities. The developed model can be applied to different regions by: 1) changing the value of the input parameter ρ_k, i.e., the number of machines that can be assigned per hectare for harvesting activity *k,* and 2) generating sets of cut blocks with different slopes for the precedence relationship between harvest activities specific to that region.

The results (Table 4-7) of the developed model in this chapter are compared with those from Chapter 3 for the same case study because it is the most comprehensive model for detailed scheduling in the existing literature. The model developed in Chapter 3 is named as "existing model" and the model developed in this chapter is named as "developed model" for comparison.

Table 4-7 Comparison of costs from existing model and developed model

Cost component	**Existing model (Chapter 3)**		**Developed model (Chapter 4)**	
	Cost (Can$)	**Percentage**	**Cost (Can$)**	**Percentage**
Operating cost of machines	2,292,247	25.40	3,862,319	64.78
Movement cost of machines	26,642	0.30	44,345	0.74
Penalty cost for not performing an activity	5,772,478	63.96	211,677	3.55
Cost of operating after the planning horizon	832,018	9.22	1,682,200	28.21
Cost of idle time of machines	1,211	0.01	941	0.02
Fixed operating cost of using machines	100,280	1.11	160,600	2.69
Total cost	**9,024,876**	**100**	**5,962,082**	**100**

The total cost has decreased significantly from 9.02 million to 5.98 million Can$ with the possibility of assigning multiple machines for each activity at each cut block and different precedence relationships for different cut blocks. The penalty cost has decreased drastically from 5.77 million to 0.212 million Can$. This decrease can be attributed to the fact that in 11 cut blocks, manual felling was not finished as per the existing model due to the low productivity of this harvesting activity. Therefore, succeeding activities did not start within the planning horizon in those 11 cut blocks. In the developed model, in 16 cut blocks, multiple fellers are assigned as shown in Table 4-8 to ensure that manual felling and processing are completed in all cut blocks to guarantee that succeeding activities start within the planning horizon. The other reason for the decrease in the penalty cost can be attributed to the fact that in 21 cut blocks succeeding and preceding activities can take place simultaneously with a small gap between the start time of those activities. Therefore, in 4 cut blocks multiple activities take place simultaneously at the end of planning horizon which was not possible in the existing model. The results of the developed model indicated more harvesting compared to that from the existing model. Therefore, as shown in Table 4-9, the contribution of the operating cost of machines within and after the planning horizon to the total harvesting cost increased from 34.66% (in the existing model) to 92.99% (in the developed model). Also, the fixed operating cost of using machines increased from 100,280 Can$ to 160,600 Can$ because more machines were used according to the results of the developed model.

Table 4-8 Details regarding machine assignments for harvesting activities (Developed Model)

Harvesting activity	Cut blocks with multiple machines assignment	Maximum number of machines assigned	Average number of machines
Manual felling and processing	16	10	2.2
Mechanical felling	0	1	1
Ground yarding	2	2	1.09
Cable yarding	3	2	1.15
Aerial yarding	0	1	1
Mechanical processing	0	1	1
Loading	3	2	1.12

Table 4-9 Comparison of harvesting volume, operating cost of machines, and cost of operating after the planning horizon resulted from the existing model and developed model

Activity	Existing Model (Chapter 3)		Developed Model (Chapter 4)	
	Volume (m^3)	Operating cost of machines and cost of operating after the planning horizon (Can$)	Volume (m^3)	Operating cost of machines and cost of operating after the planning horizon (Can$)
Manual felling and processing	134,565	1,643,578	134,565	1,642,030
Mechanical felling	27,935	147,640	27,935	147,618
Ground yarding	23,240	118,635	67,620	313,189
Cable yarding	14,860	346,657	84,880	2,206,913
Aerial yarding	10,000	715,385	10,000	715,385
Mechanical	12,755	67,268	27,935	147,913
Loading	30,000	85,102	126,000	371,471
Total		3,124,265		5,544,519

The amount of harvesting performed according to the two models is presented in Figure 4-6. The number of cut blocks in which harvesting is completed within the planning horizon increased from 13 to 17 due to the assignment of multiple machines. Moreover, the number of cut blocks in which all harvesting activities start within the planning horizon has increased from 16 to 25 cut blocks. This increase in the amount of harvesting can be attributed to the fact that, as per the results of the existing model, the manual felling and processing require some extra time after the planning horizon in 11 cut blocks. Hence, no other activities can start in those 11 cut blocks.

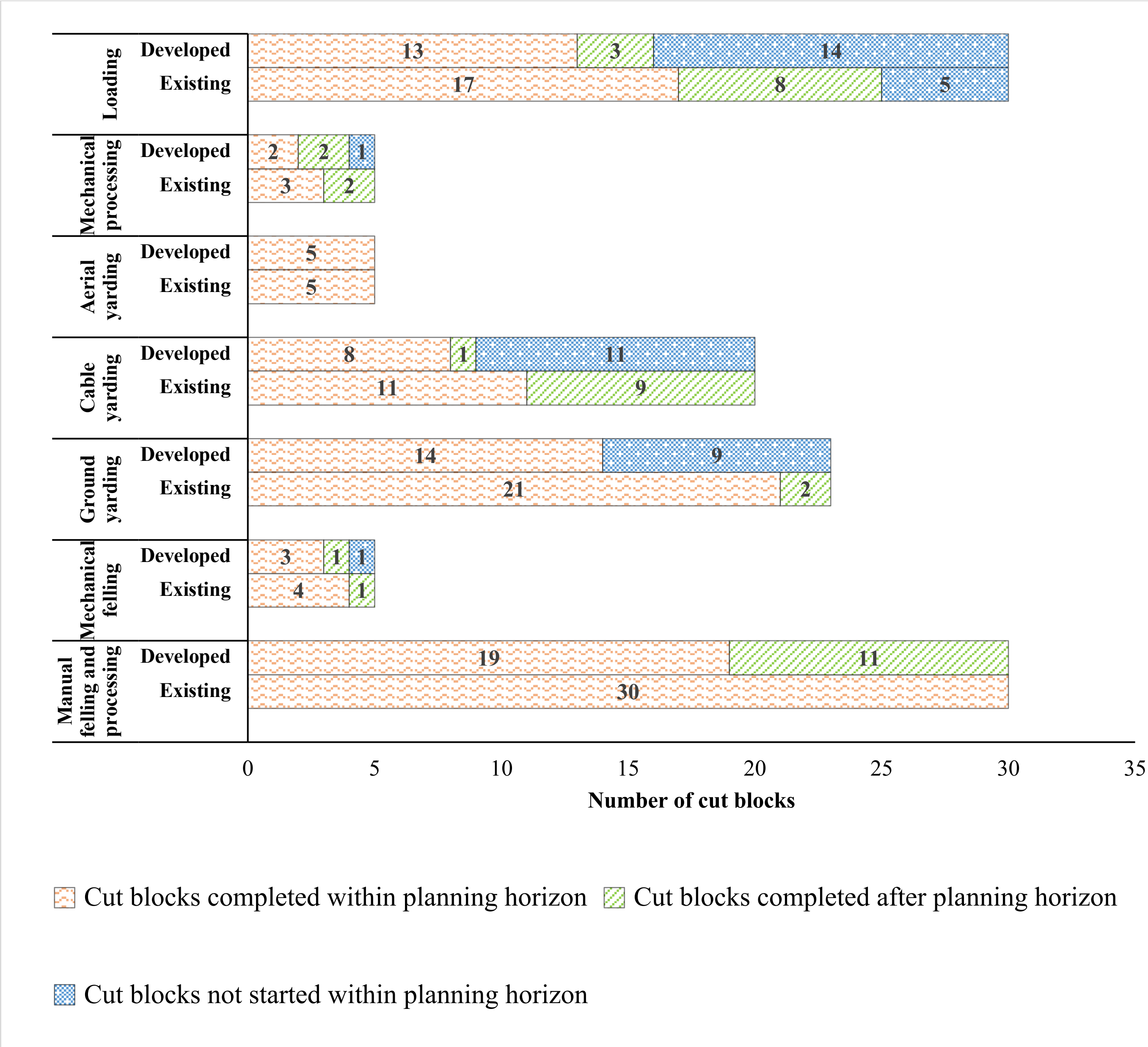


Figure 4-6 Comparison of harvesting activities completed, not completed and not started on cut blocks during the planning horizon for existing and developed model

Assigning multiple machines for each harvesting activity was also used in the studies for detailed scheduling of agricultural harvesting at multiple farms considering the precedence relationship between activities. In these studies, mathematical programming models were developed to minimize the total time of harvesting at all agricultural farms (Basnet et al. 2006; Orfanou et al.

2013; Edwards et al. 2015; Guan et al. 2018). However, in all these studies, the authors did not consider any planning horizon, which makes them different from the current study. Another possible application of multiple machine assignment can be in open-pit mine scheduling which involves a sequence of activities such as drilling, blasting, and excavating with a precedence relationship between them (Kozan and Liu 2017). In this paper, only one machine was assigned for each mining activity at a time.

We did not opt to use metaheuristics or heuristics methods to solve this problem because the solver found a very good solution with the optimum penalty cost, and the operating cost only 3.3% higher than that of the ideal operating cost case within 20 hrs. This duration is acceptable for a model that has to be executed for a planning horizon of 12 weeks.

4.6 Conclusion

In this chapter, the model developed in Chapter 3 for detailed scheduling of harvesting activities at the operational level is modified with additional decision variables regarding machine assignments and consideration of complex precedence relationships. In this chapter, we assumed that multiple machines could be assigned for each harvesting activity at each cut block. However, the ending time of all assigned machines were the same. Also, the precedence relationship between different activities depended upon the slope of the cut block.

The model was applied to the harvesting operations of a forest company in coastal British Columbia, Canada for a planning horizon of 12 weeks. AIMMS found the solution after 20 hours. As per the model solution, all assigned activities were completed within the planning horizon in 17 cut blocks and some activities required some extra time after the planning horizon in 13 cut blocks. All activities except loading started in all assigned cut blocks. The model's operating cost of machines and the penalty cost were compared with two benchmark cases. The operating cost of the model was only 3.8% higher than that of the ideal operating cost case for the same amount of harvesting performed during the planning horizon. The penalty cost of the model was identical to the that of the ideal cost case. Out of 134 available machines, 91 machines were used for harvesting, and only 1 machine had an idle time. The results of the developed model were also compared with those from Chapter 3 for the same case study. The value of the objective function has decreased significantly due to the possibility of assigning multiple machines and consideration of different precedence relationships for different cut blocks. At the same time, the amount of harvesting performed by developed model is significantly higher than that of the previous model.

Chapter 5: Detailed scheduling of forest harvesting operations on multiple cut blocks using multi-task machines

5.1 Synopsis

The modernization of forest harvesting operations has significantly increased the cost of machine ownership and has turned the forest harvesting into a capital-intensive process. In order to increase productivity and profitability, some companies have acquired multi-task harvesting machines. While many previous papers focused on optimizing the harvest scheduling to reduce the total costs of harvesting, exclusive machines for each harvesting activity were considered in their models. In this chapter, a mathematical programming model is developed to optimize the detailed scheduling of harvesting activities on multiple cut blocks using machines that can perform multiple activities. This model is an extension of our previous model developed in Chapter 4. It determines the start time and the end time of operations of each machine at each cut block, the number of machines to be assigned for each harvesting activity at each cut block, the cut block that the machine should move to after completing its operation at a cut block, and the type of activity it should perform in order to minimize the total harvesting cost. The model is applied to a real case of a large forest company in the Coastal region of British Columbia, Canada. The results show that the optimum operating cost of harvesting is only 4.5% higher than that of the ideal operating cost case. The model's results were compared with the results of Chapter 4 for the same set of 23 cut blocks in which the road was already constructed. The results show lower cost of machine movement and fewer machines needed when multi-task machines are used compared with exclusive machines.

5.2 Problem Formulation

Forest harvesting has evolved from a low-productive manual labor system with basic tools to a highly productive mechanized operation with lower labor input (Visser 2010). One major component of the harvesting cost is the machine ownership cost, as machines for harvesting have high purchase costs. In their study, Murray et al. (2022) found that the machine ownership cost for different activities varies between 35% to 40% of the total cost. Therefore, some forest companies acquire multi-task machines to increase the productivity and utilization of machines to offset this high capital cost and consequently increase profitability. Also, sometimes a road needs to be constructed within a cut block before the start of harvesting, which results in some extra activities such as the felling of trees and loading. It is important to schedule these activities in the operational level plans because the companies use the same set of machines for road construction activities as well as the main harvesting activities. For instance, in the case study discussed in Chapter 1.3, the same feller buncher is used for the felling of trees for road construction as well as for the main felling of the cut block.

In detailed harvest scheduling at the operational level, to the best of our knowledge, no previous study has considered machines that can be used for multiple harvesting activities. Also, the scheduling of activities related to the construction of roads within a cut block before the start of other harvesting activities is not considered in the detailed scheduling studies. To address these research gaps, a mathematical programming model is developed in this chapter for scheduling of forest harvesting activities, considering the possibility that the same machine can be used for multiple activities and scheduling activities related to road construction. Similar to Chapter 4, the developed model also includes a precedence relationship between harvesting activities based on the slope of cut blocks, machine assignment decisions, and the movement of individual machines between cut blocks. The model is applied to the harvesting operations of the case study presented in Chapter 1.3.

5.3 Mathematical formulation

A mixed-integer linear programming model is developed for a planning horizon of 12 weeks and weekly decisions (time steps). The model is a modification of the model developed in Chapter 4 by changing decision variables for the movement of machines to include the possibility of assigning the same machine for multiple activities, which resulted in altering 18 constraint sets and adding 5 new ones. All assumptions and case considerations discussed in Chapter 4.3 are used except the following two assumptions:

- Roads are already constructed in all the cut blocks.
- Each activity uses exclusive machines.

In this model, the construction of road in cut blocks before the start of harvesting (if required) is included and resulted in 12 possible harvesting activities. In this chapter, machines are not exclusive and can be used for more than one activity. So, in this model, machines are not exclusive to a harvesting activity, but it is exclusive to the defined type of machine (b). The list of harvesting activities and types of machines are shown in Table 5-1 and Table 5.2, respectively. In addition, following assumptions are added to the mathematical model:

- The detailed scheduling of machines for the road construction activity is not part of this mathematical model. Instead, the model just prescribes the start time of road construction, and the end time of road construction is determined based on the deterministic duration of the road construction. The duration of the road construction is proportional to the volume of trees felled for road construction.
- For cut blocks in which both manual felling and mechanical felling take place for road construction, manual felling is considered as the preceding activity for road construction to reduce the constraints related to the start time of road construction.

Table 5-1 List of harvesting activities

Activity number	**Harvesting activity**	**Number of cut blocks in which activity take place in the current planning horizon**
1	Manual felling and processing (For road)	7
2	Mechanical felling (For road)	1
3	Road construction (For road)	7
4	Mechanical processing (For road)	1
5	Loading (For road)	7
6	Manual felling and processing	30
7	Mechanical felling	5
8	Ground yarding	23
9	Cable yarding	20
10	Aerial yarding	5
11	Mechanical processing	5
12	Loading	30

Table 5-2 Details of machines

Machine type	**Name of machine**	**Number of machines**
b1	Chainsaw	60
b2	Feller buncher	1
b3	Mechanical processor	6
b4	Hoe chucker	40
b5	Cable yarder	22
b6	Helicopter	2
b7	Ground yarder	1
b8	Loader	2

In the model developed in this chapter a new index '*b*', which represents the type of machine, is added to the decision variables used in the previous chapter for the start time of machine *j* to perform activity *k* at cut block *i* (X_{jik}), the end time of machine *j* to perform activity *k* at cut block *i* (Y_{jik}), and the extra time required by machine *j* to perform activity *k* at cut block *i* after the planning horizon (V_{jik}). This index is added because the machines are not exclusive to a harvesting activity, and depending on the machine type more than one activity can be performed. Moreover, two separate binary variables are defined for: 1) the movement of a machine from the depot to a cut block, and 2) the movement of a machine between cut blocks. Both binary variables are explained below:

W_{jbik} - This variable will take a value of 1 if machine *j* of type *b* is moved from the depot to cut block *i* to perform activity *k*, otherwise it will be 0.

$W1_{jbi'ik'k}$ - This variable will take a value of 1 if machine *j* of type *b* performing activity *k'* at cut block *i'* moves to cut block *i* to perform activity *k*, otherwise its value will be 0. In this case, *k* and *k'* belongs to set of activities performed by machine type *b*. In the previous chapter, the variable for the movement of a machine between cut blocks had only 4 indices (*j,i',i,,k*) because it was assumed that machine *j* was exclusively used for one activity. However, in this work, a machine can perform more than one type of activity in the previous cut block, therefore in addition to the index for the type of machine (*b*), index *k'* is added to represent the activity performed at the previous cut block.

All the sets, notations and decision variables which are used from previous model are represented in Tables 3-2 and 4-1. Table 5-3 depicts the new sets, parameters and variables used in the mathematical programming model. The set of activities performed by machine type *b* are shown in Table 5-4. Table 5-5 lists the set of machine types that perform activity *k*. There are 12 harvesting activities for the case study in this chapter. Input parameters which were discussed in section 3.4 are used in this model, too.

Table 5-3 Notations added for the developed model

Sets	**Description**
B	Set of machine types
$J_b \subset J$	Set of machines of type b ∈ B
$\mathcal{K}_{\mathcal{B}}$	Set of activity sets performed by all machine types. Each element of $\mathcal{K}_{\mathcal{B}}$ is K_b that represents the set of activities performed by machine type *b* ∈ B

$\mathcal{B}_{\mathcal{K}}$	Set of machine types that can perform harvesting activities. Each element of $\mathcal{B}_{\mathcal{K}}$ is B_k that represents the set of machine types that can perform activity $k \in K$
$I_{3m} \subset I$	Set of cut blocks for road construction in which only manual felling for road takes place
$I_{3me} \subset I$	Set of cut blocks for road construction in which only mechanical felling for road takes place
$I_{3mme} \subset I$	Set of cut blocks for road construction in which both felling for road take place
Indices	**Description**
$b \in B$	Represents machine type
$b^p \in B$	Represents machine type for preceding activity k^p
$B_{k^p} \in \mathcal{B}_{\mathcal{K}}$	Set of machine types used for previous harvesting activity k^p
Parameters	**Description**
ν_i	Time to construct road in cut block i
Decision Variables	**Description**
X_{jbik}	Start time of machine j of type b at cut block i to perform activity k
Y_{jbik}	End time of machine j of type b at cut block i to perform activity k
V_{jbik}	Extra time required after the planning horizon by machine j of type b at cut block i to perform activity k
W_{jbik}	Binary variable; will take a value of 1 if machine j of type b is moved from the depot to cut block i to perform activity k, otherwise 0
$W1_{jbi'ik'k}$	Binary variables; will take a value of 1 if machine j of type b is moved from cut block i' performing activity k' to cut block i to perform activity k

Table 5-4 Set of activity sets performed by machine type b ($\mathcal{K}_{\mathcal{B}}$)

Set of activities performed by machine type *b* (K_b)	Harvesting Activities*
K_{b1}	(1,6)
K_{b2}	(2,7)
K_{b3}	(4,11)
K_{b4}	(5,8,12)
K_{b5}	9
K_{b6}	10
K_{b7}	8
K_{b8}	(5,12)

* Harvesting activity numbers correspond to those activities in Table 5-1

Table 5-5 Set of machine types that perform activity k ($\mathcal{B}_{\mathcal{K}}$)

Set of machine types for activity *k*	Machine type*
B_1	b1
B_2	b2
B_4	b3
B_5	(b4, b8)

B_6	b1
B_7	b2
B_8	(b4, b7)
B_9	b5
B_{10}	b6
B_{11}	b3
B_{12}	(b4, b8)

*Harvesting activity numbers correspond to those activities in Table 5-1

5.3.1 Objective function

The objective function of the model is to minimize the total cost as shown in equation (5.1). The components of the objective function (total cost) are presented in equations (5.2) to (5.7).

Min. Z = Minimize (Total costs) = Minimize (Fixed operating cost of using machines + Operating cost of machines + Movement cost of machines + Cost of idle time of machines + Penalty cost for not performing an activity during the planning horizon + Cost of operating after the planning horizon) (5.1)

$$Fixed\ operating\ cost\ of\ using\ machines = \sum_{b\in B}\sum_{j\in J_b}\sum_{k\in K_b}\sum_{i\in I_k} W_{jbik} * \pi_j \quad (5.2)$$

$$Operating\ cost\ of\ machines = \sum_{b\in B}\sum_{j\in J_b}\sum_{k\in K_b}\sum_{i\in I_k}\left(Y_{jbik} - X_{jbik} - V_{jbik}\right) * \beta_{jik} \quad (5.3)$$

$$Movement\ cost\ of\ machines = \sum_{b\in B}\sum_{j\in J_b}\sum_{k\in K_b}\sum_{k'\in K_b}\sum_{i\in I_k}\sum_{i'\in I_{k'}} W1_{jbi'ik'k} * \gamma_{i'i} * \lambda \quad (5.4)$$

$$Cost\ of\ idle\ time\ of\ machines = \sum_{j\in J} IT_j * \eta_j \quad (5.5)$$

$$Penalty\ cost\ for\ not\ performing\ an\ activity = \sum_{k\in K}\sum_{i\in I_k} U_{ik} * \tau_{ik} \quad (5.6)$$

$$Cost\ of\ operating\ after\ planning\ horizon = \sum_{b\in B}\sum_{j\in J_b}\sum_{k\in K_b}\sum_{i\in I_k}(V_{jbik}) * \theta_{jik} \quad (5.7)$$

5.3.2 Constraints

Constraint sets (3.11), (3.18), (3.20) to (3.24), (4.8), (4.9), (4.11) and (4.12) directly used from the previous models. Constraint sets (5.8) to (5.25) represent the constraints which are modified from the previous Chapters to accommodate multi-task machines.

Constraint set (5.8) states that machine *j* of type *b* can move to only one cut block *i* from the depot to perform only one harvesting activity $k \in K_b$.

$$\sum_{k\in K_b} \sum_{i\in I_k} W_{jbik} \leq 1, \forall\, j \in J_b, b \in B \tag{5.8}$$

Constraint set (5.9) ensures that machine *j* of type *b* can move from cut block *i* to cut block i^* to perform activity $k^* \in K_b$ only if it has arrived at the current cut block *i* either from the depot or cut block *i'*, in which it performed activity $k' \in K_b$, to perform activity *k* at cut block *i*.

$$W_{jbik} + \sum_{k'\in K_b} \sum_{i'\in I_{k'}} W1_{jbi'ik'k} \geq \sum_{k^*\in K_b} \sum_{i^*\in I_{k^*}} W1_{jbii^*kk^*}\ , \forall\ i \in I_k, k \in K_b, j \in J_b, b \in B \tag{5.9}$$

Constraint set (5.10) guarantees that the total number of machines move from depot or another cut blocks to cut block *i* for activity *k* is always lower than the maximum number of machines that can be assigned to that cut block based on the area of the cut block.

$$\sum_{b\in B_k} \sum_{j\in J_b} W_{jbik} + \sum_{b\in B_k} \sum_{j\in J_b} \sum_{k'\in K_b} \sum_{i'\in I_{k'}} W1_{jbi'ik'k} \leq 1 + \left(\xi_i * \rho_k\right), \forall\ i \in I_k\ , k \in K \backslash \{3\} \tag{5.10}$$

Constraint sets (5.11) and (5.12) ensure that in case machine *j* of type *b* does not move to cut block *i* either from the depot or cut block i' to perform activity *k*, then the machine's start time and end time for performing activity *k* at cut block *i* will be zero.

$$Y_{jbik} \leq M * (W_{jbik} + \sum_{k'\in K_b} \sum_{i'\in k'} W1_{jbi'ik'k})\ , \forall\ i \in I_k\ , k \in K_b, j \in J_b, b \in B \tag{5.11}$$

$Y_{jbik} \geq X_{jbik}$, $\forall\, i \in I_k, k \in K_b, j \in J_b, b \in B$ (5.12)

Constraint set (5.13) determines the start time of a machine's operation at a cut block when the machine moves from one cut block to another. As per this constraint set, the start time of activity *k* of machine *j* of type *b* at cut block *i* is always greater than the end time of activity $k' \in K_b$ of machine *j* at cut block *i'*, where it was working previously, plus the travel time required between the two cut blocks.

$$X_{jbik} \geq (Y_{jbi'k'} + (\gamma_{i'i}/\delta_k)) - M(1 - W1_{jbi'ik'k}), \forall\, i \in I_k, i' \in I_{k'}, k \in K_b, k' \in K_b, j \in J_b, b \in B \quad (5.13)$$

Constraint sets (5.14) and (5.15) are added to calculate the end time of operations of machine *j* at cut block *i* for harvesting activity *k*. As per these constraint sets, the summation of volume harvested by all machines *j* of type $b \in B_k$ is equal to the volume available for activity *k* at cut block *i*.

$$\sum_{b \in B_k} \sum_{j \in J_b} ((Y_{jbik} - X_{jbik}) * \text{♀}_{jik}) = \varsigma_{ik}, \forall\, k \in K\backslash\{3\}, i \in I_{kp} \quad (5.14)$$

$$\sum_{b \in B_k} \sum_{j \in J_b} ((Y_{jbik} - X_{jbik}) * \text{♀}_{jik}) = \psi_{ik} * (1 - U_{ik}), \forall\, k \in K\backslash\{3\}, i \in I_{kn} \quad (5.15)$$

Constraint set (5.16) in combination with constraint set (4.9) guarantee that all machines of type *b* assigned for harvesting activity $k \in K_b$ at cut block *i* end their operations at the same time as per the operational requirement of the company.

$$Y_{jbik} \geq \mathrm{ET}_{ik} - M * (1 - (W_{jbik} + \sum_{k' \in K_b} \sum_{i' \in I_{k'}} W1_{jbi'ik'k})), \forall\, i \in I_k, k \in K_b, j \in J_b, b \in B \quad (5.16)$$

Constraint set (5.17) ensures that in an unsafe slope (>50%) cut block *i* if machine *j* of type *b* moves from depot or cut block *i'* to perform activity *k* then the start time of machine *j* is always greater than the end of the preceding harvesting activity k^pat cut block i and a minimum lag between those two activities.

$X_{jbik} \geq (ET_{ik^p} + \mu_{ik}) - M * (1 - (W_{jbik} + \sum_{k' \in K_b} \sum_{i' \in I_{k'}} W1_{jbi'ik'k}))$ $, \forall i \in I_{kns}, k \in K_b, j \in J_b, b \in B, k^p \in (K\ preceding\ k)$ (5.17)

Constraint set (5.18) ensures that in a safe slope (≤ 50%) cut block *i* if machine *j* of type *b* moves from depot or cut block i' to perform activity *k* then the start time of machine *j* is always greater than the start of the preceding harvesting activity k^p at cut block *i* and a minimum lag between those two activities.

$X_{jbik} \geq (ST_{ik^p} + \mu_{ik}) - M * (1 - (W_{jbik} + \sum_{k' \in K_b} \sum_{i' \in I_{k'}} W1_{jbi'ik^*k}))$ $, \forall i \in I_{kng}, k \in K_b, j \in J_b, b \in B, k^p \in (K\ preceding\ k)$ (5.18)

Constraint set (5.19) guarantees that machine *j* of type *b* can only move to cut block *i* to perform activity $k \in K_b$ if machine j^p of type $b^p \in B_{k^p}$ has been there in the past to perform preceding activity k^p at cut block *i.*

$(W_{jbik} + \sum_{k' \in K_b} \sum_{i' \in I_{k'}} W1_{jbi'ijk'k}) \leq M * (\sum_{b^p \in B_{k^p}} \sum_{j^p \in J_{b^p}} W_{j^p b^p ik^p} + \sum_{b^p \in B_{k^p}} \sum_{j^p \in J_{b^p}} \sum_{k' \in K_{b^p}} \sum_{i' \in I_{k'}} W1_{j^p b^p i' ik'k^p})$ $, \forall\ i \in I_k, k \in K_b,\ j \in J_b, b \in B,\ k^p \in (K\ preceding\ k)$ (5.19)

Constraint set (5.20) guarantees that if machine *j* of type *b* does not move to cut block $i \in I_k$ from the depot to perform activity $k \in K_b$, then the start time of its operations will be zero.

$S_j \leq M * \sum_{k \in K_b} \sum_{i \in I_k} W_{jbik}$ $, \forall\ \mathrm{j} \in \mathrm{J_b}, \mathrm{b} \in \mathrm{B}$ (5.20)

Constraint sets (5.21) and (5.22) are added to calculate the value of penalty variables. Constraint set (5.21) ensures that if no machine moves to cut block i from the depot or any other cut block to perform activity k, then the penalty variable U_{ik} will take value 1. Otherwise, the penalty variable will take value zero as per constraint set (5.22).

$$\sum_{b\in B_k}\sum_{j\in J_b} W_{jbik} + \sum_{b\in B_k}\sum_{j\in J_b}\sum_{k'\in K_b}\sum_{i'\in I_{k'}} W1_{jbi'ik'k} \geq (1-U_{ik}), \forall\, i \in I_k, k \in K\setminus\{3\} \tag{5.21}$$

$$M * (1-U_{ik}) \geq \sum_{b\in B_k}\sum_{j\in J_b} W_{jbik} + \sum_{b\in B_k}\sum_{j\in J_b}\sum_{k'\in K_b}\sum_{i'\in I_{k'}} W1_{jbi'ik'k}, \forall\, i \in I_k, k \in K\setminus\{3\} \tag{5.22}$$

Constraint set (5.23) calculates the volume left in cut blocks in which harvesting started during the planning horizon. This value of R_{ik} will be used as a parameter ς_{ik} in the next planning horizon.

$$R_{ik} = \sum_{b\in B_k}\sum_{j\in J_b} V_{jbik} * \text{♀}_{jik}, \forall\, k \in K\setminus\{3\},\ i \in I_k \tag{5.23}$$

Constraint sets (5.24) and (5.25) are added to calculate the number of machines assigned at a cut block for a harvesting activity and the idle time of each machine, respectively.

$$N_{ik} = \sum_{b\in B_k}\sum_{j\in J_b} W_{jbik} + \sum_{b\in B_k}\sum_{j\in J_b}\sum_{k'\in K_b}\sum_{i'\in I_{k'}} W1_{jbi'ik'k}, \forall\, k \in K\setminus\{3\}, i \in I_k \tag{5.24}$$

$$IT_j = (E_j - S_j) - \sum_{k\in K_b}\sum_{i\in I_k}(Y_{jbik} - X_{jbik}) - \sum_{k\in K_b}\sum_{k'\in K_b}\sum_{i\in I_k}\sum_{i'\in I_{k'}} W1_{jbi'ik'k} * (\gamma_{i'i}/\delta_k), \forall\, j \in J_b, b \in B \tag{5.25}$$

Constraint sets (5.26) to (5.30) are added for the road construction activity. Constraint sets (5.26), and (5.27) determine the start time of road construction in cut blocks in which only manual felling, and only mechanical felling take place for road, respectively.

$$\mathrm{ST}_{i3} = \mathrm{ST}_{i1} + \mu_{i3}, \forall\, i \in I_{3m} \tag{5.26}$$

$$\mathrm{ST}_{i3} = \mathrm{ST}_{i2} + \mu_{i3}, \forall\, i \in I_{3me} \tag{5.27}$$

Constraint sets (5.28) and (5.29) work together to determine the start time of road construction and start time of mechanical felling in cut blocks where both felling types occur for road construction.

Constraint set (5.28) determines the start time of road construction (ST_{i3}), which is the start of manual felling (ST_{i1}) plus the time lag between road construction and manual felling (μ_{i3}).

Constraint set (5.29) ensures that in these cut blocks, the start time of mechanical felling (for road), i.e., X_{jbi2}, is less than the start time of manual felling plus the time required for the road construction in the manually felled part ($\mathrm{ST}_{i1} + (\nu_i * \frac{\psi_{i1}}{(\psi_{i1} + \psi_{i2})}$).

$$\mathrm{ST}_{i3} = \mathrm{ST}_{i1} + \mu_{i3}, \forall\, i \in I_{3mme} \tag{5.28}$$

$$X_{jbi2} \leq \mathrm{ST}_{i1} + (\nu_i * \frac{\psi_{i1}}{(\psi_{i1} + \psi_{i2})}) \quad , \; \forall\, i \in I_{3mme} \tag{5.29}$$

Constraint set (30) calculates the end time of road construction in cut block i.

$$\mathrm{ET}_{i3} = \mathrm{ST}_{i3} + \nu_i, \forall\, i \in I_3 \tag{5.30}$$

Equations (5.31), (5.32), and (5.33) represent the domain of all decision variables.

$$X_{jbik}, S_j, Y_{jbik}, V_{jbik}, IT_j, E_j, R_{ik} \in \mathrm{R}^+ \tag{5.31}$$

$$N_{ik} \in \text{ Integers} \tag{5.32}$$

$$U_{ik}, W_{jbik}, W1_{jbi'ik'k} \in \{0,1\} \tag{5.33}$$

5.3.3 Model execution

The model is executed for the case study, which included 30 cut blocks and 134 machines for a planning horizon of 12 weeks. In 7 cut blocks, road had to be constructed before starting the harvesting. The developed model for the case study includes 293,053 constraints, 16,432 continuous decision variables, and 363,782 binary decision variables. The AIMMS software (AIMMS 2022) is used for the execution of the mathematical programming model on a computer with Intel ® core ™ i7-6700 CPU @ 3.41 GHz processor and 16.0 GB RAM. The model in AIMMS was solved using the CPLEX 22.1 solver(CPLEX 2021).

For comparison of the cost results, no data were available from the company. Therefore, similar to Chapter 3, three benchmarks are defined: 1) the ideal operating cost case, 2) the average operating cost case, and 3) the penalty cost case. The value of these benchmarks is shown in Table 5-6. The lowest possible cost is the summation of the ideal penalty cost and the ideal operating cost. This cost does not include movement, idle time, or fixed operating costs.

Table 5-6 Value of benchmarks for comparison of results

Ideal operating cost	4,030,091 Can$
Average operating cost	5,677,421 Can$
Ideal penalty cost	2,517,184 Can$
Lowest possible cost	6,547,275 Can$

5.4 Results

The solution is provided by AIMMS after about 250 million iterations in 19 hrs. Ninety-one out of 134 machines are used in the best integer solution. Only one machine has an idle time. The value of the objective function is 6,932,153 Can$. In 13 cut blocks, the same machine is used for ground yarding and loading. The penalty cost per model’s output is equal to that of the ideal penalty cost case. So, it can be concluded that the penalty cost is optimum and cannot be decreased further. All other components of the objective function costs are shown in Table 5-7.

Table 5-7 Components of total cost

Component	**Value (Can$)**
Fixed operating cost	160,600
Operating cost	3,034,463
Movement cost of machines	29,424
Idle time cost	4,413
Penalty cost	2,517,184
Cost of operating after planning horizon	1,186,068
Total cost	6,932,153

Table 5-8 shows the total operating cost, volume, and the operating cost per volume for each harvesting activity. Due to the use of hoe-chuckers for both ground yarding and loading, more low operating cost machines are available for ground yarding. As a result, the operating cost per volume for ground yarding decreased from 5.10 Can$/$m^3$ (Tables 3-5 and 4-3) to 4.12 Can$/$m^3$.

Table 5-8 Operating cost for each harvesting activity for a 12-week planning horizon

Activity	**Operating cost (Can$)**	**Volume (m^3)**	**Operating cost per volume (Can$/$m^3$)**
Manual felling and processing (For road)	91,774	7,520	12.20
Mechanical felling (For road)	10,435	1,980	5.27
Mechanical processing (For road)	10,571	1,980	5.33
Loading (For road)	21,590	6,500	3.32
Manual felling and processing	1,150,403	94,303	12.20
Mechanical felling	85,699	16,261	5.27
Ground yarding	137,989	33,473	4.12
Cable yarding	646,334	26,249	24.62
Aerial yarding	715,385	10,000	71.54
Mechanical processing	53,225	100,30	5.33
Loading	111,059	35,698	3.11

Figure 5-1 represents the amount of harvesting performed during the planning horizon. According to the results, in 16 cut blocks, all assigned activities are finished within the planning horizon, and in the rest of the cut blocks (14 cut blocks), some activities required extra time after the planning horizon to be completed. The manual felling and processing (for road), mechanical felling (for road), mechanical processing (for road), and aerial yarding are completed in all the assigned cut blocks within the planning horizon. The road construction, mechanical felling, and mechanical processing started in all assigned cut blocks, but in some cut blocks, they are not completed within the planning horizon. In some cut blocks, loading (for road), manual felling and processing, ground yarding, cable yarding, and loading did not start within the planning horizon and resulted in the penalty cost. Road construction is the main reason that some activities did not start at the cut blocks. Activities that could not start in cut blocks that involve road construction include loading (for road) in 1 cut block, manual felling and processing in 2 cut blocks, ground yarding in 2 cut blocks, cable yarding in 3 cut blocks, and loading in 6 cut blocks.

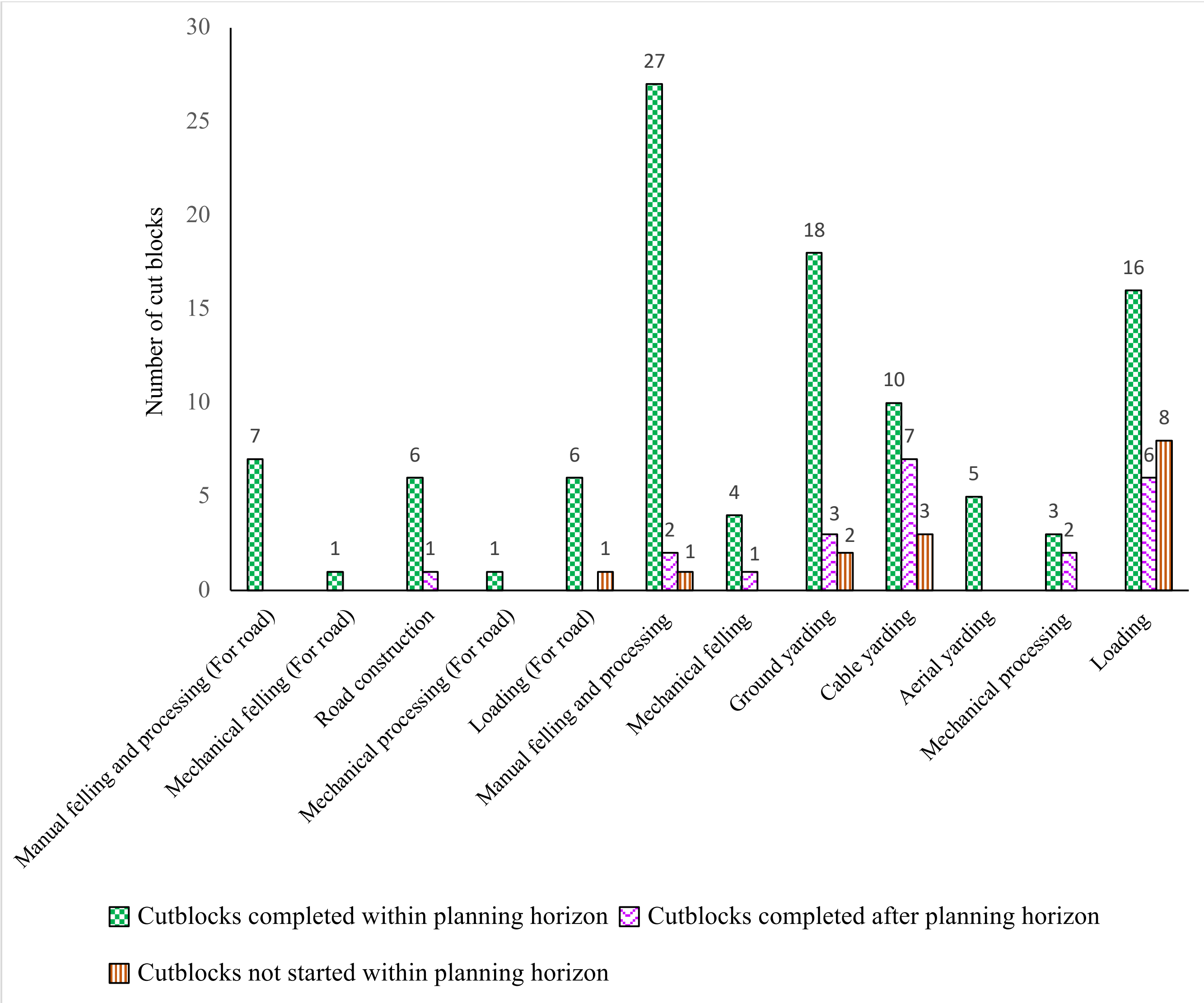


Figure 5-1 Number of cut blocks in which harvesting activities finished, started but not finished, or did not start during the planning horizon

The cost of performing harvesting activities that started within the planning horizon (including operating cost during and after the planning horizon) is compared with those of the ideal operating cost and average operating cost benchmarks (Figure 5-2). The cost from the model, i.e., summation of operating cost and cost of operating in the next planning horizon, is only 4.5% (190,440 Can$) higher than that of the ideal operating cost case and significantly lower than that of the average operating cost case. Practically, it is not possible to achieve the ideal operating cost because the number of machines with the lowest operating cost is limited, and to reduce the penalty cost, which is significantly higher than the operating cost, some machines with high operating costs are used.

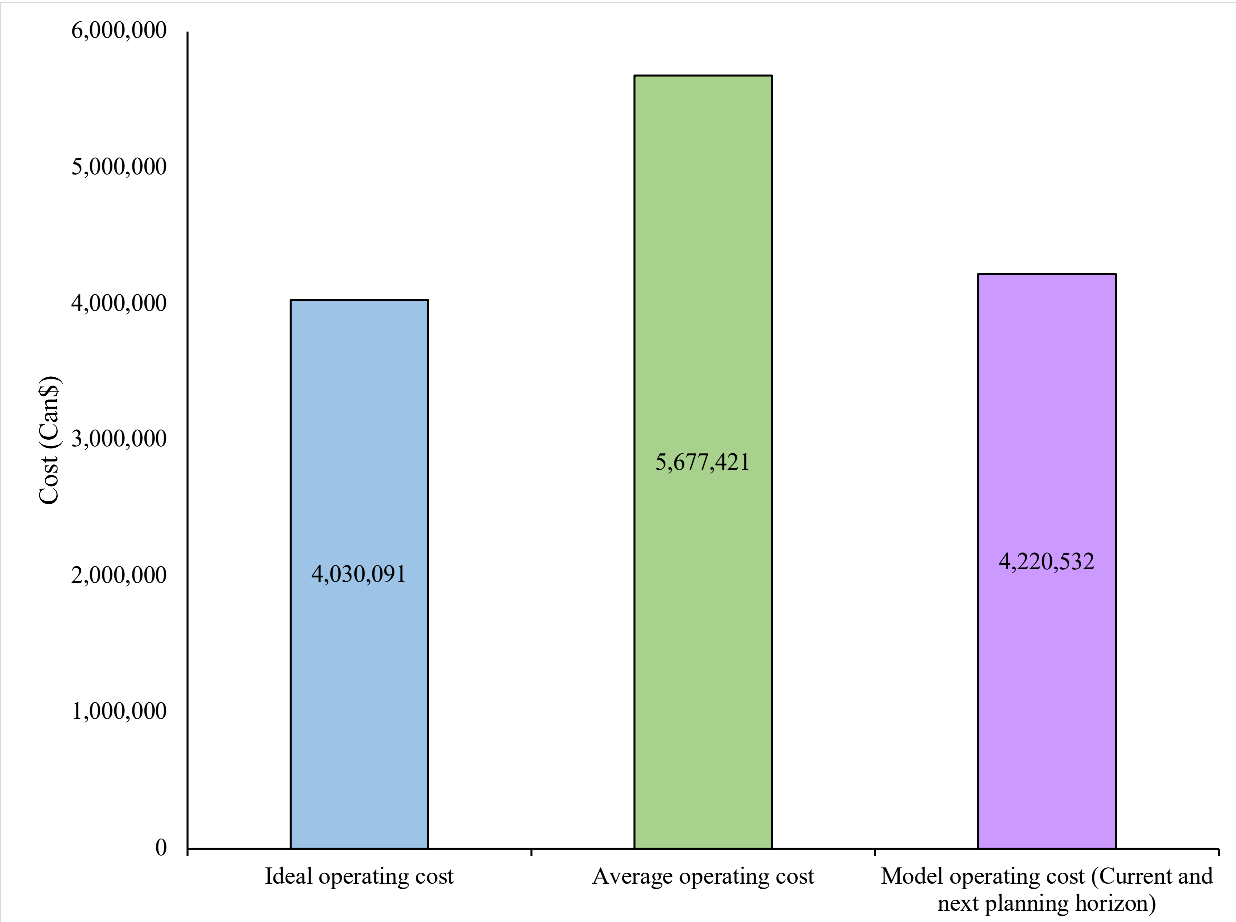


Figure 5-2 Comparison of operating costs of the developed model with those of the two benchmarks

The detailed schedule of a hoe chucker (M93) is shown in Figure 5-3 to demonstrate that the same machine performs multiple activities. According to the results, the hoe chucker moves from the depot to cut block C3. At cut block C3, it first performs ground yarding from week 8.25 to week 8.63. After finishing the ground yarding, it performs the loading at the same cut block. After its operation at cut block C3, the machine moves to cut block C15 to perform the loading activity, where aerial yarding takes place. After loading at cut block C15, the machine moves to cut block C18. In cut block C18, it first performs the ground yarding from week 10.35 to 10.52 and then performs the loading from week 10.52 to 11.69. After completing its operation at cut block C18, the hoe chucker moves to cut block C19, where it performs the loading from week 11.76 till the end of the planning horizon and will continue to perform the loading in the next planning horizon. Similar schedules are generated for all machines, but are not shown here due to brevity.

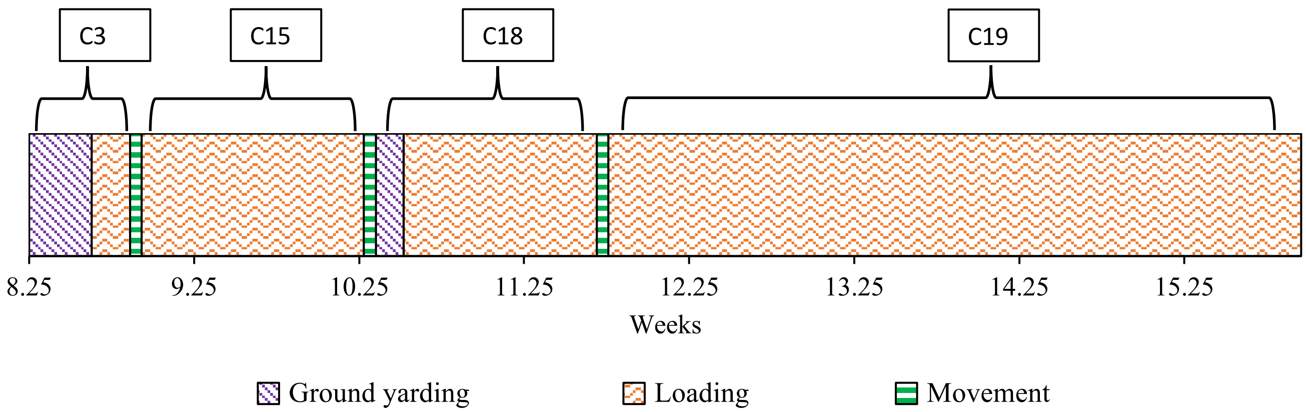


Figure 5-3 Detailed schedule of hoe chucker (M93)

The detailed scheduling of harvesting activities at cut block C14 is depicted in Figure 5-4. In this cut block, the highest number of harvesting activities occurs, i.e., 11, because it involves road construction and both types of felling. In this cut block, manual felling and processing (for road) and mechanical felling (for road) first take place to gain access to the cut block. The road construction starts 0.4 weeks (2 days) after the start of the manual felling and processing. The mechanical processing for road construction starts at week 6.85, which has a precedence relationship with mechanical felling for the road, i.e., it can start at least one week after the start of mechanical felling for the road. The loading (for road) starts at week 8.45, which is 0.4 weeks (2 days) after the completion of the road construction due to the precedence relationship requirements. Both manual felling and mechanical felling start with a lag of 0.2 weeks (1 day) after completing the loading activity (for road). In this cut block, the ground yarding has a precedence relationship with the start of mechanical felling, so it starts at week 11.27, more than

1.25 weeks after the start of mechanical feeling. Similarly, the mechanical processing has a precedence relationship with the start of the ground yarding, so it starts 0.47 weeks (2.35 days) after the start of ground yarding. In this cut block, the manual felling and processing finish at week 13.6, i.e., 1.6 weeks after the end of the planning horizon. Therefore, the cable yarding could not start in this planning horizon because as per the precedence relationship, the cable yarding cannot start at a cut block before the completion of the manual felling and processing. Similarly, loading could not start in this cut block as it has a precedence relationship with the start of the cable yarding. This results in penalty costs for both activities in this cut block. Similar schedules are generated for all the cut blocks but are not shown here due to brevity.

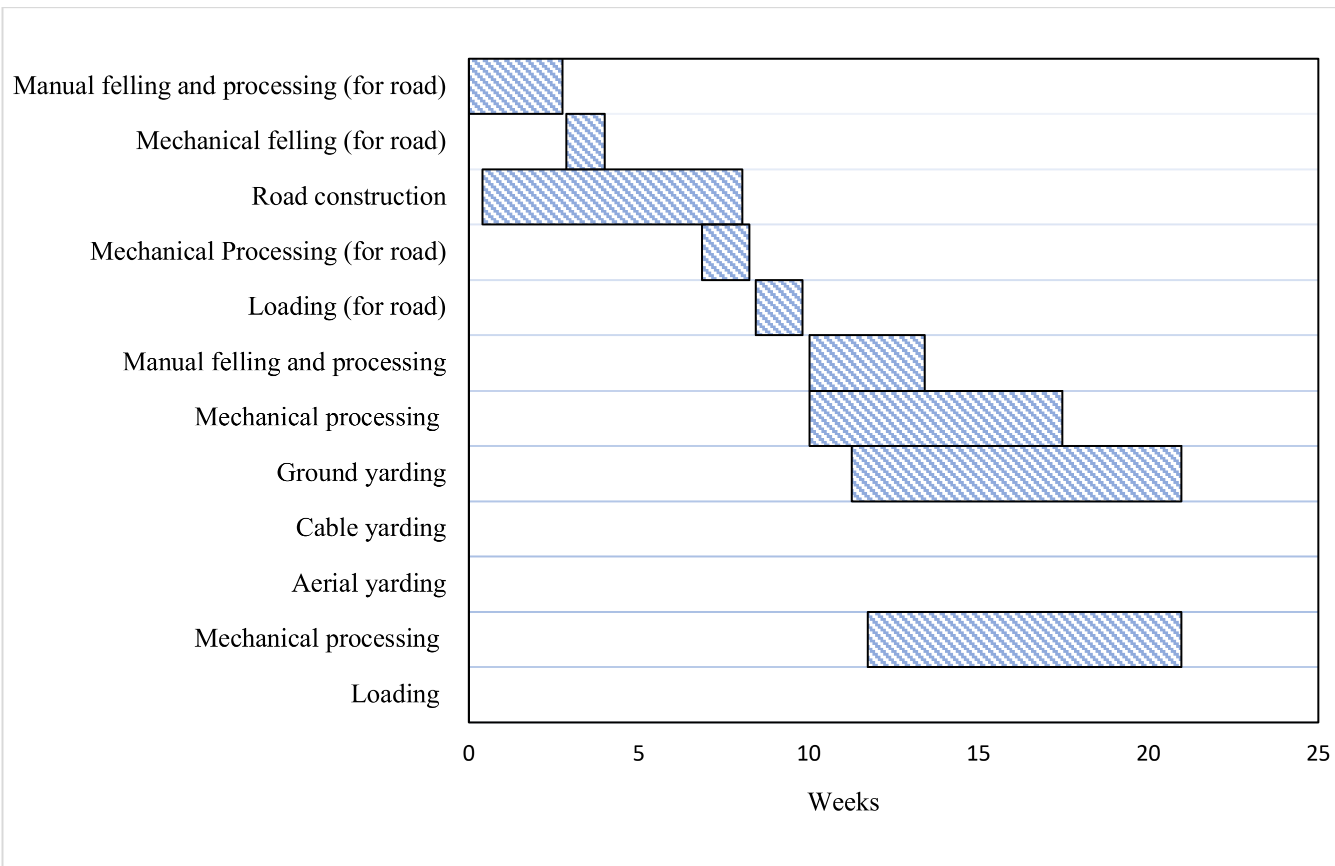


Figure 5-4 Detailed schedule of cut block C14

In order to demonstrate that the developed model ensures the continuity of operations between the planning horizons, we ran the model for two consecutive planning horizons and used the output of the first planning horizon as the input for the second planning horizon. Table 5-9 shows the schedule of manual felling at cut block C22. As shown in this table, the end time of operations for the two fellers (machine M1 and Machine M34) is 14.2 weeks, so their work cannot be completed in the current planning horizon and they require 2.2 weeks to finish their operation in the next planning horizon. In the model run of the next planning horizon, the same fellers are assigned to cut block C22, and they start their operation from time zero and finish at week 2.2. In this way, the model guarantees that if a machine is working at a cut block at the end of one planning horizon, then in the next planning horizon, it continues its operation in the same cut block.

Table 5-9 Schedule of manual felling at cut block C22

Machine	Current planning horizon		Next planning horizon	
	Start time (week)	End time	Start time	End time (week)
M1	6.9	14.2	0	2.2
M34	6.9	14.2	0	2.2

5.4.1 Sensitivity Analysis

To evaluate the impact of changes in the input parameters on the model results, the following parameters are increased and decreased by 30%:

- Penalty cost for each activity at each cut block
- Fixed operating cost of each machine
- Extra time cost of performing operation in the next planning horizon
- The maximum number of machines that can be assigned at each cut block for each activity

The results of the sensitivity analysis are shown in the Figure 5-5.

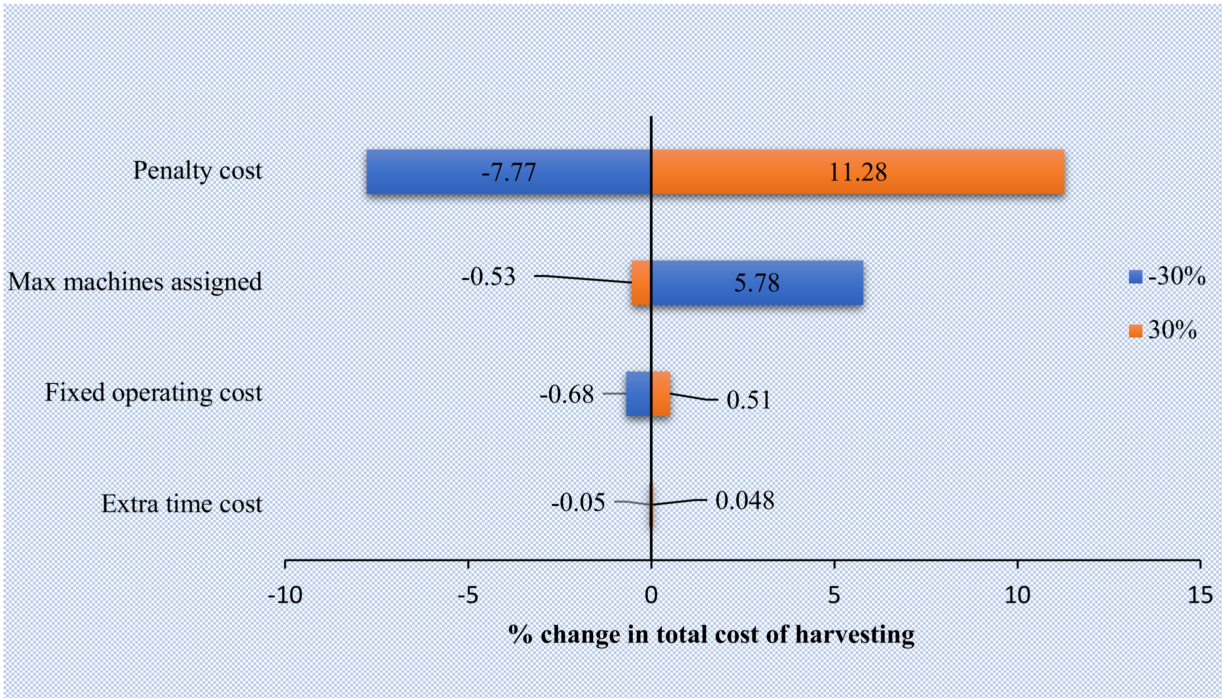


Figure 5-5 Results of the sensitivity analysis

The model is most sensitive to changes in the penalty cost values. The increase in the value of penalty cost increases the objective function value due to an increase in the penalty cost of cut blocks in which some activities cannot start. However, the amount of harvesting performed remains almost the same, because the penalty cost of not performing an activity is significantly higher than the operating cost. On the contrary, when the penalty cost decreases by 30%, the value of the objective function decreases due to a decrease in the penalty cost of cut blocks in which some activities cannot start, but at the same time, the amount of harvesting performed also decreases. The reason is that in some cut blocks the increase in the penalty cost of not performing loading is lower than the increase caused by using high operating cost machines for cable yarding. Therefore, the model prescribes not using high operating cost machines for cable yarding in some small volume cut blocks, even though it results in not starting the loading activity.

The second most sensitive parameter is the maximum number of machines to be assigned to each activity at each cut block which is determine by parameter ρ_k. By increasing and decreasing ρ_k the number of machines to be assigned to each activity at each cut block increases and decreases due to constraint (4.1). For instance, if in a cut block with an area of 40 ha, the parameter (ρ_k) increases from 0.2 to 0.26, then as per constraint (4.1), the max number of machines that can be assigned to the cut block will increase from 9 to 11. Decreasing this parameter has a more significant impact on the objective function than increasing it. When the value of this parameter increases, it results in performing loading in one more cut block, leading to a decrease in the penalty cost. However, the operating cost and fixed operating cost increase because more harvesting is performed, but the overall objective function value decreased by 0.58%. On the contrary, when the value of this parameter decreases, then in two cut blocks, some activities cannot start during the current planning horizon. As a result, the penalty cost increase, the operating cost decrease and the overall objective value increases by about 5.78%.

The impact of increasing and decreasing the fixed operating cost are not very significant on the objective function. However, they affect the number of machines used for harvesting operations and the movement cost of machines. Increasing and decreasing the fixed operating cost value results in using one fewer machine and two more machines, respectively. Due to the use of fewer number of machines, the movement of machines between cut block increases and the movement of machines from depot to cut blocks decreases. In this problem, it is assumed that the distance between the depot and cut blocks is zero. As a result, the movement cost is only related to the movement of machines between cut blocks, and there is no movement cost when machines move from the depot to cut blocks. Consequently, the movement cost increases when fewer number of machines are used. Due to the same reason, the movement cost decreases when more machines are used for harvesting. The impact of the increase and decrease of the extra time cost on the objective function is negligible because this cost is assumed to be only 100 Can$/week higher than the operating cost. However, due to an increase in the extra time cost, the number of cut blocks in which harvesting activities are done within the planning horizon increases from 16 to 17.

5.5 Discussion

The detailed scheduling of harvesting activities at the operational level is an important problem in the forestry and agriculture literature. Therefore, mathematical programming models have been developed for detailed scheduling considering the precedence relationship between harvesting activities and machine assignment decisions (Basnet et al. 2006; Guan et al. 2018). In all these models, it was assumed that each machine was exclusively used for only one harvesting activity. However, in reality, forest companies utilize machines that are capable of performing multiple activities to offset the high fixed capital cost associated with these machines. In this chapter, a mathematical programming model is developed considering the assignment of multitask machines for harvesting. We considered 8 types of machines, however the types of machines and the activities they perform can vary as per user requirement by changing the input parameters of the model (elements of sets B, $\mathcal{B}_{\mathcal{K}}$ and $\mathcal{K}_{\mathcal{B}}$).

We compared the results of the developed model with those of the model developed in Chapter 4 for the same case study of 23 cut blocks in which a road is already constructed (Figure 5-5). The model developed in Chapter 4 assumes that each machine can be assigned for only one harvesting activity, and the developed model assumes that a hoe chucker can be used for both loading and ground yarding.

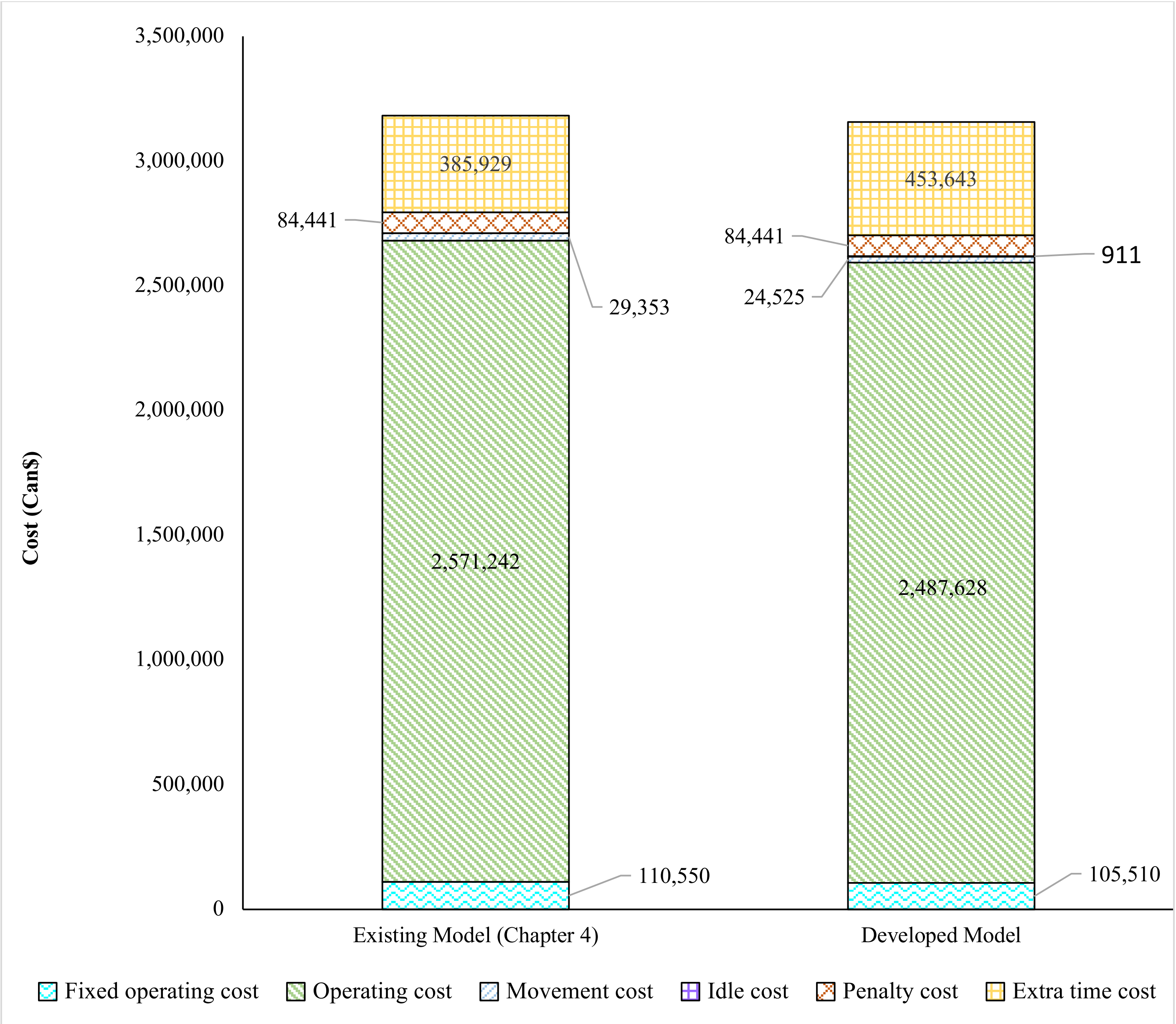


Figure 5-6 Comparison of total cost from the existing and developed model

The results of the developed model are identical to the existing model in terms of the penalty cost, which means that the same number of harvesting activities started during the planning horizon in both models. However, due to the possibility of assigning the same machine for multiple activities, the total cost of the developed model is 25,000 Can$ lower than that of the existing model. The major portion of this saving, i.e., 15,000 Can$ comes from the decrease in the operating costs during and after the planning horizon. Due to the possibility of assigning the same machine for loading and ground yarding, more low-cost machines are available for ground yarding and loading as compared to the existing model. Also, the machines movement cost between cut blocks is reduced from 29,353 Can$ in the existing model to 24,525 Can$ in the developed model because in 7 cut blocks with only ground yarding, the hoe chucker first finished the ground yarding and then started the loading. In this way, movement of separate machines to the cut block for loading has been reduced. Lastly, the fixed operating cost is reduced by 5,040 Can$ because in the developed model, fewer number of machines are used compared to that in the existing model.

Multi-task machines or resources are also considered in resource-constrained multi-project scheduling problem (RSCMPSP) in project management. Hematian et al. (2020) developed a multi-objective mathematical model for scheduling of multiple projects considering multi-task resources. In their study, the authors also included the learning and forgetting effect of human resources, which impact the efficiency of the workers. The objective function included the minimization of the total time, total execution cost, and the quality level of all the activities. However, Hematian et al. (2020) considered discrete time intervals, no planning horizon, and assumed that only one resource could be assigned for each activity at each project which made it different from our work.

We did not consider metaheuristics to solve this problem because the model needed to be executed every three months and a solution time of 19 hours is acceptable.

5.6 Conclusions

In this chapter, the model developed in Chapter 4 is extended to consider the possibility of using multi-task machines for harvesting. In the extended model, we assumed that the same machine could be used for multiple activities at the same cut block in addition to the consideration of the precedence relationship between harvesting activities, movement of individual machines between cut blocks, and the possibility of assigning multiple machines for the same harvesting activities.

The model was executed using a case study of a large forest company with 30 cut blocks and 135 machines for a planning horizon of 12 weeks. In 7 cut blocks, the road needed to be constructed before other activities could start. The model was solved using the AIMMS software package, and the solver found the best integer solution after 19 hours. In 16 cut blocks, all activities finished within the planning horizon, and in 14 cut blocks, some activities required some extra time after the planning horizon to be completed. The model assigned 91 machines (out of 134 available) for harvesting. Only one machine had an idle time. In 13 cut blocks, as per the model output, the same machine was assigned for ground yarding and loading. The operating cost of harvesting at the cut blocks and the penalty cost were compared with the those in the defined benchmarks. The operating cost of harvesting, which includes harvesting performed in this planning horizon and the next planning horizon, was only 4.5% higher than that of the ideal operating cost benchmark and significantly lower than that of the average operating cost benchmark. The model's penalty cost was equal to that of the ideal penalty cost benchmark. Hence, we concluded that the penalty cost of the model could not be improved further without changing the existing precedence relationship between activities. The developed model was compared with the model developed in Chapter 4 for detailed scheduling of harvesting for the same case of 23 cut blocks in which no road construction was required. The total cost of the developed model was about 0.8% lower than that of the existing model due to the possibility of assigning the same machine for multiple activities. The cost savings were due to reduction in the machine movement costs and fixed operating costs. The machine movement cost decreased because multiple activities could be performed by the same machine in the same cut block. The fixed operating cost decreased because due to the use of multi-task machines, fewer machines could perform the harvesting compared to the use of exclusive machines for each harvesting activity.

Chapter 6: Conclusions

6.1 Summary and Conclusions

The cost of forest harvesting contributes significantly to the delivered cost of logs, which impacts the competitiveness of the forest sector in any country. Forest harvesting includes all the activities required to convert stands of trees into industrial roundwood. It consists of felling, yarding, processing, and loading. The critical decisions in forest harvesting at the operational level are to determine the start time and end time of each harvesting activity at each cut block, the assignment of machines and crews, and how machines should move between cut blocks.

This dissertation aimed to optimize forest harvesting decisions at the operational level considering the precedence relationship between harvesting activities, movement of the individual machines between cut blocks, the possibility of assigning multiple machines at each cut block, and the possibility of utilizing machines that can perform multiple activities. To achieve this goal, optimization models were developed in this dissertation and applied to a case study in the coastal part of British Columbia, Canada.

Chapter 2 presented a review of studies in which optimization models were developed for scheduling of forest harvesting. The studies were categorized based on the planning levels. Furthermore, similar studies in different sectors were reviewed. The review highlighted that most of the studies in forest harvesting focused on economic objectives, whereas, in other sectors, the objective was to minimize the total time of harvesting. At the tactical level, few studies integrated forest harvesting decisions with timber flow and road construction decisions. The studies at the operational level focused on optimizing decisions on machine location, movement of machines between cut blocks, and detailed scheduling of harvesting. These studies did not consider the movement of individual machines, the precedence relationship between harvesting activities for multiple cut blocks, multiple machine assignments for the same activity at each cut block, and the utilization of machines that can perform multiple activities. All these aspects exist in the harvest operations of forest companies. Therefore, an optimization model should be developed considering these aspects of harvesting operations.

In Chapter 3, a mathematical model was developed for scheduling of forest harvesting, considering the precedence relationship between harvesting activities and the movement of individual machines between the cut blocks, which were not considered in the existing forestry literature at the operational level. The model determined the start and end time of each harvesting activity at each cut block and where the machine should move after the completion of each activity. The model was executed for a planning horizon of 12 weeks for a real case study. The model run included 30 cut blocks and 134 machines. The value of the best integer solution was 9,024,876 Can$. The penalty cost of not starting a harvesting activity account for 63.96% of the objection function value. This high value of penalty cost could be attributed to the assumption that at each cut block, only one machine could be assigned at each cut block. In 16 cut blocks, all assigned activities started during the planning horizon. In the rest of the cut blocks, some activities could not start during the planning horizon due to the precedence relationship between activities. As a result, only 47 out of 134 machines were assigned for harvesting during the planning horizon.

In Chapter 4, the model developed in Chapter 3 was modified by altering 7 constraint sets and adding 9 new constraint sets to include the machine assignment decisions and complex precedence relationships. The developed model also determined the number of machines assigned at each cut block for each activity in addition to the model's decisions in Chapter 3. In the model developed in Chapter 3, it was assumed that the precedence relationship between all activities is the same for all cut blocks, irrespective of their slope. However, in this model, the precedence relationship between activities could vary based on the slope of the cut blocks. The model was executed for the same case study as in Chapter 3. The value of the objective function decreased from 9,024,876 Can$ in Chapter 3 to 5,962,082 Can$ in this chapter. This decrease in the objective function value can be attributed to the fact that the penalty cost of not starting a harvesting activity during the planning horizon had decreased drastically from Chapter 3 due to the possibility of assigning multiple machines for each activity and the possibility that some activities can start simultaneously in good slope cut blocks. In 25 cut blocks, all assigned activities started during the planning horizon, compared to 16 in Chapter 3. The operating cost, movement cost, and fixed operating cost of machines increased significantly compared to those in Chapter 3 due to more harvesting. In this model, 91 machines were used for harvesting as compared to 47 in Chapter 3.

In the models developed in previous chapters and in the existing studies of detailed scheduling of harvesting (Karlsson et al. 2003; Basnet et al. 2006; Guan et al. 2018; Santos et al. 2019), it was assumed that exclusive machines were used for each harvesting activity. However, some machines are used for multiple activities in real harvesting operations. To address this issue, the model developed in Chapter 4 was modified in Chapter 5 by altering 17 constraint sets and adding some new decision variables, sets, parameters, and constraints to use machines that can perform multiple harvesting activities. In this model, 8 types of machines were considered, and it was assumed that machines were not exclusive to a harvesting activity but were exclusive to the type of machine. Also, in this chapter, the scheduling of activities related to road construction was added to the model. The model was executed for the same case study as the previous chapter with only one difference: in 7 cut blocks, a road needed to be constructed before the start of other harvesting activities. The value of the objective function was 6,932,153 Can$. In 22 cut blocks, all assigned activities started during the planning horizon, which was lower than that in the model developed in Chapter 4. This happened because, in Chapter 4, it was assumed the road was already constructed in all cut blocks. On the contrary, the scheduling of road construction activities was included in Chapter 5, and due to road construction activities in some cut blocks, a few activities like yarding and loading could not start during the planning horizon. To compare the results with the model developed in Chapter 4, both models were ran for the same set of 23 cut blocks in which no road construction was required. The value of the objective function for the developed model was about 0.8% lower than that for the developed model in Chapter 4. This decrease could be attributed to the fact that some machines could perform ground yarding and loading in the same cut block, which resulted in the availability of more low-cost machines for ground yarding and loading, less movement cost, and the use of a smaller number of machines.

The model developed in Chapter 5 was sensitive to changes in the penalty cost and the maximum number of machines that could be assigned to each activity at a cut block. A decrease in the penalty cost may result in performing less amount of harvesting because, in some cut blocks, the overall increase in the objective function e due to using high-cost machines to perform harvesting could be lower than the penalty cost of not starting a harvesting activity. An increase in the penalty cost resulted in an increase in the objective function but the amount of harvesting started during the planning horizon remained the same. The increase and decrease in the maximum number of machines to be assigned to harvesting activities at a cut block resulted in an increase and decrease in the amount of harvesting that started during the planning horizon, respectively. As a result, the increase and decrease in this parameter resulted in the decrease and increase in the penalty cost of not starting a harvesting activity, respectively.

The planning horizon of the models was selected as 12 weeks because the planning at the forest company is done quarterly, and new cut blocks are added for scheduling every 3 months. Therefore, we could not change it. However, an increase and decrease in the planning horizon will result in a decrease and increase in the penalty cost. For instance, when the planning horizon increases to 24 weeks for the model developed in Chapter 5, the penalty cost decreased from 2.5 million Can$ to about 0.55 million Can$, the operating plus extra time cost increased from 4.22 million Can$ to 5.22 million Can$, the number of cut blocks in which harvesting was completed within the planning horizon increased from 16 to 24, and the objective function decreased from 6.93 million Can$ to 5.9 million Can$.

The developed mathematical programming models in this thesis can be applied to the harvesting operations of forest companies of different regions by modifying the parameters and sets of succeeding and preceding activities in the input data files according to the harvesting system used in the region. One interesting finding of this work was that sometimes delays were prescribed in the start of some activities after the completion of the preceding activity to ensure that machines would have less idle time, as discussed in section 3.5. For harvesting companies, in this way models can provide better utilization of machines compared to manual planning. Also, from this work, it was concluded that even though it was possible to assign multiple machines for performing each activity at each cut block in the second and third models in order to start as much harvesting activities as possible within the planning horizon, multiple machines were not assigned for all activities in all cut blocks. The models prescribed multiple machine assignments only in those cut blocks in which it was impossible to start the succeeding activity within the planning horizon by assigning a single machine for the preceding harvesting activity. In this way, the developed models can provide useful information for the managers about the number of machines to be assigned at each cut block instead of manually assigning a predetermined number of machines based on the volume of cut blocks or area. Also, it was concluded that it might not be possible to reduce the penalty cost of not starting a harvesting activity at a cut block during the planning horizon to zero, even if all activities start at their earliest time at all the cut blocks and the maximum number of machines of the highest productivity were assigned at the cut blocks due to the precedence relationship between activities. For instance, in this work, in some unsafe slope (>50%) cut blocks with a high volume of timber, it was not possible to finish cable yarding within the planning horizon even after assigning the maximum number of machines for cable yarding in those cut blocks. As a result, loading could not start in these cut blocks, which resulted in the penalty cost. Also, because the operating cost (Can$/$m^3$) of machines for a harvesting activity was not the same, models prescribed using low-cost machines and continuing some portion of the harvesting activity in the next planning horizon instead of using extra machines with high operating cost and finishing harvesting activity within the planning horizon. This suggestion can be attributed to the fact that sometimes the increase in objective function value due to extra time cost for harvesting activity in the next planning horizon was lower than the increase in objection function value due to the use of high operating cost machines. Due to this aspect, the operating cost of the output of all models was always less than 4.5% higher than that of the ideal operating cost case.

The models developed in Chapters 4 and 5 allowed the simultaneous start of some activities in safe slope cut blocks with a small gap between their start times. However, in case two activities occur simultaneously at a cut block, the productivity of the preceding activity can impact the productivity of the succeeding activity. To address this issue, constraint sets (4.5), (4.12), (4.13), and (4.14) were added to the models. These constraints work together to ensure that if the productivity of the succeeding activity is higher than the preceding activity, then the start time of the succeeding activity will be delayed to ensure that the machines can perform the succeeding activity at their normal production rate. For instance, as shown in Figure 5-4, the mechanical processing at cut block C14 started 2.37 days after the start of ground yarding, even though it could have started one day after the start of ground yarding as per the precedence relationship. This delay ensured that the mechanical processing could be performed at its normal speed and its ending time was not lower than that of the ground yarding. In this way, the developed models ensure that each activity can be performed at its normal production rate and is not impacted by the lower production rate of the preceding activity.

Also, it was concluded that the total cost could decrease due to the use of multi-task machines compared to exclusive machines. For the case study, this decrease was 0.8% (Can$ 25,000) because multi-task machines were available only for ground yarding and loading and the percentage of ground yarding in this case study was around 30% as discussed in the section 1.3. However, in regions where the percentage of ground yarding is high, the savings due to the use of multi-task machines could increase. Also, cost savings could be more, if multi-task machines were available for other activities as well. The cost savings were due to savings in machine movement costs and fixed operating costs. The machine movement cost decreased because the same machine could perform more than one activity in the same cut block. For instance, the results showed that in 7 cut blocks, the same machine performed loading after finishing the ground yarding, reducing the movement of another machine to the cut block for loading. Also, due to the use of multi-task machines, fewer machines could perform the harvesting compared to the use of exclusive machines for each harvesting activity, which resulted in lower fixed operating costs.

6.2 Strengths

One of the strengths of this work from the modeling perspective is that we have gradually developed mathematical models to incorporate the precedence relationship between harvesting activities based on the slope of cut blocks, movement of individual machines between cut blocks, the possibility of assigning multiple machines for each harvesting activity at each cut block, and the possibility of utilizing machines that can perform multiple activities. These aspects of forest harvesting were not considered in the existing studies for scheduling forest harvesting at the operational level. The user can select a model developed in this work as per their requirement of the complexity level of harvesting operations. Also, in the developed models, the user can easily change the precedence relationships or sequence of activities by changing the input data values, i.e., sets of preceding activities for all activities according to the harvesting system used. In the model developed in Chapter 5 that includes multi-task machines, we considered eight types of machines; however, the types of machines and the activities they perform can vary as per user requirement by changing the input parameters of the model (elements of sets B, $\mathcal{B}_{\mathcal{K}}$ and $\mathcal{K}_{\mathcal{B}}$).

Another strength of this work is that the developed models are based on the rolling horizon approach, i.e., the models can be executed for consecutive planning horizons, and they include information about the results of previous planning horizon model execution. Some sets, decision variables, parameters, and constraints are added to the models to connect the two consecutive planning horizons. These sets, decision variables, parameters, and constraints ensure that the results of the model execution for a planning horizon can be used as the inputs of the next planning horizon. This aspect of the model ensures the continuity of operations of the machines between two planning horizons. Therefore, if a machine requires some extra time after the current planning horizon to complete its operation in a cut block, then the same machine will be assigned to the same cut block in the next planning horizon, and it will start its operation from time zero in the next planning horizon.

Another strength of this work is that the components of objective functions of all the models are defined in a way that the model can generate results as per the priorities of the management. For instance, if the management's main priority is to use fewer number of machines, then they can set higher values of the fixed operating cost, as discussed in section 5.4.1. However, at the same time, the movement cost of machines will be increased because more movement of machines will be required. On the other hand, if the priority of the management is to ensure that maximum harvesting is completed within the planning horizon, they can set higher values for the cost of extra time required after the planning horizon, as discussed in section 5.4.1.

Also, the work presented in this thesis is done in collaboration with a large forest company in BC. Real data on productivity of machines, operating costs and volume of timber were obtained from the forest company. All the assumptions of the models were approved by the company manager. All the models were applied for the company's case and all the results were validated by the manager of the forest company. The model developed in Chapter 5 will be implemented in the forest company. The model will provide useful information such as which machines to be assigned at which cut blocks and to which cut block the machine should move after finishing its operation at current cut block. This information can help managers in the planning of harvesting operations in short term. At present, this planning is done manually in the forest company.

Also, in the development of the model different subsets are defined for cut blocks and machines and constraints were defined specific to each subset. As a result of this approach in the model development, the size of the model does not increase exponentially for the real case study and the model could be solved using commercial software. Lastly, in the developed models, we added fixed operating cost of machines due to which the models strive to use fewer machines to complete harvesting. For instance, in the developed models the highest number of machines assigned for harvesting were 91 out of 134. These results can give a good estimate to users about how many machines are sufficient to perform harvesting operations and can help logging companies in capacity planning.

6.3 Limitations

One of the limitations of this work is the deterministic nature of the developed models. In all these models, any uncertainty in the machine's operations due to weather conditions or mechanical breakdowns was not directly considered. Our work addressed this issue indirectly by considering the productive machine hours. For instance, for cable yarders, we consider only 41% of the total working hours as productive. However, it is important to consider uncertainty because weather conditions and machine breakdowns can disrupt the operations of the harvesting machines. Another limitation of this work is that we did not consider planned maintenance of machines in the scheduling.

Also, in these models, we assumed a virtual depot with zero distance from cut blocks because no actual depot was there for machines in the forest company. However, in case a real depot exists, then the distance of the depot from the cut blocks can impact the route of each machine. For example, the machines may move first to cut blocks that are close to the depot.

The model developed in Chapter 5 does not schedule the machines required for road construction, like excavator and compactor. In the model, it was assumed that machines for road construction were always available at the earliest time in all cut blocks after the start of felling for road.

However, in reality, these machines may be limited, and it would not be possible to start road construction at its earliest time based on starting of the felling for road.

Also, the objective function of the model is defined in a way that the focus is on minimizing the total cost so the machines with lower operating cost (Can\$/m^3) will be preferred for assignment over machines with higher operating cost (Can\$/m^3). However, this approach may sometimes result in the assignment of machines with low productivity (m^3/week) over machines with high productivity (m^3/week) which may not be desirable for the forest companies.

Lastly, this work assumed that sufficient trained operators were available to perform all the activities. However, in some cases, all operators may not be well trained, and variations in productivity due to labor training may need to be considered.

6.4 Future Work

One of the plausible future avenues for research is to incorporate uncertainty in the operations of the machines due to weather conditions and machine breakdowns in the harvesting scheduling models developed in this work. Also, scheduling of planned maintenance of machines between harvesting operations can be incorporated into the developed models to make it more realistic. The duration between planned maintenance can be based on the age of the machines. For instance, old machines require maintenance more frequently than newer ones.

For human resources, learning takes place when a resource spends more time on a skill, and forgetting takes place when a resource does not use a skill for a long time (Hematian et al. 2020). Hematian et al. (2020) considered the effect of learning and forgetting on human resources in their work for multiple-project scheduling. Similarly, operators' experience or skill level impact on the productivity of harvesting activities can be considered for scheduling harvesting activities in future work.

All the models developed in this work are single objective focused on minimization of cost. However, objectives like reducing carbon emissions due to harvesting operations or minimizing machines' impact on the forests' soil can be added to the developed models. Another possible are for future work can be integrating log transportation decisions with the developed forest harvesting scheduling models at the operational level.

Furthermore, an in-exact solution approach like metaheuristics can be developed to reduce the model's solution time in case the model's planning horizon is less and a solution time of about 18-19 hours is not justifiable.

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Appendix

Detailed description of harvesting activities in British Columbia (MacDonald 1999; Schiess and Krogstad 2004):

- Felling – This is the first step in conversion of trees into industrial roundwood. Trees are cut either manually or mechanically. In manual felling, trees are cut by a worker carrying a gasoline-powered chainsaw. Manual felling is used more commonly in coast part than in the interior of British Columbia. It is preferred for felling large sized trees (typically more than 50 cm diameter) and on steep terrain. In mechanical felling, an operator using a machine equipped with a felling head approaches each tree and cuts it. The most common felling head used in British Columbia is a feller-buncher. The feller buncher cuts the tree and piles them into bunches. All feller-bunchers have grapple arm to hold the tree during cutting and bunching stages. Most feller-buncher use circular blades for cutting which rotates continuously during the operation, although some old models use chain saws or cone saws (MacDonald 1999). The cutting time for feller-buncher is less than one second. In British Columbia, boom mounted mechanical fellers are the most common ones. Mechanical felling is limited to gentle slope areas and is used for small sized trees (typically less than 50 cm diameter).
- Processing – This includes all the operations performed on felled tress for converting them into the final products before they are delivered to a sort yard or a sawmill. The common operations include: delimbing, i.e., removing tops and branches, and bucking, i.e., cutting trees into logs of specific length as per the requirement of the sawmill. Processing can be performed either manually or mechanically. In manual processing, the felled trees are cut into logs of required length and diameter class using a chainsaw. Manually processing is

more common in coast part of British Columbia. Mechanical processing in British Columbia is mostly performed by processing attachments mounted on excavator carriers. Dangle-head processors and stroke delimbers are widely used processing attachments in British Columbia. Dangle head processor consists of delimbing knives, a saw, grapple arms and a drive system for movement of tree through the processor (MacDonald 1999). It lifts the tree from the input pile using grapple arm and then it swings towards the output pile. While swinging drive system of the processor moves the tree through processor and delimbing knives to cut off the limbs. The saw cut off the tree into logs when the processor reaches the required length of logs. The stroke delimber consists of a sliding boom, two grapples, and two saws. The trees are lifted from the input pile by the grapple at the end of the sliding boom. After the lifting, the butt end of the tree is held by the second grapple mounted on the fixed portion of the boom, and the grip of the first grapple is relaxed. Then the boom is extended outwards till it reaches the top of the tree, and the branches are cut off by sharp edges of the grapple. After reaching the top, the saw cuts the top of the tree, and the tree is cut into logs of preferred lengths by the saw when the boom is retracted. The second saw is placed on the fixed part of the boom and used for trimming of butt end before starting the delimbing process.

- Yarding – This is the process of moving logs or felled trees from the stump site to the landing zone or the roadside. This activity is performed by either ground-based machines, cable-based machines or aerial-based machines. Ground based machines drive to the stump site and bring the timber to the landing zone or road side. The operating cost of ground-based machines is lower than that of the other two types of machines, however, its application is limited to areas where terrain is not very steep. The most common types of ground-based machines are skidders, forwarders and hoe chuckers. The skidders drag the logs or trees from the stump site to the landing zone, while holding one side of the trees or logs off the ground. The forwarder consists of a log loader and a bunk to hold the logs while yarding. It moves to the stump site and loads the logs into its bunk and then unloads them at the roadside or landing zone. It is mostly used for cut to length harvesting system. A hoe-chucker is a hydraulic loader which swings the logs from the stump site to the landing zone or roadside. Hoe-chucker provides an economical method for ground yarding for gentle terrain in coastal conditions. In cable-based machines, the timber is transported from the stump site to the landing zone or the roadside using cables attached to a stationary machine, a tree or a stump. These machines are used on terrain that is too steep for ground-based yarding. They are considerably more expensive and less productive than ground-based machines. The common type of cable yarding machines are tower and swing yarders. Towers remain stationary during the yarding and are designed to use for extended period of time in one place. On the contrary, the swing yarders can swing to pile the logs and are designed to move relatively quickly between harvesting sites. Aerial yarding machines fly the timber from the stump site to the landing zone. It is mostly used in areas with unstable terrain where it is too costly or impossible to construct roads. It is the most expensive form of yarding. The most common type of aerial based machines are helicopters.

- Loading – This is the process of loading the logs to trucks for transportation to the mills or sort yards. Loaders can either be front-end loaders or swing loaders. Front end loaders move between log piles and trucks. These loaders are mostly used on flat terrain and require a large landing zone so that there is enough room to turn between the log deck and trucks.

Swing loaders remain more or less stationary during the loading. The swing loaders pickup the logs from the log deck using grapple and swing around on to the truck.