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Article

Challenges in Mechanization Efforts of Small Diameter Eucalyptus Harvesting Operations with a Low Capacity Running Skyline Yarder in Southern China

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Abstract: This case study examines the performance of the Igland Hauler employed in small diameter Eucalyptus clear-cut operations in Guangxi, China. A yarding crew of eight persons was monitored by a snap back elemental time study for 19.23 SMH (scheduled machine hours), with 159 yarding cycles and a yarded log volume at landing of 49.4 m³ solid over bark. A gross-productivity of 2.50 m³/SMH and net-productivity of 5.06 m³/PMH$_0$ (productive machine hours excluding delay times) was achieved, leading to a machine utilization rate of 49.5%. The costs of the yarder and associated overhead as well as the personnel costs of a large crew with eight people sum up to extraction costs of 50.24 USD/m³. The high costs make it difficult to compete economically with the locally common manual extraction system as long as abundant labor at a low hourly rate is available in the region. Further performance improvement through skill development, but also technical and organizational system modification in conjunction with rising wages and decreasing labor force in rural primary production will determine the justification of employing such yarding systems. However, new silvicultural regimes with extended rotations and supply requirements of the forest products industry in China demand new operational systems.

Keywords: timber harvesting; cable yarding; running skyline; China

1. Introduction

China experienced decades of unregulated timber exploitation and deforestation during its industrial development over the second half of the 20th century, resulting in serious environmental problems [1]. However, over the last 20 years, the country's forestry sector significantly evolved due to policy reforms and management improvements in order to ensure a sustainable development. Logging bans in natural forests and enormous afforestation and reforestation efforts have increased China's forest cover to 208 million ha, which represents nearly 22% of its geographical area compared to just 10% at the end of the 1970s, as proven by the latest national forest inventory [2]. The intensification of these activities are mainly defined by the conservation orientated Six Key Forestry Programs (SKFPs), as launched in 2000 [3–6].

The SKFPs have been very successful in terms of forest restoration and afforestation efforts for enhanced ecosystem functions and biodiversity [4,7]. However, until now, it has not been possible to significantly improve the timber supply situation to the emerging domestic forest product industries. As a consequence, the country is facing an increasing timber demand-and-supply gap, estimated to reach 190 million m^3 in 2015 [8,9]. The lack of sufficient timber supply from domestic sources turned China into a global leader of wood imports, reaching annual values worth 10 billion USD [8]. With 60% of the volume, Russian timber contributes as the main source of Chinese round wood imports. However, increasing log prices due to Russia's tax on round wood exports, as implemented in 2007, and uncertainties with respect to legal origin limit the amount of available timber resources from Russia [10]. Other foreign wood suppliers of China, such as Indonesia, Thailand, Myanmar, Papua New Guinea and Gabon, face the problem of dwindling natural forest resources [10]. New Zealand currently exports large amounts of plantation-grown timber and wood fiber to China as well. However, the country also experiences increasing take up of timber resources by its domestic market after a recovery of the sawmilling industry, which will limit log export capacities to China in the near future [11]. Increased competition within global log trade and the increasing importance of transparent evidence of source of origin, generally limit the ability to obtain round wood from traditional supplying countries [9,10,12–15].

In order to become less dependent on round wood imports, the central government has promoted the development of a forest plantation-based timber industry in selected key regions of Southern China [8,16]. In accordance with the SKFPs, this newly established plantation sector is expected to release utilization pressure from the remaining natural forests in the country's traditional timber regions of the northeast and eastern China. It further emphasizes a major relocation of the forest products industry to the southern provinces. This major shift of the entire forestry sector resulted in two main types of forest plantation management regimes in the South. The majority of the plantations follow the objective of cultivating fast-growing high-yielding timber species to supply the pulp and wood based panel industries with fiber. The second type focuses on the yield of dimensional timber for a value added sawing industry through long rotations and single tree harvest, including periodic thinnings, consistent with multifunctional forest management and associated ecosystem services, which came up as a new management objective [17]. Although plantation areas have been successfully established in terms of area, yields have been below expectations so far and not competitive with outputs from plantation industries in other countries such as Brazil [16,18]. Reasons for the low productivity are numerous and ranging from silvicultural to operational deficits. Due to the limited land availability in the southern provinces, timber plantations have been mainly allocated to hilly terrain. In conjunction with a poor operation infrastructure and almost non-existent mechanization of log extraction, volume outputs of these plantation operations are rather low [16,19]. Considering increasing wages among the Chinese forestry sector of 5% annually [8] and the enormous timber demand of the Chinese wood products industry, a shift from the currently labor intensive, daily rate-based manual harvesting operations towards professionalized operations with a higher degree of mechanization is inevitable. This even more so since the majority of the workforce in harvesting operations consists of migrant workers from other Chinese provinces and Vietnam, whose availability is dwindling since urban manufacturing industries offer higher paid jobs in a more safe and comfortable working environment. Cable yarding systems seem to be suitable technologies to overcome the challenges in forest operations in southern China and have been tested in the region already as far back as the 1950s [20–22]. However, potential performance capacities and related costs of cable yarding harvesting systems, as well as the characteristic technical features required under Chinese operational conditions are hardly known.

The lack of published research on the general suitability of alternative harvesting and timber extraction systems in southern China makes it difficult for researchers and practitioners to develop local guidelines for sustainable forest operations. This study aims to examine the potential of a simple low capacity cable yarder in forest operations of southern China through a case study conducted in the Guangxi Zhuang Autonomous Region. In particular, the objectives of this study were: (1) to analyze the productivity achieved by this recently introduced extraction system, related costs and economics of current operation; (2) to evaluate the efficiency of the system under variations in crew performance, utilization and the foreseen dynamics of the labor market; and (3) to conclude on future opportunities of the success of yarding systems in Guangxi. This study may generally help to assess the potential of introducing mechanized harvesting systems in Southern China.

2. Material and Methods

2.1. Study Site and Work Conditions

This case study was based on a clear-cut operation of a six-year-old Eucalyptus (*Eucalyptus grandis* × *E. urophylla*) plantation near the city of Tengxian, Guangxi Zhuang Autonomous Region (23°23′ N 110°54′ E). The purpose of the operation was to produce rotary veneer logs for plywood production with a fixed length of 2 m at landing and short wood of flexible length as byproduct for fiber industries. A timber harvesting and extraction operation performed by a regional forestry enterprise, which is also the concessionaire of the site, was monitored for four days. Regional climate is subtropical with annual mean temperatures of 22.2 °C and precipitation of 1366 mm, concentrated during a distinct rainy season from April to August [23]. During data collection in April 2014, the weather was hot and dry, leading to shortened shift times with extended lunch breaks during the midday heat, reaching temperatures above 30 °C.

The stand selected for the study represented average stocking and operation conditions for the small diameter eucalyptus plantations common in Guangxi province as described by Engler [19]. Sites are usually located on moderate slopes with a downhill yarding direction determined by the valley location of the feeder roads. Since the block had been cut just before the commencement of this time study, stand parameters (Table 1) were estimated from adjacent blocks, not yet harvested and belonging to the same stand of equal age and stand conditions. Along two linear transects of approximately 120 m on each side of the cut block, following one tree row, a total of 25 trees were measured. These trees deemed to be representative for the stand based on their traits, selected at random locations of the transects. The top height of the standing trees was measured using a VERTEX IV (Haglöf AB: Långsele, Sweden) hypsometer and the DBH (diameter at breast height) with a diameter tape. Based on the measurements, the common cylinder volume formula complemented with a DBH-based Eucalyptus specific form factor (used form factors are 0.46 for trees with a DBH 4–12 cm and 0.44 for DBH 12–20 cm, respectively) from Brazilian allometric models [24] was used to calculate the mean tree volume. Due to the absence of local form factors, the Brazilian ones have been considered the most suitable since Eucalyptus subspecies, growing conditions, designated to the same species under similar site conditions and diameter class were comparable to those at the study site. The harvesting volume was extrapolated from average tree volume and tree spacing to be approximately 152 m^3 solid over bark (s.o.b.)/ha for the under complete stocking. However, due to high mortality after planting and no blanking, non-stocked gaps, covering about 48% of the area, reduced the expected merchantable harvesting volume to approximately 80 m^3 s.o.b./ha.

Table 1. Site and stand description with tree characteristics and standard deviations (in parentheses).

Species:	***Eucalyptus urophylla* × *E. grandis***
Age:	6 years
Terrain:	Moderate slope (7%–24%), no surface obstacles, NE-exposure
Timber extraction:	Downhill yarding, with a mean slope yarding distance of 52.4 m
Cut block size*:	0.62 ha (not fully stocked due to sapling mortality)
Spacing:	2.5 m × 4 m
Trees per ha:	1,000 (at stand establishment)
Mean DBH:	14.7 cm (± 3.7)
Mean top height:	17.8 m (± 3.1)
Estimated merchantable standing volume:	80 m^3 s.o.b./ha
Management system:	Clear-cut

*portion where time and motion study was conducted.

2.2. Description of the Yarder

The yarder utilized in this study, referred as the "Igland Hauler" by LIRA [25], is a simple, compact running skyline yarder based on the tractor PTO driven double drum winch Igland 4000/2 (Igland AS, Grimstad, Norway) (Figure 1). Since it is a discontinued machine that is no longer commercially available through the Norwegian winch manufacturer Igland, it was purpose-built for the forest contractor as a trial machine according to original plans of the steel lattice tower as designed by British machine outfitters in the 1980s. The machine was built in a local workshop under supervision of foreign experts and based on a refurbished winch set imported from Europe. In case of successful performance, fulfilling the owner's expectations, negotiations with local winch manufacturers have been ongoing in order to manufacture a small batch series of this hauler in China. The yarder is usually rigged in a running skyline configuration, but through alterations of the tractor drive axle using the stubs of the rear wheel hubs as additional drum carriers, it can also be rigged in a standing skyline configuration (see [25] for details). Within this study, only the running skyline configuration, tail rigged at ground level and the utilization of a simple highlead, non-clamping carriage was investigated. Technical specifications of the investigated hauler are listed in Table 2. The Chinese-made tractor LOVOL M754-A1 (Foton Lovol Int. Heavy Machine Industry Co. Ltd., Weifan/Shandong, P.R. China), a compact open canopy agricultural tractor with a rated power of 55 kW and a machine weight of 3190 kg was utilized as machine carrier in the studied operation.

Figure 1. Semi-mechanized yarding operation applying the Igland Hauler. Stems are yarded in tree lengths (delimbed and topped) to the landing where they are crosscut by a chainsaw operator and manually sorted and stock piled.

Table 2. Technical specifications of the Igland Hauler 4000/2.

System:	**2-drum all-terrain running skyline; optional standing skyline rigging**
Drive:	Tractor PTO of 55 kW, mechanically
Tower:	Hinged lattice tower, 6.0 m in height
Guylines:	2m × 30 m, Ø 10 mm, endfastend through shackle
Skyline:	See haulbackline
Mainline:	180 m, Ø 10 mm, line-pull 16.8 kN
Haulbackline:	300 m, Ø 8 mm, line-pull 16.8 kN (serves also as the running skyline)
Carriage:	Simple highlead, non-clamping carriage, payload of 0.5 t
Chokersystem:	Conventional choker chains, 3 tags

The fast technological progress and automation efforts among the well-established yarder manufacturers on the international market make it difficult to acquire a machine suitable for less developed countries with limited investment capacities and maintenance infrastructure. New and inexperienced users have special economic necessities regarding the equipment, which additionally needs to be adapted to the situation in China. Small cut block sizes and operational constraints in China generally limit the utilization rates per year and further add to the demand for low capital intensive equipment. Due to limited access to service networks, suitable equipment should be technically durable, easy to repair and, as far as possible, independent of sophisticated spare and service parts only available abroad. For such low cost solutions, users accept compromises in operation comfort and machine productivity. Therefore, the utilization of the Igland Hauler, a machine that seems to be outdated by the perspectives of commercial forestry in industrialized countries, might be very suitable for the new market in China.

2.3. Time and Productivity Study

Within the study, an extraction operation covering three corridors was observed. For each corridor, the machine had to be completely rigged, including 13 interim changes of the tailhold position to increase the lateral reach, ending up in mean lateral yarding distances of 4 m during operation. Yarding direction on the moderate slope (mean gradient 17.5%) was downhill. Corridor layout was radial from a central landing area. The length of the corridors varied between 58 and 90 m and can be considered to be rather short, but typical for average Guangxi cut blocks. The yarding crew consisted of eight people; all of them had undergone joint professional training with foreign experts and utilized the yarder for six months. One worker had been designated as machine operator, operating the yarder almost exclusively, although every member had been trained on the machine as well. Log hook-up was conducted by two workers; the remaining five crew members were in charge of unhooking, cross-cutting and manual piling of the logs at landing. However, only occasionally did all five workers perform this activity simultaneously. Usually, only three people were working at once on the landing, with the workers switching between resting and landing activities, which were the most physically demanding tasks.

Time studies were carried out through means of digital stopwatches by two interacting radio-wired timekeepers, following the elemental snap back timing method [26]. One timekeeper was located at the machine's position and one following the choker setters in the stand. The individual cycle elements, as timed, are defined in Table 3. Since lateral yarding is not a distinct cycle element within the utilization of a running skyline system, related times have not been separately recorded. However, estimated lateral yarding distances in form of the rectangular off-set distance from the straight skyline have been recorded for each cycle as an independent variable influencing the needed time for the Hook Up process.

Table 3. Timed yarding cycle elements.

Cycle Element	Description
Outhaul	Begins when the operator releases the mainline break and starts to move the carriage from the log deck to the designated position at the choker setter. It ends as soon as the carriage stops at the designated position and the lines touch the ground.
Hook Up (including lateral yarding)	Begins with the end of *Outhaul* and ends as soon as the load reaches the carriage.
Inhaul	Begins at the end of *Hook Up* and ends as soon as the load touches the log deck at landing.
Unhooking	Begins at the end of *Inhaul* and ends when the running skyline is tensioned again and the carriage is ready for *Outhaul*.

Net-cycle times (productive machine hours excluding delay times (PMH_0)) were modeled through stepwise multiple linear regressions using SPSS 22 (IBM Corp., Armonk/NY, USA). Yarding distance, lateral distance, terrain slope, corridor off-set angle from the slope line, stem number and ground vegetation were considered as independent variables on the predicted cycle time. Vegetation was classified (vegetation classification has been defined as: 1, none—no ground vegetation is present besides scattered dwarfing herbal vegetation not disturbing the work process; 2, normal—dwarfing herbal vegetation covers wide areas and scattered shrubby vegetation not exceeding 50 cm in height, causing no major disturbance of the work process; and 3, heavy—dwarfing herbal vegetation covers the entire area and frequently occurring shrubby vegetation, also exceeding heights of 50 cm severely disturb the work process.) as: 1, none; 2, normal; or 3, heavy disturbance due to ground vegetation. Following the approach in [19], observations that differed more than 3 times the standard deviation from the mean value have been checked for plausibility for consideration as outliers or originating from mistakes during transfer from the field forms. Generally, only cycle time observations between the 5th and 95th percentile were considered as within the valid range for modeling as suggested by e.g., [27].

Special attention was given to delay events by grouping them into categories based on the IUFRO guidelines [26]. Main categories have been “Mechanical Delays”, with the subcategories “Repair Times” (RT) and “Maintenance Times” (MT); “Operational Delays”, with the subcategories “Avoidable Operational Delays” (AOD) and “Unavoidable Operational Delays” (UOD); and the final category, “Personal Delays” (PD) (Table 4). Delays resulting from conducting the survey and formal break times were excluded from the records. In addition to the main delay categories and associated subcategories, any single delay event type that occurred was defined, and its occurrence and duration recorded accordingly. Rigging times were recorded separately from the cycle times using stopwatches.

Table 4. Definition of IUFRO (International Union of Forest Research Organizations) delay time categories [26], modified.

Delay Category	Definition
Mechanical Delays	Delays due to malfunctions of the yarder or other technical equipment employed in the yarding process. These delays are distinguished by (1) *Repair Time (RT),* which is the repair or exchange of damaged components as a principally non-cyclic interruption and (2) *Maintenance Time (MT)*, a principally cyclic interruption for the implementation of measures to avoid a successive degradation of tools and machinery due to wear and tear.
Operational Delays	Delays caused by organizational failures and inappropriate equipment operation or system application by the yarding crew, site restrictions or material characteristics. *Avoidable Operational Delays (AOD)* classifies time spent in changing the work object in form and position in order to fulfill the work task, but could have been fulfilled already by the previous laborer as part of his work step. These delays also include delays in system operation handling which can be related to insufficient skills of inexperienced crews in fulfilling the work standards. In contrast, *Unavoidable Operational Delays (UOD)*, are times not changing the work object, but are required in order to complete the work task or to keep the harvesting system running. These unproductive time elements will always occur in the system operation, regardless of the crew's skill level.
Personal Delays	Delays caused by the individual worker in order to fulfill personal needs or with the occupation of activities not related to the work implementation or any other productivity of the operation.

Cost calculations were conducted according to the [28] guidelines for machine rate estimation. Estimates were made in accordance with straight-line depreciation, with a base scenario of 800 hours annual utilization (in the form of scheduled machine hours including delays (SMH)) and an expected economic life of the machine of 10 years, in accordance with European operation conditions, as stated by [29]. A base scenario with 800 SMH per year could be considered low compared to other European figures for cable yarders (e.g. [30]), but was chosen due to the seasonal rain pattern and the low standard of local forest roads, which in combination with often delayed issuing of logging permits generally limits the potential operation time of equipment. Input figures such as machine delivery costs, individual crewmember's salaries and social benefits were supplied by the machine owning company. Fuel costs (1.24 USD/liter) and interest rates (6.55%) were set according to information received by the authors during the field visit (Table 5).

Table 5. Machine costing for the Igland Hauler and the JG-608 loader added for alternative cost scenarios.

Igland Hauler: **Cost Factor**	**Value**	**Description**
Purchase Price (USD)	45,041.00	tractor and yarder on-site (including cables and rigging equipment, valued 7,138.00 USD)
Salvage Value (USD)	9,008.20	20% of purchase price
Economic Life (a)	10	after Spinelli and Magagnotti (2011)
SMH/a	800	after Spinelli and Magagnotti (2011)
AAI Factor	0.64	after FAO (1992)
Interest Rate (%)	6.55	Agricultural Bank of China
Insurance (%)	1.00	machine owner estimate
Ownership Tax (%)	2.00	FAO (1992) estimate
Depreciation/SMH (USD)	3.61	FAO (1992) estimate, straight line depreciation
Labor Costs/SMH (USD)	100.44	8 crew members including 36.9% social benefits
Diesel Price/l (USD)	1.24	as at 26 May 2014
Diesel Costs/SMH (USD)	10.14	after FAO (1992), 74.8 hp tractor at medium load
Lubricant Costs/SMH (USD)	1.01	FAO (1992) estimate, 10% of fuel
Servicing and Repair Costs/SMH (USD)	3.61	FAO (1992) estimate, 100% of depreciation
Miscellaneous Costs/SMH (USD)	1.26	annual replacement operation related accessory
Machine rate per SMH (USD)	125.59	including all labor costs and an estimated *chainsaw rate of 2.08 USD, calculated after FAO (1992)
JG-608 Loader:		
Purchase Price (USD)	20,000.00	excavator (loader) on-site
Salvage Value (USD)	4,000.00	20% of purchase price
Economic Life (a)	10	assumption
SMH/a	800	assumption
AAI Factor	0.60	after FAO (1992)
Interest Rate (%)	6.55	Agricultural Bank of China
Insurance (%)	1.00	machine owner estimate
Ownership Tax (%)	2.00	FAO (1992) estimate
Depreciation/SMH (USD)	2.00	FAO (1992) estimate, straight line depreciation
Labor Costs/SMH (USD)	12.10	1 operator including 36.9% social benefits
Diesel Price/l (USD)	1.24	as at May, 26th 2014
Diesel Costs/SMH (USD)	8.67	after FAO (1992), 64 hp excavator at medium load
Lubricant Costs/SMH (USD)	0.87	FAO (1992) estimate, 10% of fuel
Servicing and Repair Costs/SMH (USD)	1.00	FAO (1992) estimate, 50% of depreciation
Miscellaneous Costs/SMH (USD)	0.03	annual replacement of operation related accessory
Machine rate per SMH (USD)	26.10	including labor costs, calculated after FAO (1992)

*chainsaw rate considers one unit (STIHL MS261) necessary for landing operations and does not refer to any felling related activities nor necessary equipment.

3. Results

Within the observation period, 9.52 h of productive time (PMH_0) was achieved out of the 19.23 h scheduled work time (SMH), resulting in a machine utilization rate of 49.5%. In that time frame, 159 cycles were monitored with a total of 421 yarded stems summing up to a volume of 49.4 m^3 s.o.b. Individual loads consisted on average of 2.6 stems and a payload of 0.3 m^3 s.o.b., but ranged from one to seven stems and mean payloads as small as 0.1 and up to 0.8 m^3 s.o.b. at mean stem lengths of 9 m. Among the overall gross-time distribution (SMH) of the monitored cycles, 'Hook Up' times contributed the highest share, next to the delay times, with 31.3% (Figure 2). Considering only the PMH_0, the mean "Hook Up" times represent with 2.27 min (63.2%) of the mean "Total Cycle Time" of 3.59 min (Table 6).

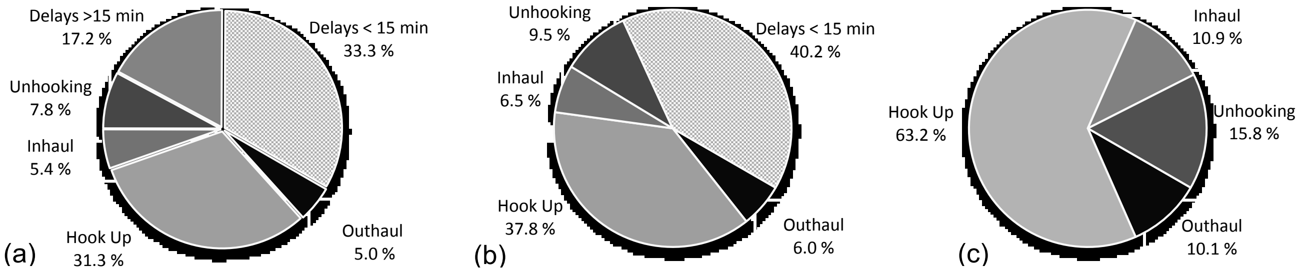

Figure 2. Total time distribution of the survey among cycle elements in dependence of delay time consideration. With (**a**) considering the time distribution among the cycle elements and all occurring delay times; (**b**) considering the time distribution among the cycle elements and the share of delay times < 15 min only; and (**c**) considering the time distribution among the cycle elements without delay times.

Table 6. Descriptive statistics of the PMH_0 (productive machine hours excluding delay times) cycle element times with standard deviations (in parentheses), the percentile threshold for validity, and the number of observations valid for modeling through regression techniques.

Cycle element	(min) Mean	Min.	Max.	Percentiles 5th	95th	Observations valid for modeling
Outhaul	0.36 (±0.11)	0.04	0.89	0.18	0.52	147
Hook Up	2.27 (±0.78)	0.30	4.31	1.08	3.68	145
Inhaul	0.39 (±0.16)	0.06	0.97	0.14	0.64	145
Unhooking	0.57 (±0.21)	0.16	1.34	0.30	0.94	146
Total Cycle Time	3.59 (±0.96)	0.86	5.87	2.08	5.15	145

The generated model for predicting the PMH_0 time in minutes for one yarding cycle of the investigated operation is determined by the following regression equation:

$$t_{cycle} = 1.304 + 0.016\text{yd} + 0.082\text{ly} + 0.019\text{sl} + 0.227\text{vg} + 0.097\text{sn} \quad (1)$$

where:

t_{cycle} = *total cycle time*
yd= slope yarding distance
ly = lateral yarding distance
sl = terrain slope
vg = vegetation category
sn = stem numbers per load

The regression model yields an R^2 of 0.46 (F = 23.4; df = 5; $p < 0.001$). The independent variables, yarding distance, lateral distance, slope and vegetation category, showed a highly significant ($p < 0.01$) effect on cycle time, whereas the variable stem numbers was still significant, but at a lower level ($p < 0.05$). With this model, a mean PMH_0 cycle time of 3.60 min could be calculated for the observed operation.

During the study, 427 delays of 37 categorized single delay event types occurred, summing up to 9.71 h of delays. Operational delays were the dominant delays, of which UOD (unavoidable operational delays) contributed 55.7%; a higher share compared to the AOD (avoidable operational delays) with 37.1% (Figure 3). Only minor shares were attributed to RT (repair times), PD (personal delays) and MT (maintenance times). The main delay time contributing single delay event was manual clearing of the landing, which include cross-cutting and stock piling of logs. The second ranked single delay event was hang ups during inhaul, followed by the rigging activities, which have been low in frequency but long in duration (Table 7).

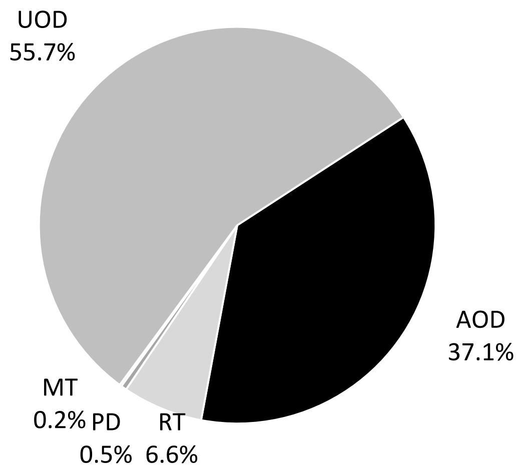

Figure 3. Share of unavoidable operational delays (UOD), avoidable operational delays (AOD), repair times (RT), personal delays (PD) and maintenance times (MT) among total delay time.

Table 7. Ten main contributing single delay event types sorted according associated delay category, total delay time, share of observed SMH, frequency during the study and mean time per single delay event.

	Single Delay Event Types	Delay Time (min)	Share of SMH (%)	Frequency	Mean Time (min)
UOD	Manual clearing of landing	124.79	10.8	117	1.07
	Rigging/down rigging of hauler	92.65	8.0	4	23.16
	Changing of tailhold position	72.55	6.3	13	5.58
	Refueling	14.00	1.2	1	14.00
	Entangled choker chain during unhooking	10.95	0.9	33	0.33
	Entangled choker chain at carriage	10.01	0.9	16	0.63
AOD	Hang ups during inhaul	114.85	10.0	72	1.60
	Discussion on radio	24.59	2.1	55	0.45
	Salvaging hanging trees/removing stumps	11.34	1.0	6	1.89
RT	Splicing of mainline	30.00	2.6	1	30.00

Most frequently occurring individual delay events have been shorter than 5 min, with durations often lasting only a few seconds, accounting for 404 of the recorded 427 delays. However, due to the overall high frequency of these short events, they contribute significantly to the overall sum of delay times (Figure 4). The longest occurring single delay event lasted 35.95 min and was associated with the rigging procedures, which could be averaged for the entire operation to 23.16 min for either installation or dismantling.

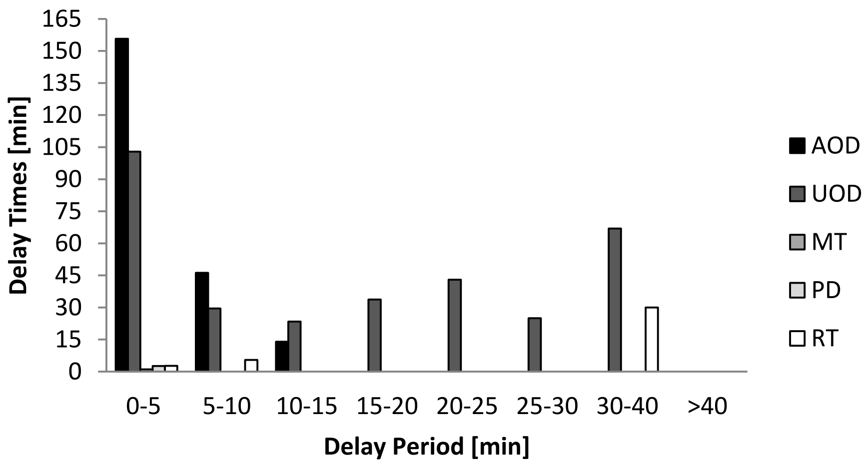

Figure 4. Total delay times of the monitored cycles grouped according to the duration of the single delay event types.

Overall gross productivity, based on SMH, including all delays, lead to mean cycle times of 7.28 min and a productivity rate of 2.50 m^3/h. The PMH_{15} (productive times including delay times up to 15 min) productivity rate, which is commonly used to describe system performances [31], included 66% of all observed delay times and had a corresponding cycle time of 6.02 min and an output of 3.03 m^3/h, respectively (Figure 5). The initial cost calculation for the hauler crew with the current set up was determined to be 125.59 USD per hour for 800 SMH operations annually. That resulted in actual yarding costs of 24.82 USD/m³ for PMH_0 (5.06 m³/h), 41.45 USD/m³ for PMH_{15} (3.03 m³/h) and 50.24 USD/m³ for SMH (2.50 m³/h) rating.

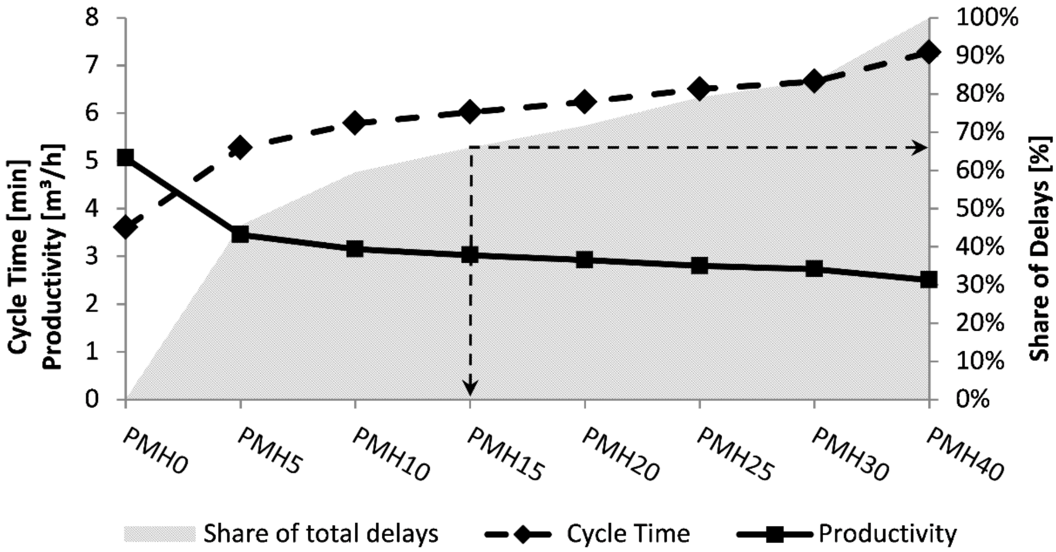

Figure 5. Performance indicators according to added delays, with performance rated through cycle time (min) and productivity (m³/h) on the left *y*-axis in dependence of different delay time threshold additions on the PMH on the *x*-axis and the overall coverage of delay times experienced in this study on the right *y*-axis.

4. Discussion

Before the study, the hauler crew underwent professional training by experienced foreign experts and were able to develop their skills through six months of independent work. However, during the time study, organizational and user experience related limitations were observed, which were reflected in the performance of the crew in the current status quo.

With a machine utilization rate of 49.5%, net productivity was twice as high as the gross productivity in this study. It is common in most Central European productivity studies to include only delays up to 15 min in the work time for the determination of productivity values, reflected in PMH_{15} [31]. However, there is a risk that particular, unavoidable, operation related delay events are underrated, leading to overestimated productivity values, which cannot be realized on the ground. In this study, PMH_{15} times accounted for two thirds of all delay times, thus the majority of the delays were covered by the conventional approach. In fact, only three delay events exceeded the 15 min duration, namely the two UOD single delay events, 'rigging/down rigging' and 'manual clearing of landing', and the RT single delay event, 'splicing of mainline'. Since the rigging procedures are fundamental for the operation of the hauler and in general a decisive cost and crew performance factor for cable yarding operations, it would be inappropriate to exclude them from the productivity analysis, only because the time amounts exceeded the 15 min threshold. However, rigging procedures are measured separately in most cable yarding studies (e.g., [32]). That is why time studies especially dedicated to rigging activities exist (e.g., [33]), but results are usually not included in productivity figures stated for a surveyed cable yarding system, either. This results in underrating operation costs and overestimating effective annual operation hours. With respect to the current system set-up, the single delay event 'splicing of mainline', though observed only once, should also be considered as a regularly occurring delay. It has to be expected that the mainline needs to be spliced frequently at the joint with the choker chains, as it was also confirmed by the yarding crew, since the chokers are attached only through a spliced eye without any sleeve or thimble. This is due to the current limited availability of cable yarding materials and suitable steel core wire ropes on the local market of Guangxi. In our case, the consideration of PMH_{15} not considering these delays, would have resulted in an overestimation of productivity by 17%.

In order to give a realistic performance figure, all delays have been included in the actual output figures, leading to a gross productivity of 2.50 m^3/SMH at mean cycle times of 7.28 min under the given conditions. During the investigation in [25] of the Igland Hauler's performance in radiata pine plantations in New Zealand, the two-man crew observed achieved 3.76 m^3/SMH at mean cycle times of 5.41 min. Since the New Zealand crew also had to stack the logs manually at the landing and faced slightly longer average extraction distances, at higher slope gradients with similar piece sizes, it can be concluded that the Chinese crew has not yet reached the skill level required in order to make use of the full potential of the system, in particular when considering the larger crew size. Garland [34] identified that in the USA, 40%–50% of the yarding production cycle times might be in human-controlled work pace activities, particularly during the hook-up process, as the most time demanding yarding element, which was also confirmed in this survey. Magagnotti *et al* [35] define the 'Operator Effect' to affect productivity up to 40%, depending on machine type, accounting for the difference between inexperienced and experienced operators. In [34], log presentation by the feller was also found to influence the hook-up decision process for determination of the optimum load by the choker setter and can further be linked to the experience level. In the current study, log presentation in the form of proper positioning and processing by the felling crew in order to ease the hook-up process left room for improvement. The frequently observed hang up delays could be directly related to these shortfalls. However, the general low load suspension as a consequence of rigging the skyline on a tail stump instead of a raised tail spar also contributed to these 'hang up' delays. The frequent interruptions by clarifying discussions on the radio further indicated that the crew had not reached an experience level ensuring a routine and well organized operation with minimum delays by the full utilization of the yarding system's technical capacities. However, this case study cannot fully determine the skill level of the operation crew. Consequently, productivity values presented in this study can only be used as indications of the system's current capacity for the management of Eucalyptus plantations in China, with respect to organizational and operational improvement as well as system adaptation.

It should be expected that the productivity of the hauler crew will improve over time due to ongoing skill development. However, significant cost reductions will only be achievable through organizational and system improvements. One important aspect is the annual machine utilization, which has a severe impact on the yarding costs per m^3, which could be reduced by higher annual utilization rates (Figure 6). Generally, a reduction in crew size in favor of skilled and productive workers, or by substitution through an additional system component like a loader, would realize more efficient operations at reduced costs. The studied trial crew consisted of eight workers, with their labor costs already significantly contributing to the overall yarding costs (Table 5). This large work team was mainly required due to the manual landing operations. Adding a small excavator with a log grapple as a loader could spare at least three people currently required for log manipulation at the landing. The JG-608

(Jingli Engineering Machinery Co. Ltd., Quanzhou/Fujian, P.R. China) is a low priced 6 t Chinese made machine, locally available and has already been successfully used during a standing skyline cable yarding operation in Guangxi [36]. Substituting three workers with this loader would reduce the yarding costs from 50.24 USD/m³ to 41.31 USD/m³ at the 800 SMH/a base scenario including machine investment and overhead costs of the loader, at a depreciation period of 10 years (Figure 6, "loader system"). Since it can be assumed that the delay times associated with the manual clearing of the landing can be reduced by adding the loader, productive time within the SMH should be increased, resulting in an estimated higher hourly output of 3.05 m³/SMH with reduced yarding costs of 33.84 USD/m³ at 800 SMH/a in the form of an 'improved loader system' (Figure 6). In addition to increasing productivity, a loader would also reduce the necessity of crewmembers working directly in the risk zone at the landing below the skyline. Since the actual potential of this running skyline system to improve Guangxi operations is hard to determine purely based on the findings of this study, alternative small-scale log extraction systems (Table 8) should be evaluated, too. Although only limited conclusions can be drawn by comparing studies with variations in work and site conditions of different geographical regions, experience gained can serve as valuable initial reference for further development of locally adapted harvesting systems.

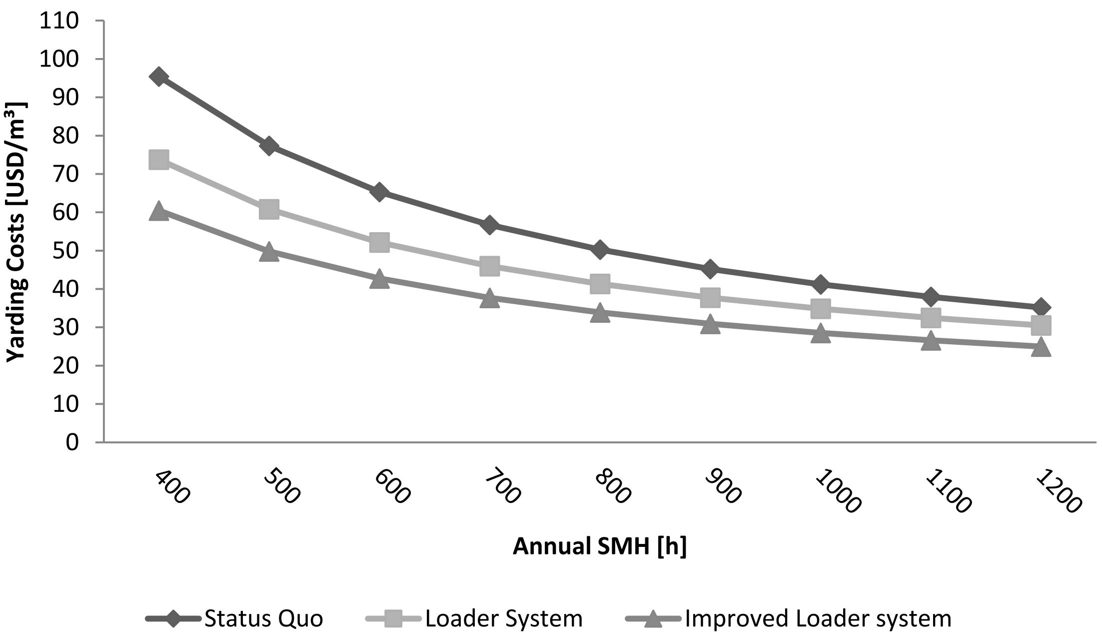

Figure 6. Yarding costs (USD/m³) as a function of annual utilization hours (SMH) related to the modeled productivity (m³/h) and a 10 year depreciation period with associated system overhead costs for the three scenarios: "Status Quo" (2.50 m³/h), "Loader System" (2.50 m³/h) and "Improved Loader System" (3.05 m³/h).

Table 8. Productivity studies of various extraction systems in small sale forestry operations.

Extraction System	Country	Productivity (m^3 s.o.b./SMH)	Mean Load size (m^3)	Extraction Distance (m)	Mean Slope (%)	Equipment Purchase Price (USD)	Study
Manual labor	China	1.38	0.03	20 (mean)	31	not applicable	Engler 2011 [19]
Logging Sulky	Tanzania	1.1	0.08	46 (mean)	10	200	Saarilahti *et al.* 1987 [37]
Buffalo	Vietnam	0.33	0.09	180 (mean)	25	772	Tuong 2013 [38]
Standing skyline	Italy	1.52	0.2	140 (line length)	60	62,578.50 (including tractor)	Spinelli *et al.* 2010 [39]
Plastic chutes	Austria	1.81	0.05	73 (line length)	35	* ~26.00 USD/m	Proell 2000 [40]
Compact crawler tractor	Italy	4.64	3.42	292 (mean)	30 (skid trail)	43,236.00	Magagnotti *et al.* 2012 [41]
Mini crawler forwarder	Japan	4.27	1.23	92 (mean)	19	14,383.30	Nakahata *et al.* 2014 [42]
Farm tractor with winch	USA	2.69	1.33	268 (mean)	17	* ~46,650.00	LeDoux & Huyler 1992 [43]

*price adjustment according to current market conditions.

Since abundant daily rated workforce at low costs are available currently, manual systems should still be taken into consideration for specific operations. Considering the study of manual extraction in Guangxi in [19], a projected productivity of the Igland Hauler with the complete eight person crew at a mean distance of 20 m would generate an output of 3.48 m^3 s.o.b./SMH (Figure 7) compared to a manual performance of 1.38 m^3 s.o.b. per scheduled man hour. At least for downhill extraction, the manual performance is currently still a common practice and competitive with respect to the local socio-economic situation with high availability of low qualified workers. The main benefit being the very low costs associated with manual extraction of only 4.82 USD/m^3 (29.60 RMB/m^3) [5] compared to the capital-intensive yarder system of the Igland Hauler with 50.24 USD/m^3. Saarilahti *et al.* [37] reported low capital demanding improvements to manual operations in Tanzania through the introduction of a logging sulky at short distances and in moderate terrain, which could further increase the manual performance but also the ergonomics of such operations. With steeper conditions, extraction in an uphill direction and longer distances, buffaloes have been successfully applied in small diameter plantations in Vietnam [38], where the operational conditions were similar to Guangxi. However, overhead costs associated with the utilization of animals through relocation costs and daily attention also during the harvesting off-season can significantly influence the hourly rate.

Another considerable extraction system over longer distances with low overhead costs could be the utilization of plastic chutes. Trials from Austria [40] show that as long as sufficient log quantities are available and the designated site is characterized by a minimum slope of 15%, efficient short wood extraction can be realized. However, additional organizational and labor demanding efforts are required for set up and during operation at the landings with respect to controlling log speed, log piling and implementation of traffic safety measures. Therefore, the system's economics were highly dependent on the wages of the individual workers. Still, the technical potential of chutes in mountainous regions of low accessibility was already confirmed by [44] in Turkey, where plastic chutes of several hundred meters in length are implemented very successfully.

Overcoming very long extraction distances is a challenge for the Igland Hauler, which is limited by the skyline to a maximum corridor length of 150 m, and also the significantly reduced productivity with longer extraction distances (Figure 7). The SAVALL 1500, a low priced standing skyline system with a semi-automatic slack pulling carriage, as investigated by [39], is able to yard longer distances up to 300 m, with a considerable higher payload capacity compared to the Igland Hauler. However, this system is restricted to uphill yarding and the availability of support and spar trees, which is a further limiting technical factor in small diameter plantations. In addition, the demand for a professional crew and the comparatively high purchase price of such systems will create barriers for small scale harvesting contractors in Guangxi, similar to the constraints with the Igland Hauler running skyline system. Compact crawler machines, as tested by [41] and [42], seem to be good technical and flexible solutions for short wood extraction if logs are already cross-cut in the stand. Due to their relative high payload capacities, efficient wood extraction can already be realized by a one- or two-man crew. However, the crawlers usually demand a skid trail system with maximum gradients of 30% [41], which imposes requirements on logging infrastructure planning and expenses. Furthermore, with increasing skidding distance their productivity would also significantly decrease due to the low travel speeds. Therefore, these machines could be an alternative mainly for short distance extractions in frequently harvested stands, or additional efforts would be needed for pre-concentration of logs to increase extraction efficiency over longer distances. However, considering the purchase price with respect to local economic constraints, even these small machines are relatively expensive and operational costs including machine movement expenses will probably exceed the financial capacities of a local contractor.

Farm tractors equipped with forestry implements such as winches have proved to be an economic alternative towards specialized forestry equipment in small scale harvesting operations, as well as with longer extraction distances [43] worldwide. However, these modified farm tractors are normally used for stem length extraction with final processing at landing. In a short wood system with log processing in the stand, specific short wood trailer are available for the tractor, further increasing the total investment. Since a wide range of domestically produced farm tractors are available with distinct price advantages compared to Western models, it would be worthwhile to further investigate the performance and costs of such equipment in various extraction systems with different features and components in Guangxi operations, compared to the Igland Hauler. Agricultural machine services in rural China are often conducted by contractors owning small and medium sized tractors [45]. Modifying their tractors with forestry implements could offer additional employment opportunities during the off-farm seasons and increase the machine utilization over the year with related cost reductions for the timber hauling rate. However, it should be considered that a farm tractor has similar restrictions to terrain and logging infrastructure as the compact crawlers, probably giving advantages to yarding systems in steeper terrain.

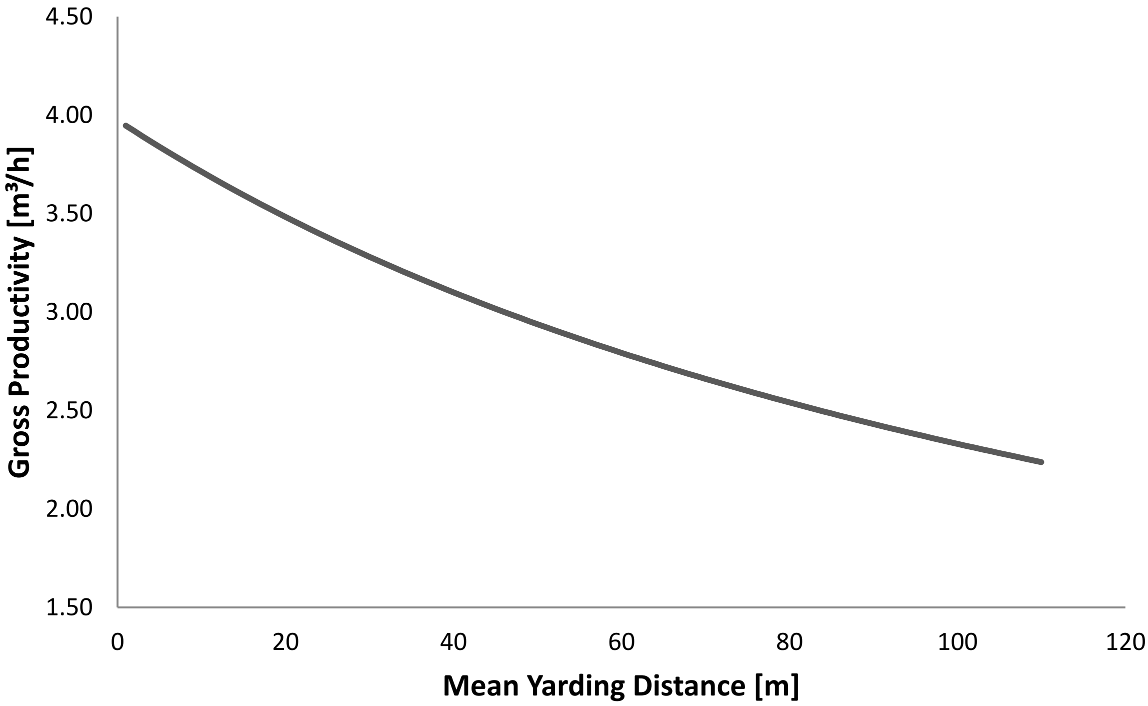

Figure 7. Gross productivity of the Igland Hauler measured in yarded volume (m^3) per hour as a function of mean yarding distance (m) based on the computed regression model (t_{cycle}) and the mean payload of the study.

Since the need for just-in-time delivery through more structured supply capacities will likely increase with the operation of large scale pulp mills in Guangxi [16], and ergonomic problems associated with manual log extraction [38] will influence productivity levels and therewith supply consistency, local manual extraction systems need to be optimized with the objective of further rationalization. Such a developments caused by market drivers has been observed in timber harvesting operations in other parts of the world in order to improve work safety, compensate for a shortage of available labor and generally improve the access to resources and the supply potential [46]. Therefore, a shift from a labor-intensive system to a capital-intensive system in the medium to long term can be foreseen in China as well. However, the suitability of mechanized systems such as the Igland Hauler need to be verified according to market driven objectives, mainly by the productivity and costs associated with such systems. To fully understand the mechanization potential in Guangxi forestry operations and to evaluate individual trial crews under local conditions, long-term monitoring of work performance would be required. Long-term monitoring approaches provide a clearer picture of actual annual utilization and performance of harvesting systems, as shown by [30]. In addition, such monitoring has the potential to identify specific improvement "hot spots", along with the suitability of target oriented training approaches and possibilities to verify their success or failure [47,48].

5. Conclusions

This case study evaluated the potential of a low capacity running skyline yarder as an alternative to the current labor intensive manual log extraction system being used in Guangxi province, China. In comparison to manual extraction at equal distances, the yarder system was 2.5 times more productive, but also 10 times more expensive. Therefore, the system's productivity was currently too low, and associated operating costs too high, to compete with manual operations, given the abundance of migrant workers at low hourly rates in the region. However, it needs to be emphasized that the trial machine was a discontinued refurbished unit, brought with considerable effort and costs from Europe to China, affecting the overall costs of the system, and did not represent locally available technology and machine production costs. If similar, locally produced equipment were to become available in the near future, initial investment costs and operating costs would be significantly reduced. Furthermore, the productivity study also revealed that the system was not utilized to its full potential yet due to the ongoing skills development process of the crew, suggesting room for future performance enhancement and cost reduction. Additional long-term monitoring approaches under different system set-ups and components could offer opportunities to identify optimal configurations under Guangxi operation conditions.

Finally, framework conditions for the introduction and operation of harvesting systems with a higher degree of mechanization will be determined by availability and qualification of labor willing to work in forest operations and the development of wages in Guangxi. Various technical solutions are available to cope with local operational conditions, of which small-scale running skyline systems such as the Igland Hauler are worthwhile to be considered.

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Author Contributions

Stephan Hoffmann contributed to the study design, data collection, data analysis and writing. Dirk Jaeger initiated the research and led the writing with significant input on the interpretation of the results.

Siegmar Schoenherr contributed to the data collection and data analysis. Bruce Talbot contributed to the interpretation of the data analysis and writing.

Conflicts of Interest

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; and in the decision to publish the results.

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