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Assessing the Productivity of Forest Harvesting Systems Using a Combination of Forestry Machines in Steep Terrain

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Abstract: Despite similarly steep terrain, the productivity of forest harvesting operations in Japan is lower than in Central Europe. Harvesting systems in Japan are typically characterized by the four production processes of felling, yarding, processing, and forwarding, whereas in Central Europe they have mostly been reduced to just two through the use of a PTY (Processor Tower Yarder). This study investigated the number of production processes as a reason for the relatively lower productivity of forest harvesting in Japan using the Combined Machine Productivity (CMP) and Combined Labor Productivity (CLP) indices. The CMP and CLP were 1.81 m^3/h and 0.45 m^3/worker/h, respectively, for a parallel production model based on a typical Japanese forest harvesting system in Japan. The CMP and CLP values were improved to 2.51 m^3/h and 0.63 m^3/worker/h, respectively, when the forwarding process was removed from the model. The CMP and CLP values were further improved to 3.04 m^3/h and 0.76 m^3/worker/h, respectively, when yarding and processing were integrated into a single process. Reducing the number of the production processes can therefore improve the productivity of forest harvesting operations in Japan.

Keywords: productivity; harvesting system; processor tower yarder; combined machine productivity; combined labor productivity

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1. Introduction

Productivity is defined as the rate of product output per time unit for a given production system [1]. In forestry, productivity in harvesting operations is a central concern in achieving an optimum balance between profitability and sustainability. When the slope gradient exceeds 40%, ground-based harvesting technology cannot provide good results [2]. Therefore, forest management in steep terrain depends on cable yarding as the primary extraction technology, which is usually deployed on difficult sites [3]. Cable yarding is a well-established practice for timber extraction in mountainous regions of the world where fully mechanized harvesting systems such as harvester–forwarder combinations cannot operate due to the steep terrain [4]. Analysis of 12 years of cable logging studies, from 2000 to 2011, showed that cable system efficiency was the most frequent keyword, with 78 out of 172 scientific references [5]. In the current study, the productivity of mechanized forest harvesting systems in steep terrain was discussed in relation to further improving profitability and sustainability.

Today, most forest harvesting operations are carried out with modern forestry machines, and their efficiency depends not only on the performance of each forestry machine, but also on how they are used in combination and on various site characteristics. In Japan, chainsaws, swing yarders, processors, and forwarders are typically used for felling, yarding, processing, and forwarding, respectively, on steep slopes where the most efficient harvester–forwarder system suitable for gentler slopes cannot be used. Cable yarding has been used for many years for timber extraction in the mountainous forests of Central

European countries [6] and is an efficient and effective harvesting system in steep terrain [7]. Regarding technical development, by the end of the 1990s, tower yarders, combined with a processor (PTY, Processor Tower Yarder) equipped with a radio-controlled carriage that automatically moves and stops, had become the standard for all manufacturers [8]. In Central Europe, system integration through the mounting of a tower yarder, crane and processing unit on a single carrier has been the main innovation path towards maintaining low harvesting costs and improving the productivity of cable yarding operations [9]. As a result, the productivity of forest harvesting operations in Japan is relatively low compared to Central Europe, as represented by Austria, where there have been significant technological innovations in cable-based harvesting machines and systems.

Many previous studies have determined the productivity of variations of the above-mentioned forest harvesting operations in Japan. According to the authors of [10], the labor productivity was 1.2 to 2.6 m^3/worker/day when a chainsaw, swing yarder, and processor were used for felling, yarding, and processing, respectively. The study described in [11] found that the labor productivity was 3.62 m^3/worker/day when a chainsaw, swing yarder, processor, and forwarder were used for felling, yarding, processing, and forwarding, respectively, and identified the use of a swing yarder as the reason for the relatively low productivity. The productivity of forest harvesting operations on moderate slopes was compared for different sizes of forestry machines and different log lengths when a chainsaw, harvester, and forwarder were used for felling, processing, and forwarding, respectively, and ranged from 5.3 to 7.5 m^3/worker/h [12]. Labor productivity was 6.64 m^3/worker/day when a chainsaw, grapple loader with a small winch, harvester, and forwarder were used for felling, wood extraction, processing, and forwarding, respectively [13]. According to the authors of [14], the overall average productivity of forest harvesting operations in Japan is 7.14 m^3/worker/day and 4.17 m^3/worker/day for final cutting and thinning, respectively.

While m^3/h or m^3/day is often used in Japan as a unit of productivity, Productive Machine Hour (PMH) is commonly used as the unit of productivity for mechanized forest harvesting operations. PMH represents the time during which the machine actually performs work, and this excludes time lost due to both mechanical and non-mechanical delays from Scheduled Machine Hours (SMH) that includes all time the machine is scheduled to work [15]. On the other hand, the study in [16] pointed out that Productive System Hour (PSH) must be used for systems consisting of several machines, while PMH has been widely used for systems consisting of a single machine and an operator. PSH is similar to PMH, but PSH includes two or more machines or sequential operations necessary to complete the task [17]. While PMH is commonly used as the unit of productivity for mechanized forest harvesting operations, PSH has been used by many studies, especially in Central Europe [3,4,8,18–27]. In addition, PMH_0 and PSH_0 do not include delays while PMH_{15} and PSH_{15} include delays of up to 15 min.

The PTY systems developed in Central Europe, such as Syncrofalke (MM Forsttechnik, Frohnleiten, Austria), as shown in Figure 1, can efficiently yard and process trees in a single production process. Productivity with the Syncrofalke for uphill and downhill yarding was found to be 11.54 m^3/PSH_0 and 8.25 m^3/PSH_0, respectively [6]. The average productivity of Syncrofalke in Central Bulgaria was calculated to be 15.20 m^3/PMH [28]. In Romania, the production rate of a PTY system consisting of a Mounty 4100 tower yarder and a Woody 60 processor (Konrad Forsttechnik) was 11.89 m^3/h, including delays [29]. In all cases, the productivity of forest harvesting operations with PTY systems was much higher than the average productivity in Japan.

According to the authors of [30,31], the low productivity of forestry operations in Japan is mainly due to the structural characteristics of small-scale forest ownership. We investigated additional reasons for the relatively low productivity of forest harvesting operations in Japan in terms of the way forestry machinery is used in combination. In this study, we evaluated the productivity of Japanese harvesting systems using two indices of the Combined Machine Productivity (CMP) and Combined Labor Productivity (CLP) and compared them with those observed in Central Europe.

Figure 1. Syncrofalke, one of the most typical PTY systems developed in Austria.

2. Materials and Methods

2.1. Classification of Production Models

2.1.1. Serial Production System

Forest harvesting systems were classified into two types, i.e., the serial and parallel production systems [32]. In the serial system the production processes are performed one after another in sequence (Figure 2). For example, after all the trees are felled by chainsaw, the yarding process starts. Conversely, in the parallel system the production processes are performed at the same time, either partially or completely (Figure 3). In this system, for example, trees are felled with a chainsaw while the yarding process is in progress. As shown in Figure 2, the total production time for the serial model (T_0) is expressed by the following equation:

$$T_0 = T_A + T_B \tag{1}$$

where T_0 is the total production time for the serial model, T_A and T_B are the production times for processes A and B, respectively. Then, the production rate of the serial production model (R_0) is expressed by the following equation:

$$R_0 = \frac{V}{T_0} = \frac{V}{T_A + T_B} = \frac{V}{\frac{V_A}{P_A} + \frac{V_B}{P_B}} = \frac{V}{\frac{V}{P_A} + \frac{V}{P_B}} = \frac{1}{\frac{1}{P_A} + \frac{1}{P_B}} \tag{2}$$

where V is the total production volume, V_A and V_B are the processed volume in the production processes A and B, respectively, and P_A and P_B are the production rate in the production processes A and B, respectively. In Equation (2), the following equation holds:

$$V = V_A = V_B \tag{3}$$

2.1.2. Parallel Production System

The total production time can be shortened by using the parallel production model as shown in Figure 3, and the time-saving rate (s) or the ratio of the total production time for the parallel model (T_s) to the total production time for the serial model (T_0) is expressed by the following equation:

$$s = \frac{T_s}{T_0} \tag{4}$$

where Ts ($<T_0$) is the total production time for the parallel model and s (<1) is the time-saving rate. Here, s is equal to 1 for the serial production model in Equation (4). In Figure 3, T_A and T_B are expressed by the following equations:

$$T_A = r_A \times T_s \tag{5}$$

$$T_B = r_B \times T_s \tag{6}$$

where r_A and r_B are the ratios of the production time for the processes A and B, respectively, to the total production time for the parallel model (T_s). It should be noted that the basic idea of r_A and r_B correspond to the utilization rate, which is calculated by dividing PMH by SMH and then multiplying by 100 to obtain a percentage [33]. Then, the following equation holds under the above conditions:

$$s = \frac{T_s}{T_0} = \frac{T_s}{T_A + T_B} = \frac{T_s}{r_A T_s + r_B T_s} = \frac{1}{r_A + r_B} \tag{7}$$

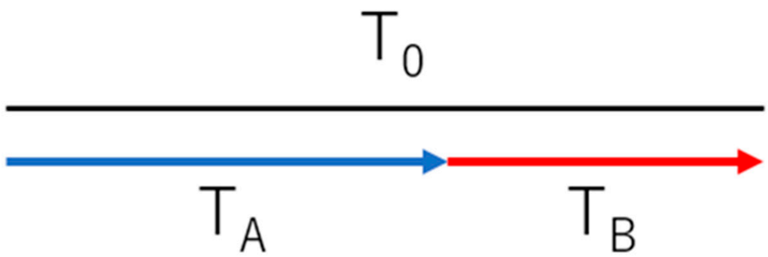

Figure 2. Serial production model. Note: T_0 = total production time for the serial model, T_A = production time for the process A, T_B = production time for the process B.

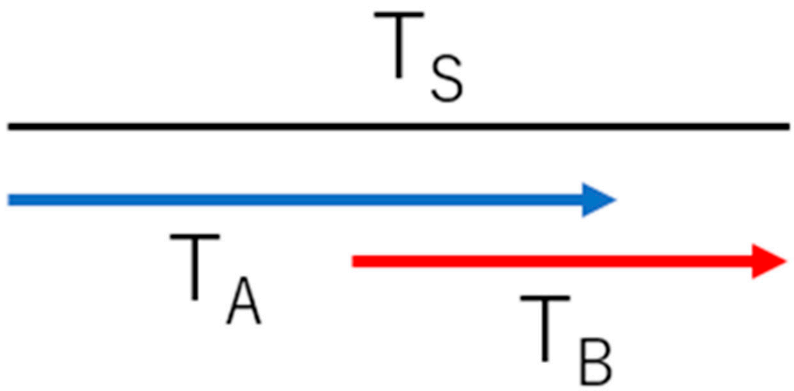

Figure 3. Parallel production model. Note: T_s = total production time for the parallel model, T_A = production time for the process A, T_B = production time for the process B.

The production rate of the parallel production model (R_s) is expressed by the following equation:

$$R_s = \frac{V}{T_s} = \frac{V}{s \times T_0} = \frac{V(r_A + r_B)}{T_0} = \frac{V}{\frac{V}{P_A} + \frac{V}{P_B}} \times (r_A + r_B) = \frac{1}{\frac{1}{P_A} + \frac{1}{P_B}} \times (r_A + r_B) \tag{8}$$

In Equation (8), $r_A + r_B$ is equal to 1 for the serial production model, and the following equation holds:

$$\frac{r_A}{r_B} = \frac{T_A/T_s}{T_B/T_s} = \frac{T_A}{T_B} = \frac{T_A/V}{T_B/V} = \frac{1/P_A}{1/P_B} = \frac{P_B}{P_A} \quad (9)$$

2.2. Combined Machine Productivity

The equation to calculate the production rates for the serial and parallel models (R) can be generalized for two or more production processes as follows:

$$R = \left[\frac{1}{\left\{\sum_{i=1}^{n}\left(\frac{1}{P_i}\right)\right\}}\right] \times \sum_{i=1}^{n} r_i \quad (10)$$

where P_i is the production rate in the production process, i (i = 1, n; where n is the total number of production processes), and r_i is the ratio of the production time of the process i to the total production time. In Equation (8), it should be noted that $\sum_{i=1}^{n} r_i$ is equal to 1 for the serial production model, and it is more than 1 for the parallel production model.

The CMP is the total or overall productivity when two or more forestry machines work in combination, and it is calculated based on Equation (11) as follows:

$$CMP = \left[\frac{1}{\left\{\sum_{i=1}^{n}\left(\frac{1}{P_i}\right)\right\}}\right] \times \sum_{i=1}^{n} r_i \quad (11)$$

where CMP is the combined machine productivity (m^3/h), P_i is the production rate (m^3/h) in the production process, i (i = 1, n; where n is the total number of production processes), and r_i is the ratio of the production time of the process i to the total production time. The CMP is based on the idea proposed by the authors of [34] and further developed as a measure of system productivity by the authors of [32], which has been widely used in Japan to estimate productivity based on the performance of each forestry machine. The PMH or PSH can be used as a unit of productivity instead of using the unit of m^3/h.

2.3. Combined labor Productivity

We also used a labor productivity model for when two or more forestry machines are used in combination. The CLP is the total labor productivity, and is calculated as follows:

$$CLP = \frac{1}{\sum_{i=1}^{n}\left(\frac{N_i}{P_i}\right)} \quad (12)$$

where CLP indicates the combined labor productivity (m^3/worker/h), P_i is the production rate (m^3/h) in the production process, i (i = 1, n; where n is the total number of production processes), and N_i is the number of workers in the production process, i. Equation (12) can be applied to both serial and parallel models. In Japan the CLP is referred to as system labor productivity and it has been used in many studies there [10,12,34–44]. As with the CMP, the PMH or PSH can be used as a unit of productivity instead of using the unit of m^3/h.

2.4. Productivity Assessment

We evaluated the productivity of several production models representing forest harvesting systems in mountainous conditions by calculating the CMP and CLP. Table 1 shows the performance values of the forestry machines used for the productivity calculation in Japan and Central Europe. The performance values of forestry machines depend on the operating conditions such as slope, terrain, yarding distances, tree volumes, machine types, operator experience, and so on, and they vary widely from one site to another. In addition, the purpose of this study is not to estimate the exact productivity but to identify the disadvantages of forest harvesting systems in Japan by comparing them with those in

Central Europe. Therefore, we determined the approximate performance values of forestry machines based on the published literature.

Table 1. Performance of forestry machines used in Japan and Central Europe for productivity calculation.

Type of Operation	Type of Machine	Country/Region	Hourly Processed Volume (m^3/h)	Number of Worker(s)
Felling	Chainsaw (×2)	Japan	8.30 (4.15 × 2)	2
Yarding	Swing yarder	Japan	3.24	2
Processing	Processor	Japan	7.32	1
Forwarding	Forwarder	Japan	5.89	1
Felling	Chainsaw (×2)	Central Europe	15.00 (7.50 × 2)	2
Yarding/Processing	PTY	Central Europe	11.54	2

In Japan, the labor productivity of chainsaw felling operations with a chainsaw at three research sites was reported to be 7.73, 2.97, and 1.75 m^3/worker/h [42], and we determined the hourly processed volume to be 4.15 m^3/h by averaging them. We also determined the hourly processed volume of yarding operations with a Japanese swing yarder to be 3.24 m^3/h by averaging the production rates of 3.29 m^3/h [44] and 3.18 m^3/h [45] for uphill yarding operations. The hourly processed volume of processing operations with a processor in Japan was determined to be 7.32 m^3/h by following [36]. The hourly processed volume of forwarding operations with a Japanese forwarder for two different-skilled operators was reported to be 3.10 and 8.67 m^3/h [46], and the average was determined to be 5.89 m^3/h.

In Germany, the labor productivity of chainsaw felling operations with a chainsaw was reported to be 7.50 m^3/worker/h [47]. The hourly processed volume of yarding/processing operations with PTY in Austria was determined to be 11.54 m^3/h based on the production rate for uphill yarding with a Syncrofalke tower yarder [6].

Figure 4 shows Model A1 for a Japanese harvesting system, where the production processes are connected in series and carried out one after another. There are four production processes in Model A1, namely felling, yarding, processing, and forwarding, and the forestry machines used for these production processes are shown in Figure 5. This type of production system is the most efficient in terms of labor productivity or CLP in this study, but it requires the longest total production time.

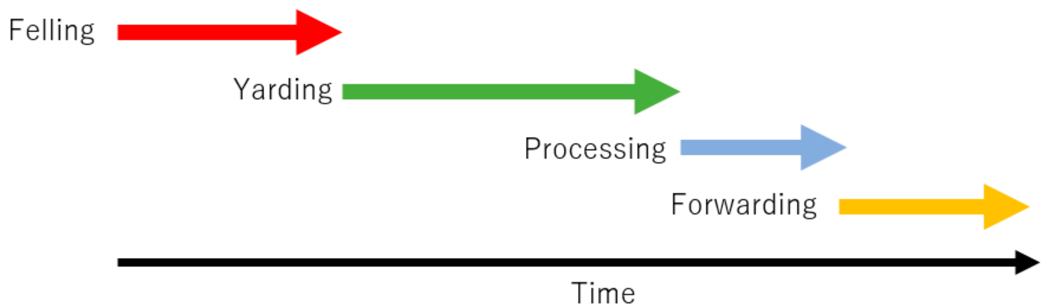

Figure 4. Production chart for Model A1.

Figure 6 shows Model A2 for a Japanese harvesting system, which omits the forwarding process from Model A1; there are thus three production processes in the model. In Model A3, the processing is merged with yarding and the timber extraction is carried out in just two processes as shown in Figure 7. Considering the poor forest road infrastructure in Japan, it may be almost impossible to use a PTY system due to its size and weight. However, it is possible to perform the same type of yarding and processing operations as a PTY system by using a tower yarder and a processor in combination, as shown in Figure 8.

Figure 5. Typical forestry machines used in Japan: (**a**) chainsaw; (**b**) swing yarder; (**c**) harvester; (**d**) forwarder.

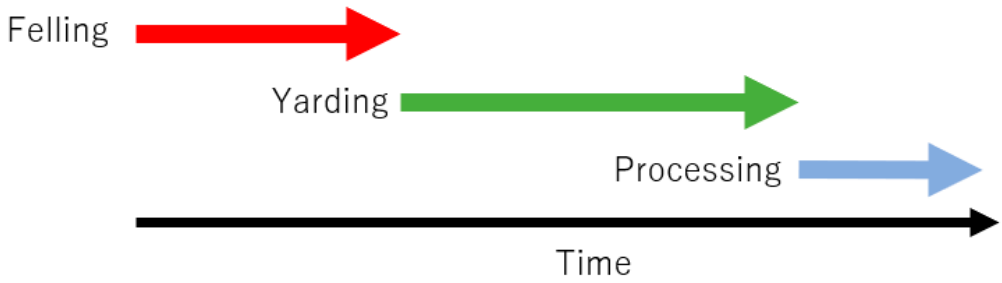

Figure 6. Production chart for Model A2.

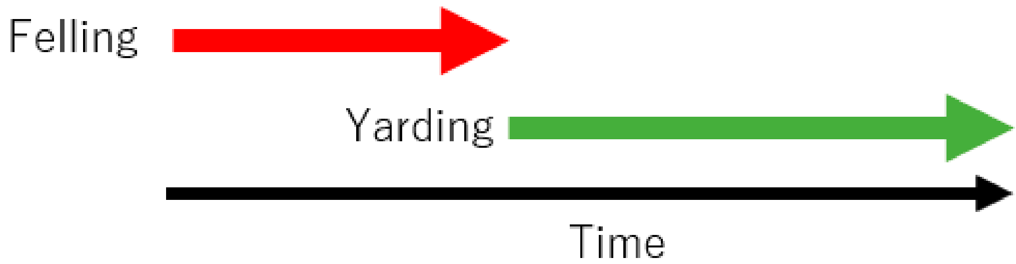

Figure 7. Production chart for Model A3.

In Model B1 (Figure 9), all machines and crew members work together to make the total production time shorter than in Model A1, and the production processes are connected in parallel. The time-saving rate of this model is set to 0.75. This type of production model is the most typical in Japan, where teamwork has traditionally been highly valued in the workplace. It should be noted that this production model requires four crew members, even if the chainsaw operators also operate the processor and forwarder. The critical disadvantages of this harvesting system are that all crew members have to remain at the harvesting site from the beginning to the end of the operations, and are expected to perform additional tasks such as cleaning or organizing even when they are not involved in operating the machines. Such situations can result in a significant loss of time and skilled manpower and, ultimately, lead to a reduction in overall productivity.

Figure 8. A truck-mounted tower yarder, radio-controlled carriage, and excavator-based harvester used in combination in Shimane Prefecture, Japan.

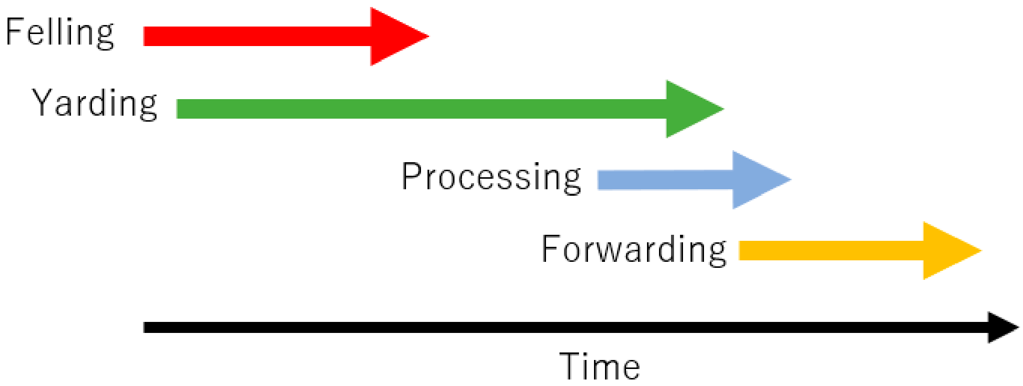

Figure 9. Production chart for Model B1.

Model B2 omits the forwarding process from Model B1, meaning there are three production processes involved (Figure 10). The time-saving rate is 0.71 in this model. In addition, Model B3 merges the processing and yarding processes, and timber extraction is therefore performed in two processes (Figure 11). The time-saving rate is 0.77 in this model. As in Model B1, Models B2 and B3 require that all crew members work together at the harvesting site.

Figure 12 shows a production model (Model C), which represents forest harvesting operations using PTY systems in Central Europe as a benchmark to evaluate the productivity of forest harvesting systems in Japan. The advantages of a PTY system are that it yards logs while processing them without requiring additional time or workforce, and there are only two production processes, i.e., felling and yarding/processing, as shown in Model C.

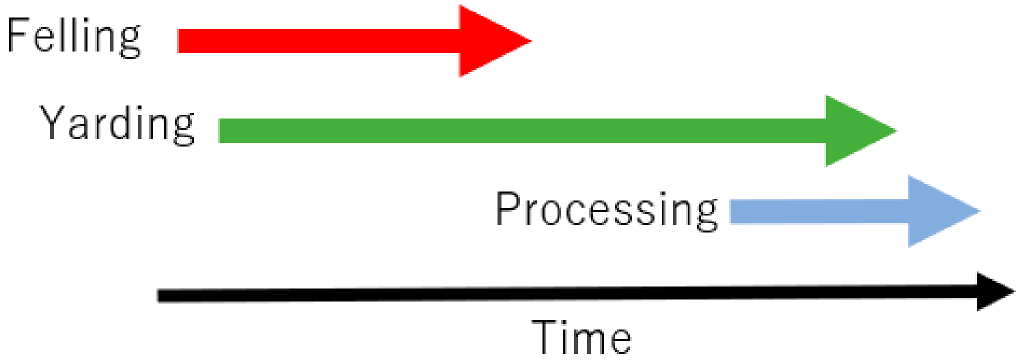

Figure 10. Production chart for Model B2.

Figure 11. Production chart for Model B3.

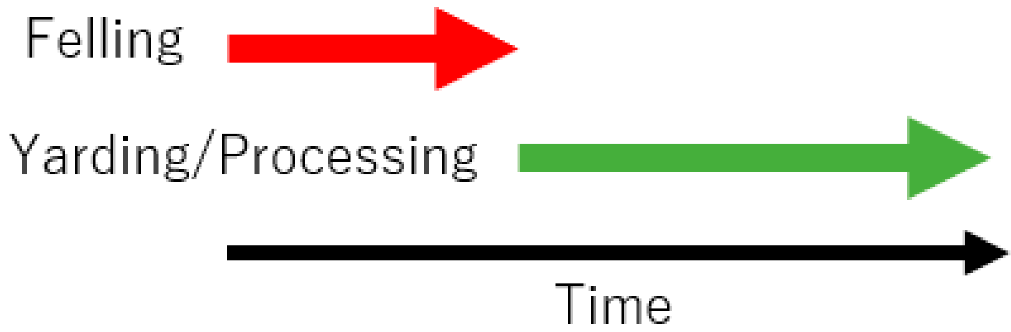

Figure 12. Production chart for Model C.

3. Results

Figures 13 and 14 show the results of the CMP and CLP calculations, respectively, for all production models. The CMP and CLP are the highest for Model C for Central Europe. The most typical production model in Japan is Model B1: it requires less production time than that of Model A1, but the labor productivity is also lower. In addition, process management in Model B1 is much harder than in Model A1 because it requires an efficient combination of machines and workforce. Although Model A1 is better than Model B1 in terms of process management, it has a critical practical disadvantage in that it is often difficult to store full trees on the forest road or landing until the next process starts.

The CMP and CLP were 1.81 m^3/h and 0.45 m^3/worker/h, respectively, for Model B1 based on a typical Japanese forest harvesting system in Japan. The CMP and CLP values were improved to 2.51 m^3/h and 0.63 m^3/worker/h, respectively, for Model B2 when the forwarding process was removed from Model B1. The CMP and CLP values were further improved to 3.04 m^3/h and 0.76 m^3/worker/h, respectively, for Model B3 when yarding and processing were integrated into a single process.

Parallel production models are supposed to be desirable because the forest harvesting operation can be completed in a shorter time than in serial models [32,48]. In fact, the respective CMP of Models B1, B2, and B3 are higher than those of Models A1, A2, and A3 (Figure 13). That is why parallel harvesting systems have been widely utilized in Japanese forestry. However, as shown in Figure 14, parallel models are less productive than serial models in terms of the CLP. A comparison of CMP and CLP in these models highlights the disadvantages of typical Japanese harvesting systems, which require more forestry machines and workforce at the same time, and process management is highly complicated and difficult to carry out efficiently. Forestry machines and workforce are sometimes idle at the harvesting site, as shown in Models B1, B2, and B3, introducing further inefficiency.

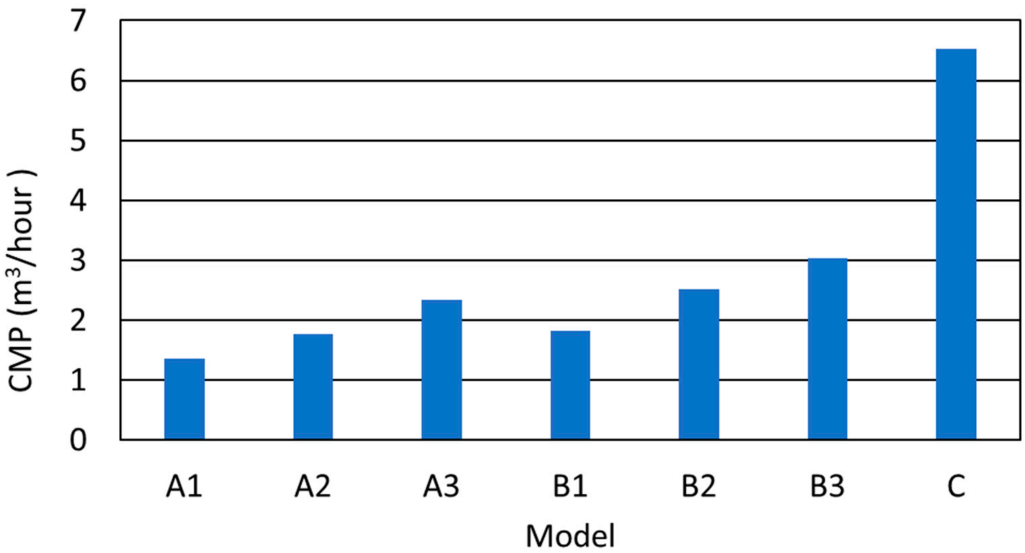

Figure 13. Comparison of the CMP among models for productivity evaluation.

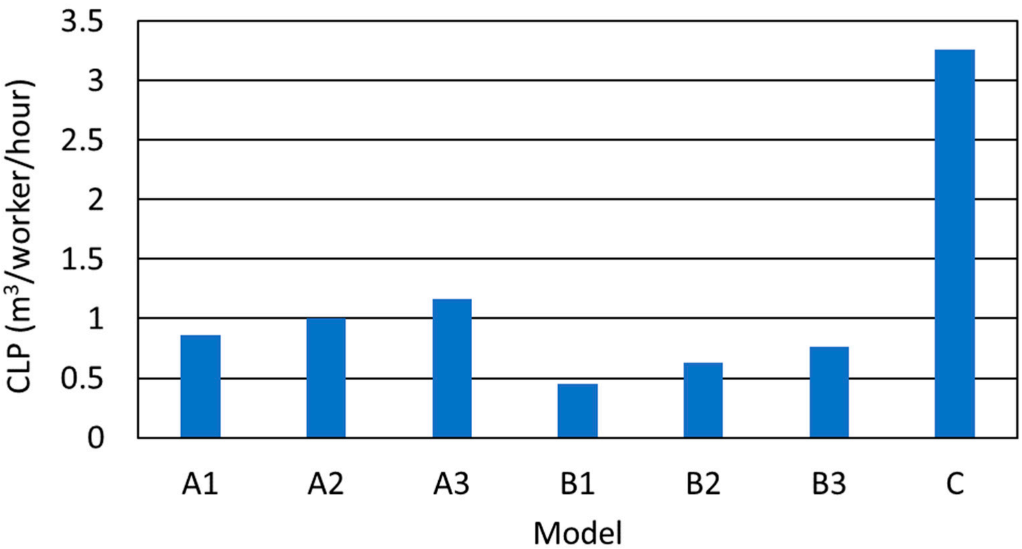

Figure 14. Comparison of the CLP among models for productivity evaluation.

Figure 15 shows the variation of the ratios of the production time for each process to the total production time for the parallel models B1, B2, and B3. As shown in this figure, the ratios become higher as the number of production processes is reduced. The ratio of idle time for Model B1 is the highest among the three parallel models, and the ratio of idle time for felling is the highest among the four production processes in Model B1. As a result, the imbalance of production rates between processes is a fundamental problem in the parallel production systems typical in Japan.

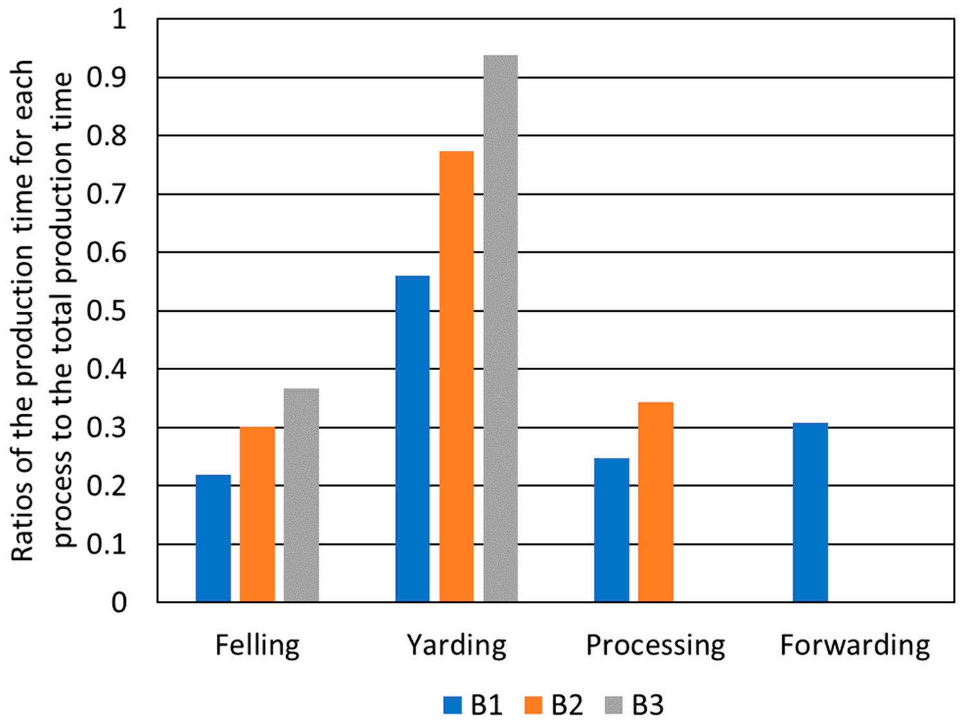

Figure 15. Ratios of the production time for each production process to the total production time for the parallel models.

Figure 16 shows the variation in the number of crew members for each production model according to the elapsed time. In this figure, it is assumed that 300 m^3 of timber is harvested and that the total production time is 220.7 h for Model A1. The number of crew members required for Models B1, B2, and B3 is higher than for Models A1, A2, A3, and C. The number of crew members for Models A1, A2, A3, and C varies in the same way. It should be noted that production models with PTY systems used in Central Europe refer to the serial models A1, A2, and A3 and not to the parallel models B1, B2, and B3, which are more common in Japan.

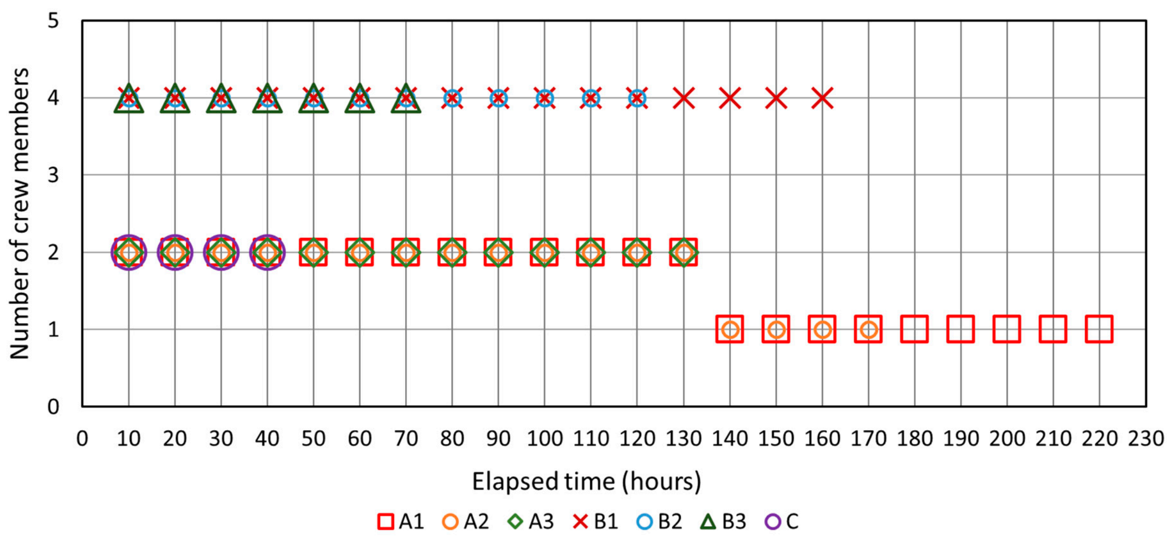

Figure 16. Variation in the number of crew members for each production model according to the elapsed time.

Figure 17 shows the variation in the volume of yarded full trees for each production model as a function of time. Cable yarding systems require well-coordinated transport to available storage space at the landing, otherwise the operation will run out of storage space and be shut down until serviced by a log truck [9].

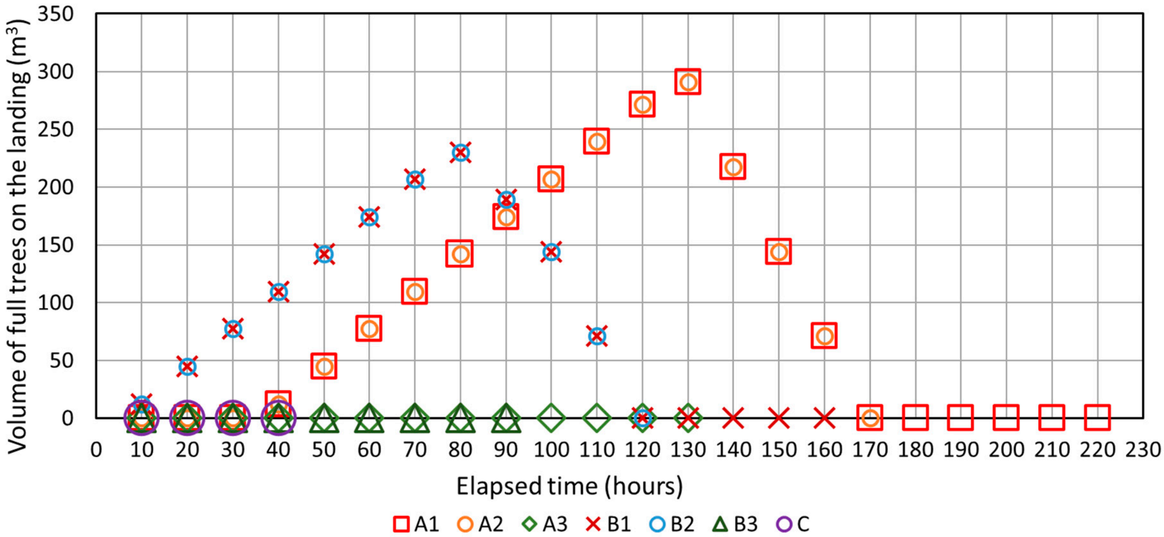

Figure 17. Variation in the volume of yarded full trees on the landing for each production model according to the elapsed time.

For Models A1 and A2, the volume of yarded full trees on the landing reaches 300 m^3 after 128.7 h. For Models B1 and B2, the volume reaches the maximum (235.2 m^3) after 78.7 h. As a result, these production models can be applied to harvesting sites that have a large area available for full tree storage. On the other hand, such a large area for full tree storage is not necessary for Models A3, B3, and C, where PTY or an equivalent system is used for the combined processes of yarding and processing. In a typical Japanese harvesting system such as Model B1, the imbalance of productivity between yarding and processing often causes extra waiting time for a processor, and the use of a PTY system can be an appropriate solution to this problem.

4. Discussion

In general, the productivity of forest harvesting operations is influenced by many factors. The main factors influencing the productivity of mechanized harvesting are the environment such as tree and terrain characteristics and climate, machine characteristics including bucking instructions, and the operator's mental and physical capabilities and work technique [1]. The productivity of the cable crane application is strongly influenced by the log volume, length of skyline, silvicultural prescription (harvesting intensity), and lateral extraction distance, and, in addition, the terrain slope, stand density, and direction of the yarding (uphill/downhill) have an influence on the extracted volume per time [47,49]. The productivity of harvesters depends on several factors, such as the tree size, stand type and productivity class, species, harvesting intensity and type, ground conditions, machine class, and operator skill [50]. A review of 70 studies of cable yarding operations found that different yarding conditions result in different effective factors, and that factors that have a large effect on one system studied may not be present in another system, or at least may not have a significant effect on performance [4]. The study in [4] also noted that weather is likely to have a significant effect on performance. It is very likely that heavy rain and wet conditions in the stand will decrease performance because the choker setter's movement will be more cautious and consequently slower and, in addition, the workers' motivation may be lower in rainy working conditions [4].

Due to the large number of factors that need to be considered as independent variables, there have been no practical models to accurately estimate the productivity by using all of the above factors. In this study, the CMP and CLP were calculated using a limited number of examples from the published literature, and this is one of the major limitations of this study. Nevertheless, the productivity of each Japanese machine shown in Table 1 is close to the standard productivity data published by the Forestry Agency of Japan [51], where 3 m^3/h for chainsaw felling, 10 m^3/h for processors, 8.3 m^3/h for forwarders, and 3.3 m^3/h for swing yarders was recorded. It should also be noted that the purpose of this study is to clarify the reasons for the relatively low productivity of forest harvesting operations in Japan in terms of the way forestry machinery is used in combination, and that it is not an accurate estimate of productivity.

The results showed the strong advantages of forest harvesting systems in Central Europe compared to those in Japan. It was suggested that the number of production processes is key to productive harvesting when two or more machines are used in combination. In Europe, the most successful forest harvesting systems in terms of productivity are based on two combined production processes. As an example of two-process production on gentle slopes, the harvester–forwarder system is widely used, where trees are felled and processed by a harvester, and then logs are collected and transported by a forwarder. The study in [52] calculated the system productivity of a small-scale combination harvester–forwarder in industrial plantation first thinning operations and pointed out that the system productivity is limited by the least productive component. On steep slopes, trees have been felled with a chainsaw, yarded, and then processed by a PTY and, nowadays, the harvester–forwarder system is feasible even on steep slopes by using harvesters [53,54] and forwarders [55], or by using a winch-assisted system [56–58]. All these systems are two-production processes and, furthermore, there are also potential possibilities of single process production, as seen in the development of harwarders [59–61]. The harwarder has shown the greatest potential to compete with the two-machine system in final fellings with relatively small stand volumes and short extraction distances [62]. The two-in-one harvester/forwarder [52] is another innovative technology, and the system productivity using this machine can be calculated as a serial production system.

Despite the importance of the number of production processes, the typical Japanese harvesting system consists of four production processes, with the addition of a forwarder to transport logs along the spur/secondary road, whereas harvesting systems on steep slopes in Japan used to consist of the three processes of felling with a chainsaw, yarding with a tower yarder, and processing with a processor in the 1990s [63]. In addition, tower yarders have been replaced by swing yarders or grapple loaders, which have a shorter reach for extracting trees than tower yarders. As a result, Japanese harvesting systems require high-density spur roads, especially when grapple loaders are used for tree extraction. The study in [64] raised concerns about the sustainability of this type of practice because it is usually carried out on steep slopes in high rainfall areas with little or no planning, drainage, or stabilization. Today, this type of practice often attracts public criticism in Japan because it can cause landslides during periods of torrential rain. In fact, on 4 July 2020, record-breaking rainfall hit the southern Japanese island of Kyushu, and many landslide disasters occurred in clear-cut areas, where spur roads had not been maintained after their construction. It is necessary to improve the productivity of forest harvesting operations on steep slopes in Japan, especially with a tower yarder and swing yarder, not only for increasing profitability but also for environmental sustainability.

5. Conclusions

This study showed that the productivity of forest harvesting systems in Japan is typically lower than in Central Europe in terms of the CMP and CLP. The reasons for this are not only the lower performance of forestry machines and the lower standard of forest roads in Japan, but also the difference in harvesting systems, especially the number of production processes employed in timber extraction. It was also found that the parallel production models are less productive than the serial production models in terms of the CLP, and that serial production models achieve the best productivity when processing is merged with the yarding process, and the forwarding process is eliminated. Forest harvesting systems in the mountainous countries of Central Europe, which have steep slope conditions similar to those in Japan, suggest the direction that Japanese forestry mechanization should follow. Finally, it is recommended that Japanese forestry should reduce the number of production processes to two by introducing the cable yarding system used in Central Europe, rather than making any further efforts by maintaining the four-process production system.

Future research is needed to flexibly adjust the hourly processed volume of each machine based on variables such as site slope, tree volume, road networks, silvicultural methods, and yarding and hauling distances by using computer simulation. This will allow us to generalize the production models in this study and take the next step in accurately determining the productivity according to different operating conditions.

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Data Availability Statement: All data used in this study is shown in Table 1. Anybody can get the same results as ours by using this data.

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