INFRES – Innovative and effective technology and logistics for forest residual biomass supply in the EU (311881)

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Coupled vs. De-coupled Logistics for Wood Chip Production – D3.3

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Preface

The Finnish Forest Research Institute (Metla) is coordinating this research and development project ‘Innovative and effective technology and logistics for forest residual biomass supply in the EU –INFRES’. The project is funded from the EU’s 7th framework programme. The primary focus of INFRES is enhancing high efficiency and precise deliveries of woody feedstock to heat, power and biorefining industries. INFRES is also concentrated on developing new technology from machines for logging and processing of energy biomass together with transportation solutions and Information control, technology ICT systems to manage the entire supply chain. The aim is to improve the competitiveness of forest energy by reducing the fossil energy consumption and the material loss during the supply chains. New hybrid technology is demonstrated in machines and new improved cargo-space solutions are tested in chip trucks. Flexible fleet management systems are developed to run the harvesting, chipping and transport operations. In addition, the functionality and environmental effects of developed technologies are evaluated as a part of whole forest energy supply chain.

This publication, “Coupled vs. De-Coupled Logistics for Wood Chip Production,” is focused on improving the understanding, efficiency and applicability of couple vs. de-coupled forest biomass supply chains. Throughout Europe many different forms of both coupled and de-coupled supply chain systems have evolved in the collection of forest biomass, adapting to the local conditions that apply. Given the diversity that exists across a region as large as Europe, the combination of different coupled vs. de-coupled systems is large and varies widely.

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Title	**Adapted Forestry Practices for Integrated Timber and Energy Biomass Production**
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Abstract	The increased demand of forest residual biomass for energy purposes has raised the issue of identifying cost efficient supply chains in order to meet the demand of different customers. Because of the lower energy unit per density unit, fossil fuel has a strong comparative advantage concerning transportation costs. This publication, "Coupled vs. De-Coupled Logistics for Wood Chip Production," is the third in a series of subsequent publications regarding the INFRES project and is focused on improving the understanding, efficiency and applicability of couple vs. de-coupled forest biomass supply chains. Throughout Europe many different forms of both coupled and de-coupled supply chain systems have evolved in the collection of forest biomass, adapting to the local conditions that apply. Given the diversity that exists across a region as large as Europe, the combination of different coupled vs. de-coupled systems is large and varies widely. This report This report focuses on three primary aspects including 1) provide the economic trade-off associated with firm level decisions regarding capital and labor choices (couple vs. de-coupled) and to draw implications related to an estimated production function from one coupled bioenergy supply chain in central Europe 2) give an overview of two Austrian studies focused on different aspects of the de-coupling question 3) provide detailed results from a study of a de-coupled supply chain in steep mountainous conditions (Raffaele Spinelli et al. 2013). This last goal is achieved by development of a discrete event model for simulating handling and processing cost under varying work conditions, so as to conduct standardized comparisons and sensitivity analyses; and second to determine whether and when chipping on the pad (coupled) is preferable to chipping at a proper roadside landing (de-coupled).
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1. Introduction

Many studies forecast a significant increase in the use of energy biomass over the next coming years (Berndes, Hoogwijk et al. 2003, European Commission 2012), and the forest industry is already exploring this new growing market. Biomass recovery does add to the complexity of forestry, but it also offers a significant opportunity to increase efficiency, raise value recovery and reduce harvesting and management costs (Björheden 2000). The recovery of forest biomass generally requires some form of processing – chipping or bundling – aimed at increasing the density and the homogeneity of the feedstock. Throughout Europe, there have emerged many different types of forest biomass supply chains that are adapted to the particular conditions that exist locally, including both geographical/natural conditions, market conditions, technological and economic. Given the residual biomass weight/density properties that exist, it is generally advantageous for the processing of forest biomass (chipping) to occur as early as possible, in order to accrue the maximum benefit along the supply chain (Johansson et al. 2006). Under ideal access conditions, the biomass can be chipped in the stand, and chips rather than trees or residue can be extracted to the roadside landing (Kalaja 1984). Among other things, direct delivery of chip loads to the roadside reduces landing space requirements, and makes this system most suited to those situations where the forest infrastructure is poor or fragmented (Kofman 1993). In many cases, however, difficult terrain conditions prevent terrain chipping, and the biomass is first extracted to the roadside and then chipped. The situation become even more difficult when moving to remote upland areas, which are a main potential source of forest biomass in mountain countries like Italy, Austria, Switzerland and parts of France (Freppaz et al. 2004). Here, the quality of the access network declines rapidly, to the point where no standard truck and trailer convoys can reach the forest landings.

The focus of this research report is on this linkage or coupling activity between the chipper and the transport equipment within forest residue and biomass supply chains and to better understand those attributes which may lead to more efficient and optimal biomass collection operations. As such, we distinguish between two general types of biomass supply chains, coupled and de-coupled.

Coupled Biomass Supply Chain

The coupled biomass supply chains are defined by those where the chipper (primarily mobile truck-mounted chipper or a chipper on a forwarder) is either directly or indirectly coupled with the transporting activity. In these operations, the chipper operates in or near the stand along forest roads and loads directly into a truck or container for transporting wood chips to a terminal or heat plant facility. In many cases, chipper has some operating capacity (onboard container or bin) which allows some operational flexibility to continue chipping while waiting for trucks to arrive. The chipper then empties or dumps the chips from their bin/container into the trucks for transport. In other cases where chipper has no onboard container, they can only operate when a truck is present for loading. Coupled system has also been called as a hot system referring to the fact that phases in the supply chain closely interact and their productivities are interlinked.

De-Coupled Biomass Supply Chain

The de-coupled biomass supply chains are defined by those where the chipping activity and the transportation activity are separated and function independently of each other. These de-coupled supply chains are typical for conditions where accessibility becomes an issue, steep terrain, mountainous conditions and particularly inaccessible for large trucks. In these hillside and mountain operations it is common to have a landing pad inaccessible to heavy road vehicles, and connected to a proper roadside landing by a low-standard trail, only accessible with tractors, forwarders and light tree-axle trucks. Under these conditions, the two-stage de-coupled transport becomes unavoidable, especially if extraction is performed with cable systems, as it often happens in steep mountain operations. The problem is how to organize the operation so that the overall handling and processing cost is the lowest. This is extremely important, because harvesting and transportation cost can represent approximately 70 % of the total biomass cost (Panichelli and Gnansounou 2008), which represents one of the most important barriers to the increased use of biomass (Rentizelas et al. 2009). In one case, the question is a typical point-of-comminution problem (Björheden 2008) in identifying whether it is optimal for material to be forwarded to the roadside landing and chipped there, or alternatively for the wood energy material to be chipped on the pad with a highly mobile chipper and forward the chips to the landing to be loaded into transport trucks. In another case, (Holzleitner et al. 2006, Kanzian and Stampfer 2006)) where forest material is already forwarded to the roadside, the question primarily concerns the organization of the transport process and determining whether chips are blown directly onto a truck by the chipper during the chipping process or is it preferable to de-couple the process and have the chipper and the transporting activities operate separately. In the second case the material is chipped and stored on a pile first and a truck and trailer unit with a mounted clamshell loader loads and transports the chips independently of the chipper. De-coupled systems are also called cold harvesting systems, where a shorter or longer storage period cuts the linkage between e.g. chipping and truck transport of chips. Here the productivities of subsequent phases in the supply chain are not dependent from each other.

It is clear that what is optimal depends on many factors, including: the distance to be covered, the type of chipper one can take to the pad, the payload that can be moved by the forwarding units with the different products (i.e. un-comminuted wood and chips), the speed that can be reached by the forwarding units and finally the interactive delays inherent to each system (Stampfer & Kanzian 2006, Holzleitner et al. 2013). The theoretical advantage of chipping on the pad is that chips can make for a heavier payload compared to loose residues, while its disadvantage is that bigger and more productive chippers can be used at the roadside landing. However, this is a theoretical statement, valid only to a point, where one can actually mount an industrial chipper on an all-terrain vehicle and take it to the pad. Besides, this statement falls short of defining a break-even point between reduced payload and increased chipping productivity, which is best determined with the experimental method. Any decision should also account for the potential benefit of chipping directly into the road transport vehicles, which can be accrued only when chipping at the roadside landing. Even in this case, however, the benefit must be proved: if it is true that chipping directly into the trucks can save the additional cost of loading, it is also true that such procedure is a main source of interaction delays, which may cause considerable cost. Potentially, discharging the chips on the ground avoids most of the interaction delays (Stampfer and Kanzian 2006), and the additional time consumption of frequent alignment of the chipper with the transportation unit. Besides, filling the trucks with a loader may be faster, and result in a significant reduction of truck idle time.

Therefore, the goals of this review are: 1) provide the economic trade-off associated with firm level decisions regarding capital and labour choices (couple vs. de-coupled) and to draw implications related to an estimated production function from one coupled bioenergy supply chain in central Europe, 2) give an overview about the different de-coupling points in the supply chain of wood chips, their advantages and disadvantages and the studies that have previously been completed and 3) provide detailed results from a study of a de-coupled supply chain in steep mountainous conditions (Spinelli, et al. 2013). This last goal is achieved by development of a discrete event model for simulating handling and processing cost under varying work conditions, so as to conduct standardized comparisons and sensitivity analyses; and second to determine whether and when chipping on the pad is preferable to chipping at a proper roadside landing.

2. Economic Discussion of Profit Maximization in a Coupled vs. De-Coupled Supply Chain

In order to illuminate the economic choice confronting individual firms involved in forest biomass supply chains and specifically the decision related to the input combination in the coupled vs. de-coupled biomass supply chain, we devote some attention to the firm's behavior from a general economic context. Most firms, including those comprising forest biomass supply chain operations, seek to maximize profit (∏). This objective is realized through the firms' choice of inputs related to their output or production function (Q), which can generally be described as some function of capital (k) and labour (l).

$$Q = f(k, l)$$

Where;

Q = total production or output

Factors of Production or output

l = labour

k = capital

$$MP_k = \frac{dQ}{dk} \qquad MP_l = \frac{dQ}{dl}$$

MP = marginal product or factor productivity of labour and capital

And trade-offs between factors of production (capital and labour) are defined by the marginal rate of technical substitution (MRTS), or the ratio of the marginal products for capital and labour.

$$MRTS_{k,l} = -\frac{\left(\frac{dQ}{dk}\right)}{\left(\frac{dQ}{dl}\right)}$$

$MRTS_{l,k}$ = marginal rate of technical substitution of labour for capital

The firm then maximizes profit as defined by maximizing the profit function of total revenue minus total cost.

$$Max\ \Pi = P_Q * Q - P_l l - P_k k$$

Where;

P_Q = Output Price

P_l = Price of Labour

P_k = Price of Capital

While we may not know the precise functional specification of this firms production function, it is safe to assume that the inputs of capital and labour are jointly related; meaning the choice of one impacts the choice of the other, particularly if we consider the bioenergy firm involved in the biomass supply chain with the primary inputs being capital (equipment such as truck-mounted chipper, transport trucks, trailers) and labour (truck-mounted chipper driver, transport truck driver, management personnel). Thus, the marginal productivity of capital (and labour) defined above is a function of labour (and capital). In practical terms, the decision of the firm to add one unit of capital (in terms of equipment) necessitates the addition of another unit of labour in order to operate the equipment and vice versa.

This joint relationship between labour and capital for firms involved in biomass supply chains certainly varies as the operational characteristics specific to each firm vary. However, in order to provide some baseline context from which to compare/contrast technological change that may alter the joint relationship between capital and labour, especially as it relates to the coupled vs. de-coupled supply chain choice, we collected data from one small-to-medium size bioenergy firm in southern Germany and estimated a traditional Cobb-Douglas production function, characterized as:

$$Q = Ak^{\alpha} l^{\beta}$$

This production function has been used widely in various economic contexts, primarily due to the advantageous mathematical and economic properties. Data was collected for the past ten years on the actual labor, capital and output for this bioenergy firm which currently operates two mobile truck-mounted chippers in a coupled supply chain operation where forest residue is chipped at the forest roadside into container trucks. The authors recognized the limitation of sample size in these estimated parameters and offer these limited results with the necessary statistical small sample size caveats. However, obtaining firm level data for more than thirty years is exceedingly difficult given that these types of firms involved in this market have not existed much more than ten years.

The results of the ordinary least squares estimation on the equation above are provided below.

Regression Statistics	
Multiple R	0.90
R Square	0.81
Adjusted R Square	0.76
Standard Error	0.20
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	1.210	0.605	15.351	0.003
Residual	7	0.276	0.039		
Total	9	1.486			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	1.0288	4.0315	0.2552	0.8059
Capital	0.1799	0.0824	2.1843	0.0652
Labor	0.9649	0.5012	1.9251	0.0956

These estimated parameter coefficients result in the following estimated production function for this bioenergy firm, leading to several interesting implications.

$$Q = 2.8 k^{.18} l^{.96}$$

Implications:

- The sum of the estimated parameter coefficients α and β is equal to 1.14, indicating evidence of increasing returns to scale. Thus, a doubling of inputs results in output that is more than double.
- This implies existence of scale economies for these types of firms where profitability increases with size and increasing firm size is a function of geographical proximity of available biomass supply. In order to achieve these scale economies, collection of biomass from less accessible (steep terrain, mountainous) locations may become more prominent, placing greater significance on de-coupled supply chain systems, particularly in central and southern Europe.
- Over the past ten years, there has been significant input neutral technological change as manifest by the constant *A* (equal to 2.8). Thus this firm and potentially this industry have consistently produced more output for the same level of inputs.
- The relative importance of the two inputs of capital and labour differ significantly, with labour being far more critical in the production of the firm as opposed to capital. This seems intuitive, especially as it relates to this particular industry and this particular firm given the ability of labour to increase the efficiency and productivity of capital far more than the alternative. Thus for any given capital and labour combination, the marginal productivity of labour (in terms of impact on output) is greater than that for the marginal productivity of capital.
- This prior point seems to suggest that changes in the firms production combination of capital and labour (movement from a coupled to de-coupled system) may be more labour sensitive as opposed to capital sensitive given how changes to each affect the output and the marginal productivity of the other. However, different firms operating in different forest conditions would result in different outcomes.

2.1 Review in recent findings of coupled vs. de-coupled systems in the wood chip supply chain

The ideal conditions for wood chip production are characterized through direct access of biomass in the stand and chip it on-site rather than extracting the trees to the roadside landing. In addition to that, under ideal conditions, supply chain steps would be synchronized so that no needless intermediate steps are executed and no delay time occurs. Of course, reality deviates from perfect conditions; regions may be mountainous, roads small and unpaved, weather conditions may impede the access to the stand or domestic law restricts payload capacity of transportation units and therefore the utilization of the whole loading volume. Thus it is important to compare studies from different regions and supply chain characteristics in order to have an indication of what is actually optimal or preferential.

The study of Holzleitner et al. 2013 evaluates the logistics of wood chip supply when using a self-loading trailer-truck. The focus was set on the different supply costs and the productivity of chipping and transportation. Concerning the authors, the main factors that influence the productivity are the distance of transportation, the load volume and the materials bulk density. Therefore they compare the traditional coupled system of direct loading of trucks, meaning that the chipper blows the chipped material directly onto a truck with the alternative de-coupled system of chipping the material onto a pile first. In a second, independently conducted step, a trailer-truck unit does the loading by itself. Therefore a commercial logging truck was rebuilt for the wood chips transport and a conventional grapple was changed against a clamshell bucket. The study was conducted in the Austrian mountains.

In Figure 1 the two different concepts are shown. The fuel wood storage place depends on the capacity that is available. Since the mountainous conditions in Austria limit road width to 4.5 meters, the shared space for chippers and trucks is a significant constraint. Therefore, with the direct loading concept forest residues are transported to an adequate intermediate storage. This contains the steps of driving the transportation vehicle empty to location, loading the residues, driving loaded to the intermediate storage and unloading the residues. Here, interferences can occur – indicated by the red bolts - meaning that operational delays of transport vehicles cannot always be avoided or waiting times occur in one step increasing operational costs. At the intermediate storage residues are chipped directly by the chipper into a truck. Also here a frictionless cycle may be violated when delay times occur because the chipper is not available for a certain time span and the truck has to wait or vice versa. Truck waiting delay represents the highest share of delay time for chippers working at a landing in coupled chains, representing up to 60% of total work site time (Spinelli and Visser, 2009). Besides harvesting, transport and chipping accumulate the main costs of processing wood chips. (Holzleitner et al, 2005/2006). The second concept is based on the idea of loosening the close links between the steps. If there is no intermediate storage capacity available, the material is stored at the forest road. Here, in a first step the chipper chips the material on a pile onto the ground and in a second step the truck loads the chips independently.

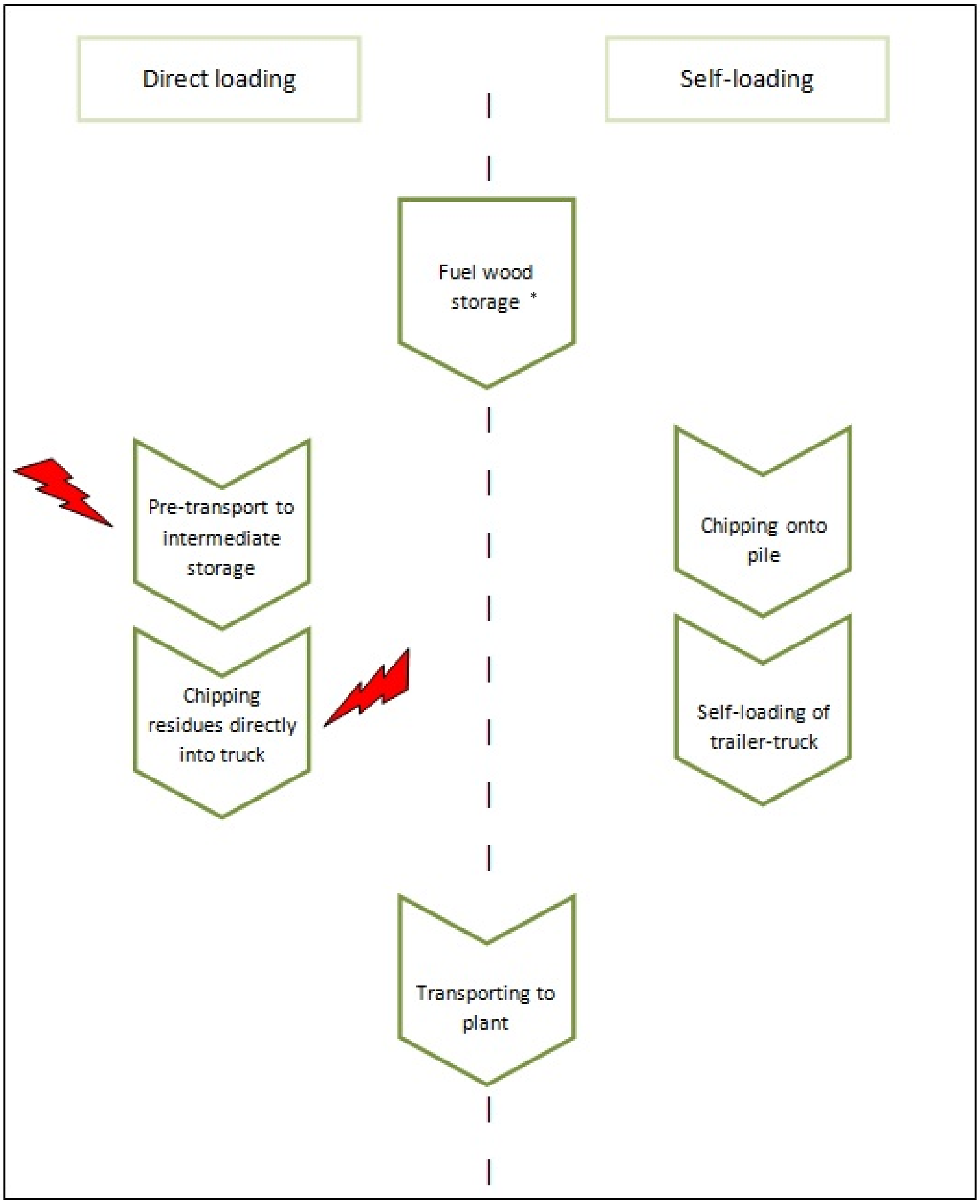

Figure 1: Direct loading vs. Self-loading, Source: Holzleitner et al. 2013, Figure 1.
* Fuel wood storage refers to forest residues available in the stand.

The results from this study show that up to a distance of 60 km the supply costs of the self-loading concept are lower than the costs of the direct loading system. The difference is highest at a distance of 30 km and declines with increasing distance. The reason for the higher costs of the self-loading concept is the time the trucks have to wait for the chipper and the pre-transport of logging residues to an intermediate storage. The latter causes higher costs due to the additional work-step and also because of the lower bulk density of the unchipped material. At distances above 60 km the cost of direct loading is cheaper.

Several issues have to be taken into account in this study: The competitiveness of the self-loading concept is heavily scenario driven, meaning that if the additional pre-transport in the first concept wasn't necessary, bulk density and therefore payload of the trucks would be different and also law restriction would be different, thus likely altering the results.

In another study, done by Kanzian et al. (2013), the authors conduct a multi-criteria optimization problem in order to minimize CO2 emissions and maximize profit in the forest energy supply networks. The study was applied at a regional level and covered five provinces of Austria. The objective function considered different decision variables and their costs. First, possible chipping locations were identified, being at the forest road, terminal or plant. Second, transport modes were distinguished between chipped material or solid fuel and different volumes. Third, the decision variable, if terminals to balance the supply should be used, enters the function. The use of terminals has different reasons. First, because of biomass recovery constraints due to seasonal weather conditions and limited road infrastructure of alpine regions in Austria, they serve as supply balance by storing material throughout the year as buffer. In addition to that, the stored green material dries naturally, causing lower drying costs, lower moisture and higher energy content per weight unit, leading to reduced transport costs and higher load volume. On the other side, as a negative aspect, procurement costs increase.

The model is solved by the weighted sum scalarization approach to obtain Pareto optimal points, meaning that the sum of the two conflicting objectives – minimize CO2 emissions and maximize profit in the forest energy supply networks – have to be minimized. Weights were stepwise changed from maximum profit to minimum CO2 emissions. The Pareto optimal solution contains a set of many solutions, where no improvement in one objective can be made without worsening the other subject to given constraints.

The results show that in order to minimize CO2 emissions during operational work, a combination of different transport modes and different nodes within the supply network should be applied. The authors find that, before being transported to the heat plant, 30% of the material should be chipped at the terminal, 50% should be chipped at the forest road and 10% should be transported directly without being chipped. These results and the optimal de-coupling or point of comminution are driven by spatial/terrain factors.

When changing weights in favour of higher profit, the results show that CO2 emissions reaction sensitivity is low, peaking in a 4.5% raise when the weight of profit is set to 1. However, profit more than doubles. When profit is maximized, the relative share of forest chipped material on total supply is approximately 6-7 %, while the approximate share of terminal chipped material is about 86%. The rest is transported solid to the plant.

Total transport distances increase with increasing profit weighting. In the profit maximizing scenario, transport distances increase from 45.7 to 48.1 km. While the transport distance of chipped material from the forest decreases from 39 to 17 km, and from the terminal from 33 to 23 km, the distance for solid wood from the forest increases from 7 to 16 km.

The study of Kanzian et al. (2013) shows that if just focusing on profit maximization, the concept of storing un-comminuted material at the terminal and chipping it there is advantageous. The reason is that chippers can operate more productively at a terminal and the costs of moving are less.

Nonetheless, one should be aware that the study didn’t take into account seasonal demand patterns and supply restrictions. Optimal terminal inventory levels weren’t either taken into consideration (Kanzian et al. 2013). Concerning the transportation distances the question arises that even if the increase of transport distance of solid wood more than doubles, it really outweighs the decrease of the other transport distances, due to location restrictions of the plants.

3. Detailed Study of a De-Coupled Alpine Supply Chain

3.1 Materials, Methods and Experiment layout

In this study, the authors conduct a comparative analysis study between chipping on the yarder pad or at the landing in an alpine (yarder) forest supply chain. Field data were collected for building the simulation model to compare the different de-coupling points by including the interaction delays between discrete events.

The experiment involved utilizing the same industrial chipper for chipping on the yarder pad where the yarder unloads trees and at the roadside landing. As in many other mountain operations, the pad and the landing were connected by a steep gravel road, inaccessible to heavy road trucks. The chipper was a drum type, powered by a 250 kW independent engine and was mounted on a two-axle trailer towed by a 130 kW farm tractor, which was used only for relocating the chipper between two adjacent chipping stations. The chipper was fed by a separate 15-t self-propelled loader and managed directly by the loader operator through remote control. When chipping on the pad, the machine discharged directly into 20 m^3 trailer bins, towed by farm tractors (coupled chain). Trailer bins were then towed to the roadside landing and their content was dumped on the ground. During the study 1 to 3 bin trailers were used at the same time, to minimize waiting delays. When chipping at the landing, loose residues were extracted from the pad using a 10-t class forwarder, which stacked the residues on a large buffer pile (de-coupled chain). The chipper worked from the pile and discharged on the ground. In both cases, chips were later picked up and loaded onto heavy road trucks using a powerful self-propelled loader.

All operators included in the study were experienced professionals, who knew their job and equipment. In order to minimize the effect of different operator adaptation and motivation levels, the study included only operators that were judged to have a high degree of uniformity in motivation and adaptation to the studied machines/systems (Harstela 1988). All operators had at least 5 years of experience with the type of machine they were using, of which about 2 years with the specific unit object of the study. On the other hand, no attempt was made to normalize individual performances by means of productivity ratings (Scott 1973), recognizing that all kinds of normalization or corrections can introduce new sources of errors and uncontrolled variation in the data material (Gullberg 1995).

The study site was located on the hills overlooking Florence, at an elevation of about 700 m above-sea-level. The study material consisted of 20 chipper hours, 30 trailer hours (27 trips) and 24 forwarder hours (25 trips). During this time, the operation produced 929 m^3 of loose chips, or 263 green tons.

3.2 Data collection

In order to derive the appropriate production functions, the authors carried out a typical time-motion study, designed to evaluate machine productivity and to identify those variables that are most likely to affect it (Magagnotti and Spinelli 2012). Each processing cycle was stop watched individually, using Husky Hunter hand-held field computers, running the dedicated Siwork3 time study software (Kofman 1995). Productive time was separated from delay time (Björheden 1995), and the production of a biomass load was considered as a cycle, for both forwarding and chipping. All delays were included in the study, and not just the delays below a certain duration threshold, because such practice may misrepresent the incidence of downtime, especially on comparatively long observation periods (Spinelli and Visser 2008). However, delays generated by the study itself were separated and removed from the data set.

Output was estimated by counting all the loads produced, and by measuring their individual bulk volumes. Volumes were converted into weights by taking a representative number of loads to a certified weight bridge. Ten 1-kg chip samples were collected from each test, and their moisture content was determined according to the European standard CEN/TS 14774-2. Chip moisture content was 35.4% (standard deviation = 3.9). At this moisture content, the mean payloads of the forwarder and the chip shuttles were 4.8 and 6.0 tonnes, respectively.

Machine costs were calculated with the harmonized method recently developed within COST Action FP0902 (Eliasson et. al 2013), for an estimated annual utilization of 1600 scheduled machine hours (SMH) and a depreciation period of 8 to 10 years, depending on machine type. The labour cost was set to 20 Euro SMH^{-1}, inclusive of indirect salary costs. The costs of fuel, insurance, repair and service were obtained directly from the operator. The calculated operational cost was increased by 20% in order to include relocation and administration costs, the former already capable of representing up to 10% of the total machine cost (Väätäinen et al. 2006). All costs were calculated separately for the machines in a working state and in an idle state, as when down or being loaded (shuttles). Assumptions and results are shown in Table 1.

Table 1: Costing assumptions and machine rates

Unit		Chipper	Chipper	Shuttle	Shuttle	Forwarder	Forwarder
State		Working	Idle	Working	Idle	Working	Idle
Investment	€	350,000	350,000	100,000	100,000	240,000	240,000
Resale	€	105,000	105,000	30,000	30,000	72,000	72,000
Service life	Years	10	10	8	8	10	10
Utilization	h year^{-1}	1,600	1,600	1,600	1,600	1,600	1,600
Interest rate	%	4	4	4	4	4	4
Depreciation	€ year^{-1}	24,500	24,500	8,750	8,750	16,800	16,800
Interests	€ year^{-1}	9,590	9,590	2,775	2,775	6,576	6,576
Insurance	€ year^{-1}	2,500	2,500	2,500	2,500	2,500	2,500
Repairs	€ year^{-1}	12,250	12,250	4,375	4,375	8,400	8,400
Diesel	€ h^{-1}	46	0	13	0	17	0
Lubricant	€ h^{-1}	5	0	1	0	2	0
Total	€ h^{-1}	81	31	26	12	40	21
Crew	n.	1	1	1	0	1	1
Labour	€ h^{-1}	20	20	20	20	20	20
Overheads	€ h^{-1}	20	10	9	2	12	8
Total rate	€ h^{-1}	121	61	55	14	72	50

3.3 Model building

These data were statistically analyzed to build a discrete event simulation model capable of representing the total operation, including interactions between discrete events. The simulation was designed to run on Arena 14 software (Rockwell Automation 2012), which is especially suited for supply chain management applications (Abu-taieh and El sheik 2007). The study data was first organized into an Excel spread sheet. Element time data were then imported into the Arena Input Analyzer (AIA) distribution-fitting software. AIA reads the data contained into the text file, automatically builds a histogram representation of the data and tries to fit several statistical distributions. AIA also determines quality of fit by performing both a Chi-Square and a Kolmogorov-Smirnov (K-S) test. In this case, we only used the K-S, since the distributions were continuous. Distributions with p-values lower than 0.05 were accepted, while distributions with larger p-values were rejected. When the test failed, the data was checked for outliers, assuming that these points would be generated by some special causes. A statistics package, Minitab 16, was used to display the box plot of each data set in order to identify and remove outliers. Data points exceeding 1.5 times the interquartile range were considered outliers. If the K-S test failed again after correction, then empirical distributions were used. No normal distributions were used in the software model since they could theoretically generate negative values during simulation runs (Kelton et al. 2001). Even when a normal distribution returned the best fit, other distributions limited to positive values (e.g.

Weibull) were used. Table 2 shows the distributions used for the different machines and time elements.

Table 2: Distributions used for the model

Point of comminution	Activity	Units	Distribution	Arena Expression
Landing	Chipping	Seconds	Exponential	EXPO(431)
	Chipper delays (probability 34%)	Seconds	Lognormal	33 + LOGN(2.08e+003, 6.05e+003)
	Travel unloaded - forwader	m/s	Weibull	1.57 + WEIB(0.472, 3.35)
	Loading - forwarder	Seconds	Triangular	TRIA(285, 490, 550)
	Travel loaded - forwarder	m/s	Triangular	TRIA(1.57, 2.55, 2.75)
	Unloading - forwarder	Seconds	Triangular	TRIA(225, 407, 600)
	Forwarder delays (probability 34%)	Seconds	Gamma	83 + GAMM(1.41e+003, 0.638)
	Discrete events (probability 50%)	Seconds	Exponential	50 + EXPO(745)
Pad	Chipping	Seconds	Uniform	UNIF(670, 1.22e+003)
	Chipper delays (probability 34%)	Seconds	Lognormal	33 + LOGN(2.08e+003, 6.05e+003)
	Park tractor	Seconds	Exponential	120 + EXPO(74.7)
	Travel unloaded - tractor	m/s	Beta	1.73 + 1.62 * BETA(1.24, 1.41)
	Travel loaded - tractor	m/s	Beta	2.14 + 0.39 * BETA(1.33, 1.25)
	Unloading - tractor	Seconds	Empirical	DISC(0, 266.5, 0.3, 286.5, 0.4, 306.5, 0.7, 326.5, 1, 345.5)
	Tractor Delays (probability 34%)	Seconds	Gamma	83 + GAMM(1.41e+003, 0.638)
	Discrete events (probability 50%)	Seconds	Exponential	50 + EXPO(745)

The information coming from the study was used to create a rough flowchart draft of the two alternative chain models, namely: “chipping on the pad” and “chipping at the landing”. Two simulation models were then designed using Arena 14 to obtain the final process maps. In Arena, what flows through the chart is an object called entity. For this particular case study, the entity was designed to be a single load (of un-comminuted sections or chips, depending on the process). The process itself was modelled in such a way that each load went through several activities, was affected by delays, and eventually was collected at the landing site.

Both models were verified by comparing the simulated average time per load with the actual data, using the Mann–Whitney–Wilcoxon statistical test. This was made for a first batch of 5000 simulated loads, with the additional purpose of excluding the occurrence off runtime errors. The difference between real and simulated data was small, being 1.49 and 1.97%, respectively for chipping at landing and chipping on the pad.

However, the time study did not last long enough to offer a reliable representation of delay time, which is typically erratic (Spinelli and Visser 2008). Therefore, delays were modelled based on another database available to the Authors, and obtained from a large study of delays in chipping operations (Spinelli and Visser 2009). This database contained information for about 500 chipper cycles and as many tractor or forwarder cycles, and it was used to model delay event probability and duration. Delay generation was performed by two separate blocks inside the models, one for personal and operational delays (except for those caused by machine interaction), and the other for mechanical delays. This allowed for a strong statistical representation of all delays in the simulated environment.

Using this new improved model, both chains were simulated for a pad-to-landing distance ranging from 500 to 5000 meters, which was varied in 500 m units. The forwarding of chips was simulated for a number of shuttles ranging from one to three. Four treatments were compared, and namely: chipping at the landing and chipping on the pad with one, two and three shuttles. Each combination of distance, shuttle number and chain type was simulated 30 times. Each run was stopped when 250 tons of chips had been accumulated at the landing, assuming this quantity as the typical amount of residues produced from the average forest lot in Italy (Spinelli et al. 2013). The total number of iterations was 1200, corresponding to a mass flow of 303,228 tonnes of chips. Simulated work time amounted to 54,852 hours, for a total expenditure of 7,456,707 €. Simulated fuel consumption was 1,081,734 L of diesel. Clearly, such a large observation period could only be obtained through simulation. An actual field study of this size would have been far too expensive.

3.4 Results

Table 3 below shows the main statistics for the treatments on test. The overall system productivity was defined as the total mass output divided the operation residence time (simulated duration). The mean system productivity ranged between 4.7 and 9.8 fresh tonnes per hour. Differences were statistically significant at the 1% level. Overall system productivity grew with machine fleet. It was higher when using two or three chip shuttles, rather than only one chip shuttle or a loose-biomass forwarder.

Table 3: Productivity, cost, fuel use and utilization

Treatment		A	B	C	D
Point of comminution		Landing	Pad	Pad	Pad
Shuttles		1	1	2	3
Chipper productivity	t h^{-1}	10.8^a	13.1^b	11.8^c	11.0^a
System productivity	t h^{-1}	4.7^a	4.8^a	7.3^b	9.8^c
Production cost	€ t^{-1}	25.7^a	27.3^b	22.7^c	22.7^c
Fuel use	L t^{-1}	4.54^a	2.99^b	3.25^c	3.50^d
Chipper utilization	%	60.4^a	19.8^b	30.5^c	41.1^d
Transport utilization	%	80.3^a	72.1^b	58.6^c	55.1^d

Notes: different letters in superscript indicate that the differences between the mean values presented on the same row are statistically significant at the 1% level.

Excluding interaction delays, the mean productivity of the chipper varied between 11 and 13 fresh tonnes per hour. Mean chipper productivity was higher when the chipper was forced to longer waiting times, as in treatments B and C.

The mean chipper utilization ranged from 20 to 60%. It was highest when chipping at the landing and discharging in a pile on the ground, which removed all waiting for transports. Conversely, mean chipper utilization was lowest for treatment B, when the chipper was forced to wait for the single chip shuttle to reach the landing, dump its load and come back to the pad. Mean transport utilization varied between 55 and 80%, and it was highest for treatment A (chipping at the landing), which enjoyed complete machine independence and was spared all interaction delays. Utilization differences between treatments were all significant to the 1% level. As expected, chipper and transport fleet utilization had an inverse relationship. High chipper utilization was obtained by detaching a large number of transports to serve it, which decreased transport utilization. Using fewer transports increased their utilization (less queuing), but it also decreased chipper utilization.

The mean production cost varied from 23 to 27 € per fresh tonne. The full range of variation was between 13 and 47 € per tonne (Figure 2). The cost was highest for treatment B, and lowest for treatments C and D. There was no statistically significant difference between the mean costs recorded for these last two treatments. Chipping on the pad and using two or three shuttles for chip extraction was 10% less expensive than chipping at the landing. However, when only one chip shuttle was available, chipping on the pad was 6% more expensive than chipping at the landing.

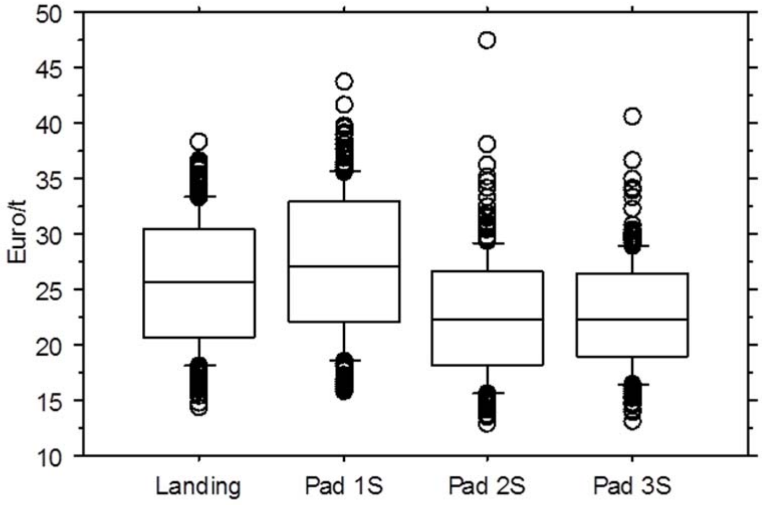

Figure 2: Box plot for production cost (€ t^{-1})

Note: Pad 1S refers to treatment B, chipping on the pad with one shuttle; Pad 2S to treatment C with two shuttles and so on. The upper and lower sides of the box represent the standard deviation whereas the whiskers and dots show the range of variation and the outliers respectively.

Total fuel use varied between 3 and 4.5 L diesel per tonne of fresh chips. Fuel use was highest for treatment A, chipping at landing. The best compromise between reduced production cost and low fuel use was offered by treatment C, chipping on the pad with two shuttles.

Extraction distance and treatment had a significant effect on all performance indicators, except for chipper productivity (Table 4). Extraction distance and treatment impacted system balance, which was upset by the increasing distance and partially restored by adding a new chip shuttle to the system. In general, distance had a stronger effect than treatments, at least within the wide distance range considered in this study. Such effect was particularly strong on overall production cost, whose variability was explained by distance for over 80%. The effect of distance on chipper utilization could be compensated by adding a new shuttle, which explains why this effect was relatively weak in that specific case. The high significance of the interaction factor pointed at the strong relationship between distance and treatment in their effect on system balance, which was the ultimate reason for the different performance of the four treatments.

Table 4: ANOVA tables for the effect of treatment and distance

Effect	DF	SS	η^2	F-Value	P-Value
Chipper productivity (t h^{-1})					
Treatment	3	219.600	0.04	15.251	<0.0001
Distance	1	0.141	0.00	0.029	0.8639
Interaction	3	2.661	0.00	0.185	0.9068
Residual	1192	5722.128	0.96		
Unit cost (€ t^{-1}) Log-transformed					
Treatment	3	0.134	0.01	28.166	<0.0001
Distance	1	10.238	0.83	6441.577	<0.0001
Interaction	3	0.065	0.01	13.555	<0.0001
Residual	1192	1.895	0.15		
Chipper utilization (%) Arcsine-transformed					
Treatment	3	2.23E^{-04}	0.26	286.111	<0.0001
Distance	1	2.62E^{-04}	0.30	1007.962	<0.0001
Interaction	3	7.44E^{-05}	0.09	95.269	<0.0001
Residual	1192	3.10E^{-04}	0.36		
Transport utilization (%)					
Treatment	3	1.870	0.18	171.301	<0.0001
Distance	1	4.371	0.41	1201.027	<0.0001
Interaction	3	0.093	0.01	8.485	<0.0001
Residual	1192	4.338	0.41		

Figure 3 shows the relationship between production cost, distance and treatment. Treatment B is the most expensive, along the full range of distances. The productive capacity of a single shuttle is much below the capacity of an industrial chipper, which causes a dramatic loss of productivity and a parallel increase of production cost. Once the balance between chipper and shuttle fleet is restored, chipping on the pad (treatments C and D) proves less expensive than chipping at the landing (treatment A). The difference between treatments C and D is minimal, and changes with distance. Detaching one additional chip shuttle is a discrete step with a fixed unit cost, which is offset as distance increases. In general, the longer the extraction distance the higher the benefit derived from a larger transport fleet, and from the higher payload capacity achieved when hauling chips rather than loose residues.

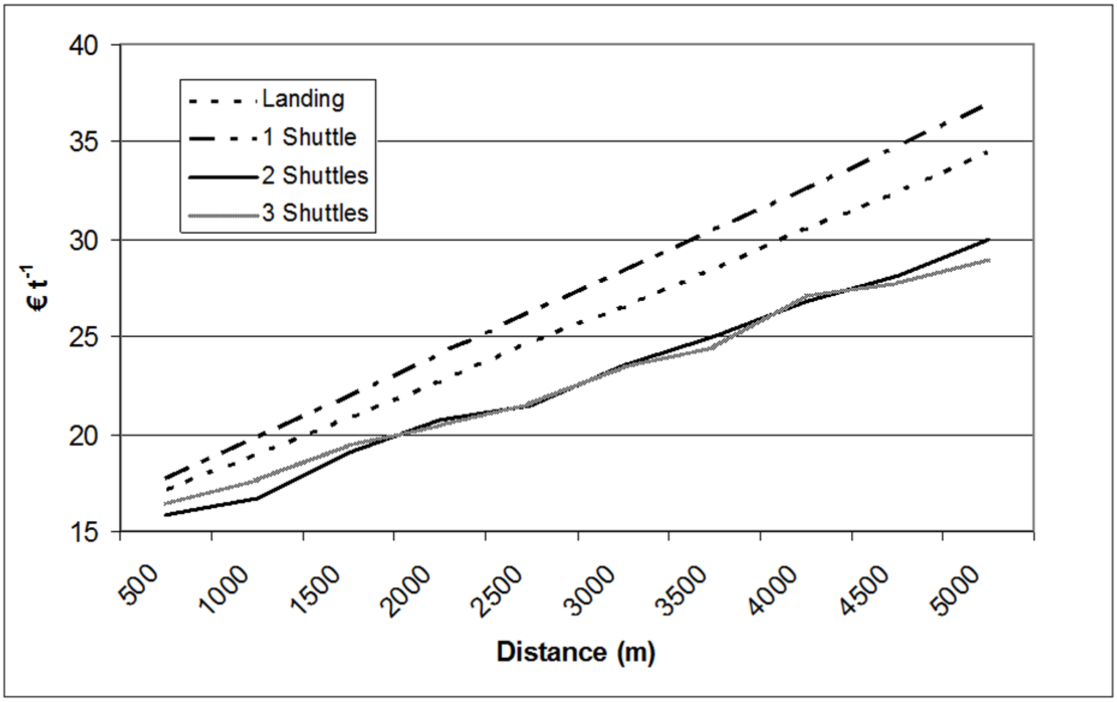

Figure 3: Relationship between production cost, extraction distance and treatment

Fuel use is highest when extracting loose residues and chipping them at the roadside landing (Figure 4). Fuel use is lowest when chipping on the pad and hauling the chips with a single shuttle, but this solution incurs the highest production cost. The best combination is offered by treatment C, where chips are processed on the pad and hauled with two chip shuttles. This solution offers both low fuel consumption and low production cost.

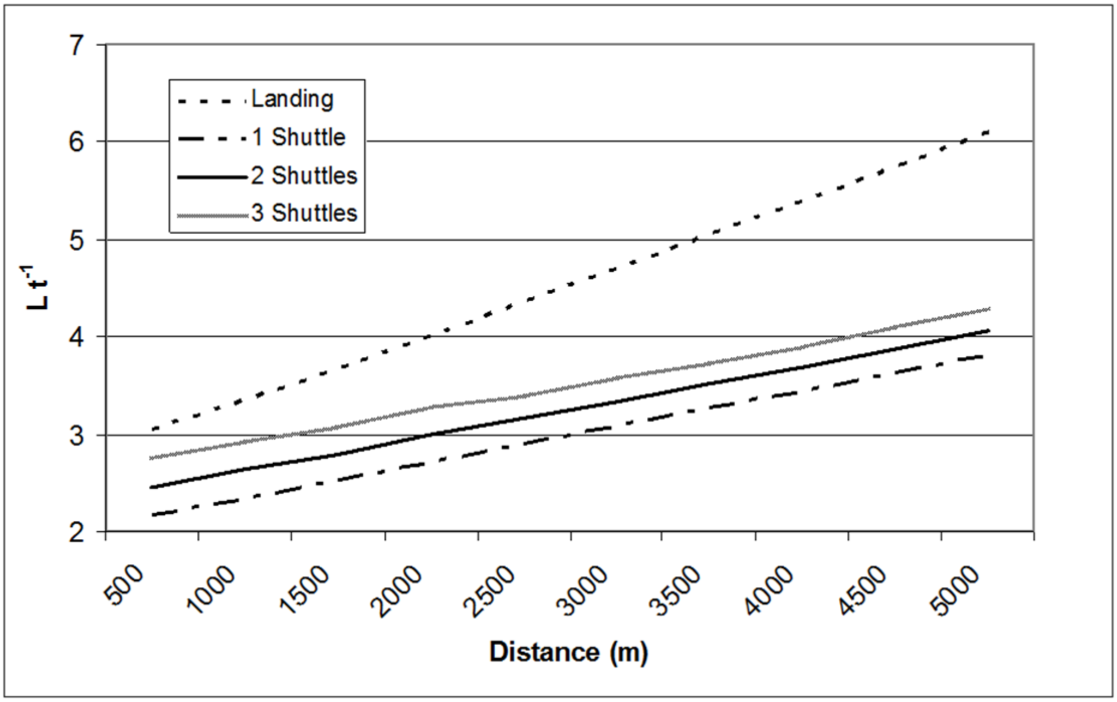

Figure 4: Relationship between fuel use, extraction distance and treatment

3.5 Discussion

The simulated chipper productivity results here matches quite well the figures obtained from previous studies of similar machines under similar conditions (Spinelli and Hartsough 2001). The same is true for chipper utilization (Spinelli and Visser 2009). The significantly higher productivity recorded for chipping on the pad as compared to chipping at the landing finds several possible explanations. First, piles built at a landing were bigger, taller and more entangled, which slowed down feeding. Second, the chipper on the pad experienced variable amounts of waiting delay, during which the loader could rearrange the piles, so as to make feeding faster, once the next chip shuttle arrived. Corroboration of individual productivity and utilization figures reinforces confidence in the general reliability of our model, which goes beyond the analysis of single work steps and tries to mirror a whole chain that starts with un-comminuted biomass at a yarder pad and ends with chips at the roadside landing.

Simulation is the best method for studying complex supply chains, where individual links interact with each other and interactions are driven by a combination of independent factors. In our specific case, distance, payload capacity, shuttle speed and chipper productivity are the main drivers of system behaviour. Net productivity and randomly occurring delays can be modelled in order to represent the contingency of time requirements for each activity, and for the whole chain (Asikainen 1995). Deterministic models can be used for the purpose, but they are much less realistic than proper stochastic models (Talbot and Suadicani 2005). Over the past 20 years, stochastic simulation has been used to represent forest harvesting chains (Johnson 1986). Researchers have tried both discrete-event (Aedo-Ortiz et al. 1997) and dynamic (McDonagh et al. 2004) simulation, but the former seems to have been far more successful (Oinas and Sikanen 2000, Mobini et al. 2012). For this reason, we have opted for discrete-event simulation, obtaining a good representation of the supply chains on test.

Our model can represent the varying interaction of chipper and chip shuttles under changing work conditions. It also estimates separately work time and delay time, allowing the association of each machine state with a specific cost. In the idle state, a machine will use no fuel, and therefore models that apply the same cost for work and delay time are less accurate in their cost estimates.

What is more, our stochastic model represents uncertainty much better than any deterministic model, which may assist risk-averse operators to assess the probability of occurrence of each cost range for any of the tested options and distances. For instance, assuming an extraction distance of 2500 m there is a 68% chance that production cost will range between 23 and 26 € per fresh tonne when chipping at the landing, and between 19 and 24 € per green tonne when chipping on the pad with a support fleet of two chip shuttles. Knowing the field of variation of projected costs, entrepreneurs will be best equipped to make their decisions about accepting any given job or price. In this respect, it is important to notice that the cheapest option also presents the largest field of variation. That is the obvious result of the additional uncertainty introduced by interaction delays, which are practically absent in the more expensive option represented by chipping at landing. Under these circumstances, a decision maker can opt for the system offering lower supply cost but higher uncertainty, or for the more expensive system that offers a safer result. The final decision will depend on the fine balance between risk-aversion and cost reduction.

In this respect, readers must be remember that the better performance of chipping on the pad with two or three chip shuttle depends on the higher payload and speed of chip shuttles compared to loose-residue forwarders, and on the possibility to use one driver for two shuttles. If these conditions are not realized, then the result might be very different. Introducing an enlarged space forwarder capable of carrying a larger payload may tilt the scales in favor of chipping at landing. The same could occur if all chip shuttles were run by their individual drivers, whose wages would represent a net cost when idled during container loading. We have not tested these specific cases because we did not have the base data to simulate them, but readers must be aware that the numbers generated by our model are only valid for the specific assumptions used to build it. In contrast, the modelling technique itself can be used to simulate a larger variety of conditions once the base data for modelling these conditions are made available.

In our case, the higher speed and payload of the chip shuttles are decisive factors. When chipping at the landing, utilization is highest for both the transport and the chipper, but that is not enough to tilt the scales. Used for hauling loose residues, the forwarder is not productive enough, at least not in its current standard configuration. The gap between the two alternative chains grows with distance, which demonstrates that transportation is the weak link.

In any case, distance is by far the most important factor in determining supply cost, since it accounts for 80% of the variability in the data. That is no wonder, given the very wide range of distances explored in our simulation. The maximum value in the distance range is ten times larger than the minimum value, which explains the strong effect of distance as an independent variable. More distance means more work, regardless of how the work is organized. Both main chains are rationally organized and their performance cannot differ as much as to overcome the effect of such a large distance variation. In fact, if any of the two chains was clearly superior to the other, there would be no need to use sophisticated simulation techniques to demonstrate its superiority.

Both chains are sensitive to system balance. When chipping at the landing, system balance can be obtained either by commissioning more forwarders to assist the same chipper, or by getting the same forwarder to work longer hours than the chipper. When chipping on the pad, system balance admits one solution only: commissioning an increasing number of shuttles as distance gets longer. In both cases, distance is the factor upsetting system balance, which can be restored by manipulating the number or the schedules of the transport units.

Finally, some practicalities that have a strong impact on chain viability. It goes without saying that chipping at the landing is only viable if a proper roadside landing is available. If not, this could be built, but building cost should be added to the calculation. In contrast, chipping on the pad is an option only if the track leading from the pad to the landing allows for exchanging of incoming and outgoing chip shuttles. Otherwise one is forced to use one chip shuttle only, which is the most expensive solution and should always be avoided. If the extraction route intersects or includes a public road, then chipping on the pad is preferable because chip loads are contained, whereas loose residues make up for bulky loads, and the convoy is often too tall and/or wide for circulation on public roads, unless the biomass has been previously bundled (Spinelli and Magagnotti 2009).

4. Summary and Conclusions

This report focuses on improving the understanding, efficiency and applicability of coupled vs. de-coupled forest biomass supply chains. Throughout Europe many different forms of both coupled and de-coupled supply chain systems have evolved in the collection of forest biomass, adapting to the local conditions that apply. Given the diversity that exists across a region as large as Europe, the combination of different coupled vs. de-coupled systems is large and varies widely. The findings may be summarized as follows.

- Under ideal conditions where the terrain and accessibility are not constraining factors, generally coupled supply chains offer greater cost efficiencies given the ability to increase load density and thereby cost efficiency early in the supply chain (in the stand or forest road). In addition, these coupled systems offer fewer steps and less equipment to purchase, relocate and operate. However, there are many areas where ideal conditions do not exist and some form of de-coupling must occur. Under these conditions it is important to understand the parameters that influence production efficiency in the de-coupled environment.
- Individual firm level data is collected from one forest bioenergy firm in southern Germany in order to estimate a Cobb-Douglas production function. The results suggest a production function with increasing returns to scale further implying scale economies in this industry, placing greater importance on accessing and obtaining forest biomass in less-than-ideal locations in mountainous forests and steep terrain where de-coupled systems are increasingly necessary.
- The results from this estimated production function also suggest that for this firm in southern Germany which operates a coupled biomass supply chain, that marginal productivity of labour is far greater than that for capital, implying that technological advancements and improvements should favour labour.
- The results from two different studies in Austria are provided that evaluate the cost efficiency of coupled vs. de-coupled systems. In the first case, the results illustrate the trade-off associated with increasing bulk density vs. transportation distance and for distances (between the roadside and the plant or terminal) less than 60 km, the de-coupled system is cheaper and beyond 60 km the direct loading more cost efficient. In the second Austrian study a larger scale optimization (pareto optimal) model is used to optimize forest biomass flows to heat plants from different objective functions (minimize C02 emissions or maximize profit). The results related to which supply points should be sourced by chipped or bulk material vary depending on the objective and the location (network, travel time/distance, spatial) attributes.
- The detailed study results of a de-coupled supply chain in Italy illustrates the changes to total supply cost and cost variability as a function of extraction distance, type of operation and the number of chip shuttles available. This information, particularly for mountainous conditions will help identify the profitability of an operation, or when assessing the competitiveness of alternative options. The costing assumptions can be changed in order to gauge the sensitivity of supply cost to such factors as diesel fuel price, usage intensity and depreciation schedules, among others. For any given set of working conditions, the model can point at the cheapest and safest supply system. In the specific case considered by our simulation, chipping on the pad with a chipper and two shuttles (coupled system, balanced) is the best compromise solution of low supply cost and fuel consumption. Fuel savings could be maximized by reducing the transport fleet to one shuttle, but that would also maximize cost. In contrast, chipping at the

landing (de-coupled system) would incur a higher cost and fuel consumption than chipping on the pad.

- Under the specific conditions of this Italian study, chipping on the pad with a chipper and two shuttles was the best compromise solution of low supply cost and fuel consumption. At a mean cost of 22.7 € per fresh tonne, this solution was 10% cheaper than chipping at the landing. Adding a third chip shuttle did not allow a meaningful reduction of supply cost, but resulted in a 7% increase of fuel consumption. Distance was by far the most important factor in determining supply cost, and accounted for 80% of the variability in the data. Under these circumstances, the higher speed and payload of the chip shuttles made it preferable to chip on the pad (coupled system), provided enough shuttles are available. Used for hauling loose residues, the forwarder was not productive enough, at least not in its current standard configuration

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References

Abu-taieh, E. & El sheik, A., Commercial simulation packages: a comparative study. International Journal of Simulation, 8, 2007, 66-76.

Aedo-Ortiz, D., Olsen, E. & Kellogg, D., Simulating a harvester-forwarder softwood thinning: a software evaluation. Forest Products Journal, 47, 1997, 36-41.

Asikainen, A., Discrete-event simulation of mechanized wood-harvesting systems. University of Joensuu, Faculty of Forestry, Research Notes, 28, 1995, 86 pp.

Berndes, G., Hoogwijk, M. & van den Broek, R., The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass and Bioenergy, 25, 2003, 1-28.

Björheden, R., Forest Work Study Nomenclature, Swedish University of Agricultural Science, Department of Operational Efficiency, Garpenberg, Sweden, 1995, 15 p.

Björheden, R., Integrating production of timber and energy-a comprehensive view. Conventional systems for bioenergy. IEA Bioenergy Task 18 workshop, Charleston, South Carolina, USA, 19-25 September 1999., New Zealand Forest Research Institute, Rotorua, 2000.

Björheden, R., Optimal point of comminution in the biomass supply chain. Proceedings of the OSCAR Nordic-Baltic conference on forest operations, Copenhagen, Denmark, 2008.

Eliasson, L., Costing model - machine cost calculation, downloaded from: http://www.forestenergy.org/pages/costing-model---machine-cost-calculation/ on Oct. 8th, 2013.

European Commission, Energy roadmap 2050.Impact assessment and scenario analysis. COM(2011) 885 final, Brussels, 2012. doi:10.2833/10759.

Freppaz, D., Minciardi, R., Robba, M., Rovatti, M., Sacile, R. & Taramasso, A., Optimizing forest biomass exploitation for energy supply at a regional level. Biomass and Bioenergy, 26, 2004, 15-25.

Gullberg, T., Evaluating operator-machine interactions in comparative time studies. International Journal of Forest Engineering, 7, 1995, 51-61.

Harstela, P., Principle of comparative time studies in mechanized forest work. Scandinavian Journal of Forest Research, 3, 1988, 253-257.

Holzleitner, F., Kanzian, C., Fenz, B. & Stampfer, K., Waldhackguterzeugung aus Schlagrücklass. Fallbeispiele im Laub- und Nadelholz. Universität für Bodenkultur, Department Wald- und Bodenwissenschaften, 2006.

Holzleitner, F. , Kanzian, C., Fenz, B. & Stampfer, K., Simulation-based analysis of a self-loading trailer-truck for wood chips in mountainous regions. In: Dissertation of Holzleitner, F., Analyzing time and fuel consumption of timber harvesting and transport processes based on long-term machine data. BOKU, Vienna, 2013.

Johansson, J., Liss, J.E., Gullberg, T. & Björheden, R., Transport and handling of forest energy bundles—advantages and problems. Biomass and Bioenergy, 30, 2006, 334-341.

Johnson, L. , Perspectives on the application of simulation to industrial forestry. Proceedings of the Society of American Foresters National Convention, Fort Collins, Colorado, USA, July 28 - 31, 1986.

Kalaja, H., An example of terrain chipping system in first commercial thinning: Esimerkki Ensiharvennuspuun Korjuusta Palstahaketusmenetelmällä, Ministry of Agriculture and forestry, Finnish Forest Research Institute, 1984.

Kanzian, C., Kühmaier, M., Zazgornik, J., Stampfer, K., 2013. Design of forest energy supply networks using multi-objective optimization. Biomass and Bioenergy 58, 294-302.

Kelton D., Sadowski R. & Sadowski D., Simulation with Arena. Second Edition, McGraw-Hill, Boston, 2001, 611pp.

Kofman, P., Flishugning. Dokumentation af nuværende systemer [Chipping. Documentation of existing systems]. Maskinrapport 12 Miljøministeriet, Skov-og Naturstyrelsen. København. ISBN 87-601-3947-1 (In Danish), 1993, 39 pp.

Kofman, P., Siwork 3: user guide. Danish Forest and Landscape Research Institute, Vejle, Denmark, 1995, 37 pp.

McDonagh, K., Meller, R., Visser, R. & McDonald, T., Improving harvesting system efficiency through system and machine simulation. Southern Journal of Applied Forestry, 28, 2004, 91-99.

Mobini M., Sowlati T. & Sokhansanj S., Forest biomass logistics for a power plant using a discrete-event simulation approach. Applied Energy, 88, 2011, 1241-1250.

Oinas, S. & Sikanen, L., Discrete event simulation model for purchasing of marked stands, timber harvesting and transportation. Forestry, 73, 2000, 283-301.

Panichelli, L. & Gnansounou, E., GIS-based approach for defining bioenergy facilities location: A case study in Northern Spain based on marginal delivery costs and resources competition between facilities. Biomass and Bioenergy, 32, 2008, 289-300.

Rentizelas, A., Tolis, A. & Tatsiopoulos, I., Logistics issues of biomass: The storage problem and the multi-biomass supply chain. Renewable and Sustainable Energy Reviews, 13, 2009, 887-894.

Rockwell Automation, ARENA Simulation Software. Available from http://www.arenasimulation.com/Arena_Home.aspx, [accessed on February 16 2012], 2012.

Scott, A., Work measurement: observed time to standard time. Work study in forestry. Forestry Commission Bulletin 47: 1973, 26-39.

Spinelli, R., Hartsough, B.R., A survey of Italian chipping operations. Biomass and Bioenergy, 21, 2001, 433-444.

Spinelli, R. & Visser, R., Analyzing and estimating delays in harvester operations. International Journal of Forest Engineering, 19, 2008, 36-41.

Spinelli, R. & Visser, R., Analyzing and estimating delays in wood chipping operations. Biomass and Bioenergy, 33, 2009, 429-433.

Spinelli, R. & Magagnotti, N., Logging residue bundling at the roadside in mountain operations. Scandinavian Journal of Forest Research, 24, 2009, 173-181.

Spinelli, R., Magagnotti, N. & Facchinetti, D., Logging companies in the European mountains: an example from the Italian Alps. International Journal of Forest Engineering, 2013. http://dx.doi.org/10.1080/14942119.2013.838376

Stampfer, K., & Kanzian, C., Current state and development possibilities of wood chip supply chains in Austria. Croatian Journal of Forest Engineering, 27, 2006, 135-145.

Talbot, B. & Suadicani, K., Analysis of two simulated in-field chipping and extraction systems in spruce thinnings. Biosystems Engineering, 91, 2005, 283-292.

Väätäinen, K., Asikainen, A., Sikanen, L. & Ala-Fossi, A., The cost effect of forest machine relocations on logging costs in Finland. Forestry Studies, 45, 2006, 135-141.

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