

# Development of Harvesting Machines for Willow Small-Sizes Plantations in East-Central Europe

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## Abstract

*The production of plant biomass in small farms within the Central and Eastern European countries requires the application of agricultural machines adjusted to the scale of production. In the article, new machines for small-sized plantations of energy crops have been presented. Furthermore, the results of strength analysis of three-point linkage mower frame are presented by finite element method. The advantage of the proposed solutions is their simple construction, which is connected with low production cost and simple machine operation. The energy-crop harvesting machines are especially intended for small biomass producers in East-Central Europe, and the purchase of professional machines is financially inaccessible. The proposed machines are mounted in front or at the back of a typical farm tractor and the chipping units are power-take-off driven. The numerical simulation was carried out using finite element method to study the structural strength of a mower frame. All machine designs proposed by the Rzeszow University of Technology are legally protected by patents and utility models. The presented agricultural solutions have been worked out by authors and a part of them is still being developed in cooperation with biomass producers.*

*Keywords: biomass, energy plants, harvester, renewable energy sources, willow*

## 1. Introduction

Woody biomass can come from many sources, including forestry thinning operations logging slash, wood product residues, urban waste wood and wood-related industries. While material for woody biomass can come from many sources, this profile will focus on the production of trees specifically for bioenergy.

Biomass as raw material for European energy production has received raising interest during the last decades from policy makers, energy utilities and farmers (Djomo et al. 2011, Schweier and Becker 2012b). The utilization of natural and renewable energy sources is mainly caused by aspiration to protect environmental and depleted stocks. Among all kinds of renewable energy sources in Poland, the great potential for fast utilization is in biomass especially in biomass of fundamental raw materials i.e. in straw, wood and energy plants. This is also a reaction to the European

Commission (EC) recommendations that established the binding target of 20% share of renewable energy sources in the EU energy consumption by 2020 (COM 2008). In Poland, it has to reach a level of 15% by 2020.

Short rotation coppice (SRC) consists of densely planted, high-yielding varieties of either willow or poplar, harvested on a 2–5 year cycle, although commonly every 3 years (DEFRA 2004). Among the various crops for biomass options, SRC is especially regarded as strategic resources of wood products that are fast-growing and high-yielding species (Djomo et al. 2011).

Analysis of properties of different types of renewable energy sources (RES) presented by authors (Trzepieciński et al. 2013) leads to the conclusion that woody biomass in East-Central Europe is a RES type characterized by the best synthetic technical and operating parameters. The biomass energy is commonly available and, at the same time, it is characterized by low

unit cost, high availability and energy comparable with traditional mineral fuels, which allows the common use of biomass in dissipated power engineering based on co-generation systems. Intensive breeding programs of willow production resulted in high production rates for a wide range of climates within the EU.

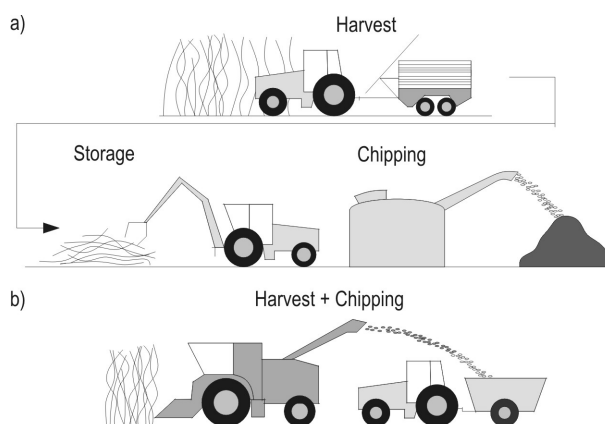
The deficiency of specialized machines adapted to arable areas and their high cost are the following obstacles indicated by potential small producers of biomass, as pointed out by Niemiec et al. (2012b). Increasing of the amount of energy plant plantation causes the necessity of exploration of new technologies allowing efficient harvesting and further processing. Among the various crops, SRC is especially regarded as a strategic resource of wood products, being a fast-growing and high-yielding species that can be managed as a coppice system (Schweier and Becker 2012a). Short rotation coppice is a very extensive form of land management in comparison to conventional agriculture, as crops are harvested in a 2–4 year cycle.

The use of the above presented machines in agricultural practice can be useful in solving the most important problems of environment protection, as shown by Spinelli et al. (2008) and Vervijst and Telenius (1999):

- ⇒ application of environmentally friendly technology in management system of sewage sludge in production of both energy and industrial plants,
- ⇒ utilization of woody biomass for heating purposes or generating of electrical energy not affecting the increase of global warming,
- ⇒ elimination of human hazardous substances included in sewage sludge in compliance with the possibility of their environmental control.

Different harvesting machines have already been developed. Two main harvesting approaches have been developed for short rotation woody crops, i.e. the harvest-and-storage system (Fig. 1a) and harvest-and-chip system (Fig. 1b). In both cases chips are produced from wet stems, collected in an attached trailer and stored as wet chips.

In the harvest-and-storage system, wet stems are cut, transported to a storage location to dry, and chipped afterwards to obtain dry chips (Berhongaray et al. 2013). The storage of wet chips implicates a risk of losing dry matter, and possibility of requiring further drying. In the harvest-and-storage system wet stems are cut first and then transported to a storage location. After drying, they are chipped to obtain dry chips. To reach lower moisture content, chips can be dried and stored under roofs or covered chip piles (Balsari and Manzone 2010).



**Fig. 1** Presentation of the harvest-and-storage (a) and harvest-and-chip (b) systems

Advantages and disadvantages, costs and harvest capacities of harvesting technologies e.g., Log Lines, Bundle Lines, Chip Lines and Bale Lines were presented and discussed in the latest publications of Abrahamson et al. (2010), Schweier and Becker (2012b, 2012c), Savoie et al. (2012) and Ehlert and Pecenka (2013). In the East-Central European countries, plantations are usually grown on extremely small areas. Furthermore, they are characterized by low technological level. The cost of the harvesters equipped for SRC cropping is approximately 420,000 € (Ehlert and Pecenka 2013). In addition, for the economic operation of highly productive harvest systems, cultivation areas of more than 300 ha are required (Scholz et al. 2009), if the harvester is used for SRC cropping alone. For small biomass producers in East-Central Europe, purchase of professional machines is financially inaccessible and unprofitable. The aim of the article is a presentation of new machines for small-sized plantations of energy crops. The advantage of the proposed solutions is their simple construction, which is connected with low production cost and simple machine operation. The proposed machines are mounted in front or at the back of a typical farm tractor and the chipping units are power-take-off (PTO) driven. All technical solutions of machines proposed by the Rzeszow University of Technology (RUT) are legally protected by patents and utility models.

## 2. Woody biomass crop

### 2.1 Biomass harvesters

Mechanization in the harvesting of short rotation coppice on farmed land is a prerequisite for the expansion of short rotation coppice cropping (Ehlert and

Pecenka 2013). On the market, there are many professional high efficiency energy-crop harvesting systems for SRC used for cut and storage. Furthermore, SRC are commonly harvested in a combined cut and chip system with modified forage harvesters used for maize and other crops. They are either self-propelled or tractor mounted. Class Jaguar forage harvesters with different cutting heads dominate in the European agriculture. The productivity of these harvesters was studied by Spinelli et al. (2009). The average machine productivity was 25–35 green tons (gt) per scheduled machine hour ( $\text{smh}^{-1}$ ) and  $25\text{gtsmh}^{-1}$ , respectively. Only few studies, e.g. by Becker et al. (2010) and Schweier and Becker (2012c), were identified to analyze other combined cut and chip machines than the Claas Jaguar. The average share of productive working time of New Holland forage harvester FR 9060 equipped with the cutting head FB 130 was 71% (Schweier and Becker 2012a). It took  $1.34\text{pmh}^{-1}$  to harvest one hectare and the average machine productivity was  $31\text{gtsmh}^{-1}$ .

Today, there are few harvesting machines applying cut and storage system and most of them are prototypes (Scholz et al. 2009). Among professional machines, attention should be paid to Empire 2000 with the productivity of  $0.75\text{ha smh}^{-1}$  and  $17.8\text{gtsmh}^{-1}$  (Danfors and Nordén 1995), Laughry with the productivity of  $0.13\text{ha smh}^{-1}$  (Mitchell et al. 1999) and Fröbesta with the productivity of  $0.36\text{ha smh}^{-1}$  and  $15.7\text{gtsmh}^{-1}$  (Danfors and Nordén 1995). The productivity of four machines tested in the study (Forestry Commission 1998) varied between  $0.09\text{--}0.22\text{ha smh}^{-1}$ . Resulting costs were two times higher than in the cut and chip system. As stated by Schweier and Becker (2012b), the cut and storage system is still under development but there is great potential for the future.

## 2.2 Harvesting on small-sized plantations

### 2.2.1 SRC harvesting methods

Today, as reported by Ehlert and Pecenka (2013), few harvesting machines apply this concept and most of them are prototypes. SRC are usually harvested in winter after leaves fall and before leaves set, preferably when soils are frozen (Forestry Commission 1998). In small-sized plantations, there are two different systems to harvest willow, the combined harvest-and-chip system and the harvest-and-storage system. Willow is harvested with an agricultural forage harvester (e.g., for maize and sugarcane), either self-propelled or tractor mounted, whose standard header is replaced by a special cutting head. Chips are blown into an accompanying tractor-pulled trailer, which transports the chips to an interim or final storage (Sambra et al. 2008).

At the RUT establishing technology of energy plant plantation, harvest methods and technology of sludge processing were elaborated. The main aim of machine solutions proposed by the authors is their readjusting to agricultural needs of quite small farms especially in Poland. Due to simple construction of the proposed machines and instruments, they are also cost attractive. One of the premises in performing operations connected with the construction of new machines for planting, logging and processing of plant biomass with ligneous shoots is high cost of high-productivity machines (Niemiec et al. 2011, Niemiec et al. 2012a). So, their application in small farms is not profitable.

Meaningful growth of the amount of energy plant plantations, mainly plants with ligneous shoots, requires further exploration of new technologies that would allow efficient harvesting and processing. Over the last years, progress has been recorded in submitting solutions of specialized machines for harvesting and processing of biomass logging from ligneous shoots e.g., mowers, wood chipping machines, chaff cutter for wood, but the problem still exists and requires further research. Machines for small plantations and the adapter for terrain hypsography are particularly investigated.

In the case of establishing protective treatments, logging and processing of the biomass in plantations of the energy plants, farm tractors are the basic prime mowers of specialized machines. Moreover, farm tractors usually transport the crop from plantations to further processing or to final management of energy biomass.

There are not many commercial offers of machines characterized by low productivity and intended for working in small plantations, and also verified in practice. Characteristic feature of Polish agriculture is the size reduction and low degree of mechanization as well as limited buying power. In this situation, the search for construction solutions adjusted to the requirements of small farms is justifiable.

Machine solutions proposed by the RUT are legally protected by patents and utility models (Table 1). To provide the required power and efficiency, the chipping units are mostly *PTO* driven.

Considering the efficiency of application of machines proposed for production, logging and processing of the biomass in small farms, a few factors should be taken into account. First of all, the size of a farm should be considered and in consequence the demand on manpower and degree of accessibility of high power farm tractors. The terrain hypsography and soil structure should be considered from the point of view of possibility of machine utilization. The advantage of

**Table 1** Machines developed at the Rzeszow University of Technology

Machine	Patent, <i>P</i> / Utility model, <i>UM</i> no.	Year
Wood cutter	<i>UM</i> – 116926	2007
Mower for tree-like plants	<i>P</i> – 386842	2010
Feed mechanism of cut material in wood cutter	<i>UM</i> – 119154	2010
Mobile harvester for biomass logging of plants with ligneous stems	<i>UM</i> – 120576	2011
Harvester for crop and chipping of ligneous stems of energy plants and branches	<i>UM</i> – 119895	2011
Harvester for crop and chipping of ligneous stems of energy plants	<i>UM</i> – 120965	2012
Unit for harvesting and chipping of ligneous stems of plants	<i>UM</i> – 121680	2013
Harvester for crop and chipping of ligneous stems of energy plants and branches	<i>UM</i> – 121863	2013

the proposed solutions is their simple construction, which is connected with low production cost and simple machine operation.

The whole-tree harvesting is the basic method of the willow harvesting in small-sized farms. In this method there are several ways of harvesting:

- ⇒ manually, using a bill hook or similar implement,
- ⇒ motor-manually, using a chainsaw or brush cutter,
- ⇒ using tractor-drawn equipment.

Obviously the manual and motor-manual approaches are suited for small areas only, where timber is harvested for household consumption. Kofman (2012) has shown that tractor-drawn equipment can be used on larger areas of coppice, while self-propelled machines are best suited for very large blocks. Some tractor-drawn machines collect shoots on a loading bay. The bundle of the shoots is easy for transporting and subsequent handling. Some machines transport the shoots to the landing, while others unload directly onto the field.

### 2.2.2 Three-point linkage mower

The design process of a new machine started from building a conceptual spatial model of a construction with Autodesk Inventor program. Autodesk Inventor allows to determine kinematic constraints between particular movable parts of the machine, and the program enables to observe possible collisions between parts of the machine. Autodesk Inventor allows kinematic and dynamic analysis of working mechanisms. In order to determine relations between mate components, a wide range of motion constraints and elastic or damping elements, as well as definition of friction coefficient in every constraint, may be used. To under-

stand the essence of the kinematic effects, the program demonstrates the simulation in a form of spatial visualization directly on the model of the analyzed mechanism.

During the designing of mechanical elements, the question arises whether a specific element with stand load appears in normal operations. In complex constructions, analytical determination of the most efforted places responsible for element destruction is very difficult and often impossible. In order to solve this problem, the optimization of numerical construction of the mower has been considered using *ABAQUS* program based on finite element method (*FEM*). *ABAQUS* allows analyzing physical models of real processes by putting special emphasis on geometrical nonlinearities caused by large deformations, material property, nonlinearities and complex friction conditions. The dimension of the geometrical model of the mower frame corresponded to the conception model.

A prerequisite to begin the computation using *FEM* is the preparation of an accurate numerical model of the selected construction, and then simplification and digitizing of the model in *ABAQUS* in order to receive equivalent model to the mathematical model of continuous medium. Simplification of the model consists in removing unnecessary details such as small holes, roundings and chamfers, which do not influence meaningfully the accuracy of solutions for the purpose of fast processing of the model. Digitizing consists in the division of the continuous medium on finite numbers of elements of specified shape. In order to obtain the required accuracy of the searching solution, the used elements should be small as much as possible so that they may be approximated inside elements functions using multinomial models. Nevertheless, the reduction of elements number leads to an increase in the number of



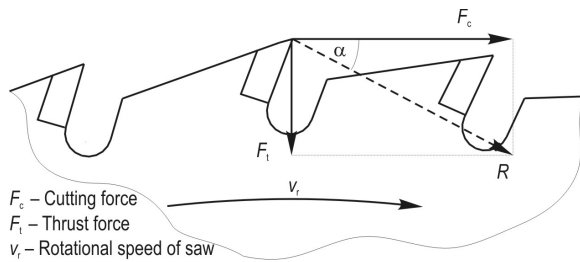


Fig. 2 Components of cutting resistance

searched function of node values, which simultaneously results in lengthening the computation time. So, most often, heterogeneous division of the model on elements was used. In places of expected high stress, gradient mesh elements should be concentrated. The following stage in developing the FEM model is to take into consideration boundary conditions and parameters describing material of the mower frame. The mower frame is constructed of S355J2G3 constructional steel. The values of basic mechanical parameters of this steel were determined using tensile test and they are as follows: Young’s modulus  $E=210,000$  MPa, Poisson’s ratio  $\nu=0.33$ , yield stress  $R_{eH}=353$  MPa. The material density  $\rho$  is  $7865$  kg/m<sup>3</sup>. It was assumed that circular saw is made of 145Cr6 tool steel with the following material properties:  $E=210,000$  MPa, Poisson’s ratio  $\nu=0.33$ , yield stress  $R_{eH}=380$  MPa. The analysis also took into consideration the weight of the mower.

The end of the cantilever jib on which the saw is attached is exposed to resultant forces from the cutting process. Values of these forces were determined so as to introduce construction into first plastic strain. The momentary resistance of stem cutting may significantly affect the way and the value of frame loading. To determine the resistance against cutting, a simplified model of the forces distribution (Fig. 2) can be used. Assuming that the circular saw cuts the material parallel to the ground, the cutting resistance  $R$  can be divided into two components. The force required to overcome the cutting resistance, which is parallel to the cutting movement of the cutting edge –  $F_c$ , is determined from equation:

$$F_c = r_c \times w \times t \tag{1}$$

Where:

- $r_c$  specific cutting resistance;
- $w$  chip width;
- $t$  chip thickness.

Specific cutting resistance  $r_c$  for willow stems for cross-cutting with sharp-edged blade, assumed to be  $3.2$  daN mm<sup>-1</sup> (Spychała et al. 2010). Chip width  $w$  is

equal to the thickness of the circular saw tooth used in the machine and it is  $4.5$  mm. The feed value is equal to the thickness of the chip  $t$  during cutting willow stems – about  $0.4$  mm per tooth (Spychała et al. 2010). Operating speed of the machine is  $6$  km h<sup>-1</sup> and the rotational speed of the circular saw is  $n=2100$  rev. min<sup>-1</sup>. After inserting the above values into Eq. (1), the value of the force acting on a single tooth of the saw is  $5.76$  daN.

The value of thrust component of force  $F_t$  perpendicular to the cutting force  $F_c$  is determined from Eq. (2). Thrust coefficient  $c_t$  value for the cutting edge with blunt edges is on average  $0.5$ .

$$F_t = c_t \times F_c \tag{2}$$

Where:

- $F_c$  cutting force;
- $F_t$  thrust force;
- $c_t$  thrust coefficient.

The value of the thrust force acting on a single tooth of the circular saw was  $2.88$  daN.

In the three-year energy willow plantation, the stems diameters are very different. It was assumed that the greatest loading of the mower frame occurred when cutting simultaneously two willow stems with a diameter of  $70$  mm. Under these conditions, the load is transmitted simultaneously through five circular saw teeth (Fig. 3). The arrows present the directions of action of cutting forces and thrust forces acting on the teeth during cutting.

The mower frame is composed of  $38307$  4 node elements called C3D4 in Abaqus terminology. The finite elements mesh of the mower frame is shown in Fig. 4. In order to improve the computational accuracy, the local mesh densification is assumed.

Calculations were performed using the implicit finite element code. In the implicit method, the inter-

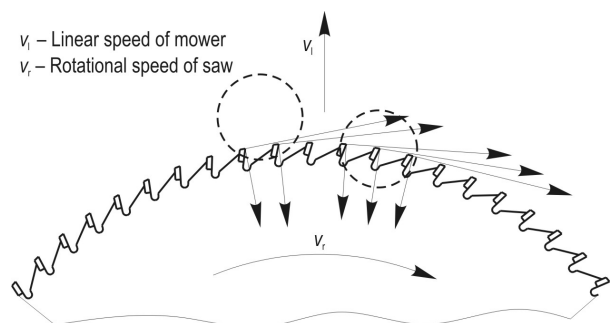


Fig. 3 Simultaneous cutting of two willow stems with a diameter of  $70$  mm

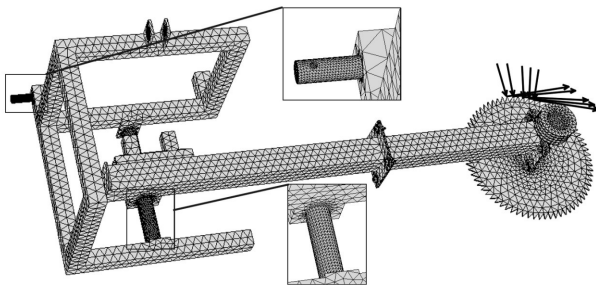


Fig. 4 The finite element mesh of the mower frame

nal forces are made to balance with the external force through an iterative procedure, from which the deformed state after a time increment can be obtained. One of the merits of this method is that the time increment can be relatively large because of conditional stability of the implicit time integrator, and static solutions can always be obtained by natural characteristics of the method. To solve the Newton-Raphson's iterations, the time step is controlled by Abaqus automatic incrementation technique. The double precision executable is used in this analysis. The global equation in models based on FEM is represented as:

$$F(t) = [K]\{d\} + [M]\{\ddot{d}\} \quad (2)$$

Where:

[K] global stiffness;

[M] mass;

[F] force matrices;

d nodal displacements;

$\ddot{d}$  nodal accelerations.

The analysis available from ABAQUS, which is used in the model, handles non-linearity from large displacement effects, material non-linearity and

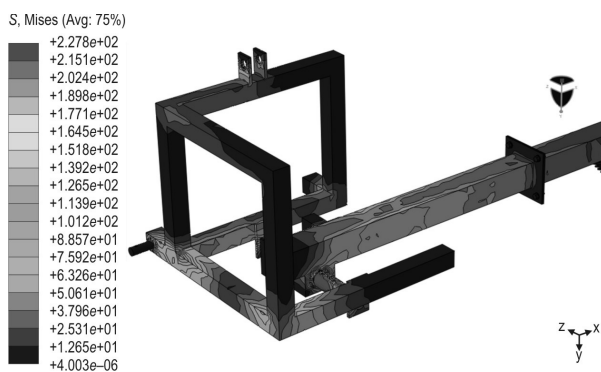


Fig. 5 Distribution of Huber-Mises-Hencky stress (MPa) in the mower frame

boundary non-linearity such as contact, sliding and friction. The solution is obtained as a series of increments with iterations to obtain equilibrium within each increment. Implicit method enables full static solution of the deformation problem with convergence control.

The aim of the simulation was to determine the places in construction with potential failure. In order to determine factual strain values in the mower frame, it is necessary to make analytical or experimental evaluation of the real value of load forces of the frame. The value of equivalent von Mises stress localized in the mower frame does not exceed the allowable stress for S355J2G3 steel (Fig. 5). The most loaded place is the welded beam between the mower frame and the cantilever jib (Fig. 6). The analyzed construction is relatively simple, so it was possible to determine approximately the places endangered to fail without the application of advanced programs. However, the present analysis will be used to analyze more complex machines e.g., willow and bush harvester.

For economic and trouble-free harvesting of small willow plantations with free arrangement of stems, single-row mower is developed. The structure of a developed and patented mower for cutting down woody plants (Fig. 7) is composed of the frame (1), three-point linkage (2) for attaching to an agricultural tractor and

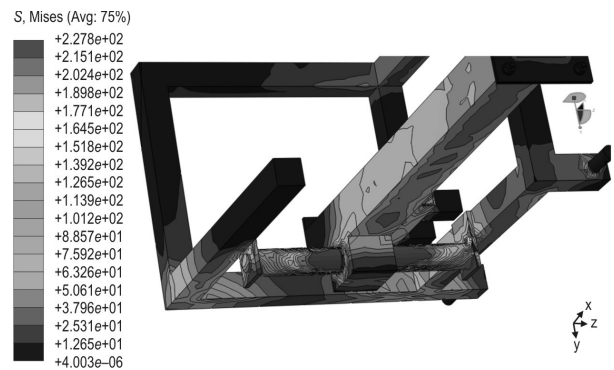


Fig. 6 Distribution of Huber-Mises-Hencky stress (MPa) in the beam between the mower frame and cantilever jib

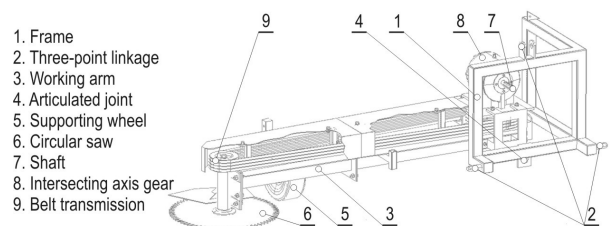
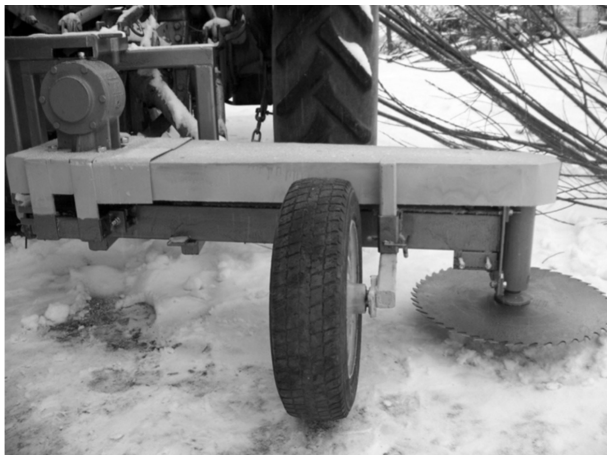


Fig. 7 Model of a tractor mower for woody plants



**Fig. 8** Prototype of the patented tractor-mounted mower for woody plants

working arm (3) coupled to the frame using articulated joint (4). The ground wheel (5) is mounted to the working arm near its end. At the end of the working arm, a circular saw (6) with a diameter of 600 mm is mounted. To provide the required power and efficiency, the saw is PTO driven. The drive of the circular saw is transmitted from PTO by using a shaft (7), intersecting the axis gear (8) and the belt transmission (9). All movable elements of the machine are protected by safety guards. The other construction solution of the circular saw drive is a long shaft between the saw (6) and the intersecting axis gear (8) instead of the belt transmission (9). The prototype of the tractor-mounted mower for woody plants is presented in Fig. 8.

The modification of the presented mower for woody plants is the mower with the retractable arm and hydraulic drive of the circular saw (Fig. 9). The mower structure consists of the frame (1) adapted to three-point linkage of agricultural tractor and the working arm (2) with the extension arm (3). At the end of the extension arm, the circular saw (4) and the ground wheel (6) are mounted. The working arm (2)

is connected with the frame using articulated joint (5). The remote control hydraulic cylinder is coupled with the extension arm (3). The end of the working arm (2) has rollers mating with the guide (7). The circular saw is driven by the hydraulic engine (10). The drive of the circular saw is transmitted by the reduction gear (8) and the hydraulic pump (9). The mass of the complete tractor-mounted mower was about 450 kg, and it should be mounted in three-point linkage of medium-sized standard tractors (minimum 60 kW).

**2.2.3 Harvest-and-chip machines**

In the harvest-and-chip method, there are two main ways of harvesting:

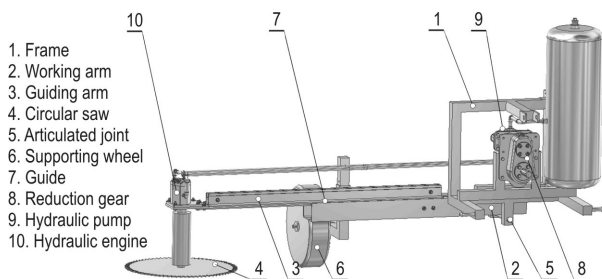
- ⇒ tractor-mounted equipment,
- ⇒ self-propelled machines.

Tractor-mounted equipment is cheaper and has a lower weight than self-propelled machines, but has a lower productivity as shown by Kofman (2012).

Biomass may be processed directly in chips by the tractor-mounted harvester (Fig. 10a), especially developed for cutting specified pieces of bevelled energy plants or branches, which are the discards from e.g., cross-cutting of the fruit tree in an orchard. Cutting assembly of the harvester has replaceable heads with three, four or six cutters allowing for the change of cutting length of stems. The machine is intended for harvesting and chipping plants with ligneous stems and branches. The harvester is mounted on the agricultural tractor using three-point linkage (1) and it has a drum cut system. The drive of the harvester is transmitted from power-take-off of the agricultural tractor by belt and gear transmission. The cutting assembly (2) of the harvester has two drums (3) to which circular saws (4) are mounted. The drums (3) have strips (5) that make biomass easy to retract into the throat of the cutting assembly (6). The cutting assembly is composed of feed assembly and knives (9) mounted on two rotational heads (8).

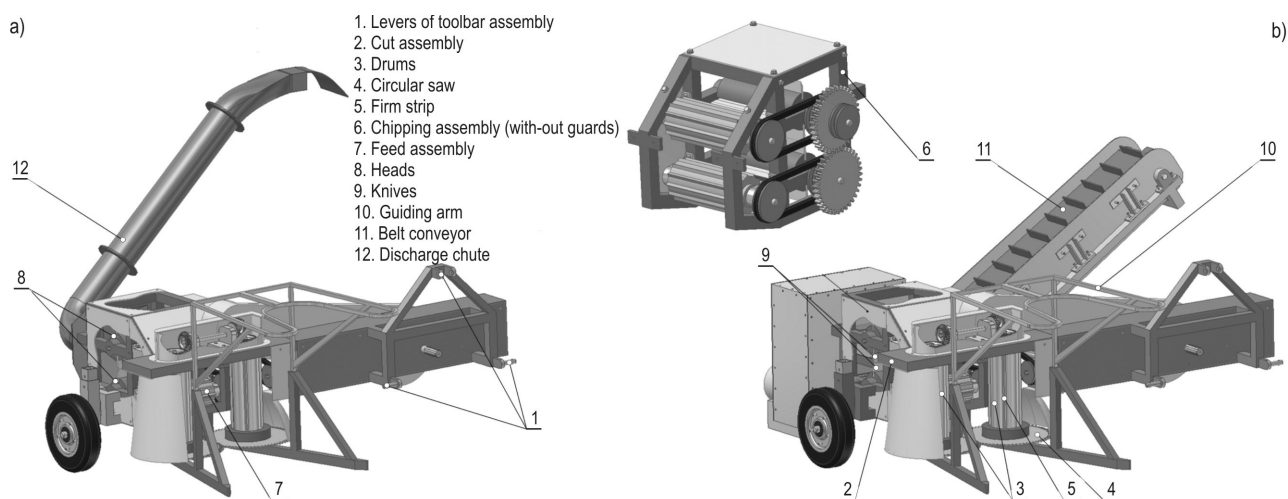
An alternative model of harvest-and-chip machine (Fig. 10a) is used for harvesting willow coppice, using a harvest-and-billet system (Fig. 10b). It is capable of producing much coarser chips or even chunks. The normal setting of the machine produces 40–60 mm chips, but by removing some of the knives and lowering the drum speed, 150–200 mm billets can be produced. Tests performed with willows demonstrated the high potential of the new concept as a low cost billets production. The maximal diameter of cut willow stems is 100 mm (Fig. 11).

Both cutting and chipping systems are protected by overload coupling. To facilitate the motion of stems to the machine throat, the cutting assembly is equipped



**Fig. 9** Model of a tractor mower made in Autodesk *INVENTOR* program





**Fig. 10** Model of harvester with discharge chute (a) and belt conveyor (b)



**Fig. 11** Billets with a diameter of 100 mm

with the guiding arm (10) which bends high stems. The longer chips are transported on the trailer by using the belt conveyor (11) (Fig. 10b). The short chips are transported alternatively by using discharge chute (12) (Fig. 10a).

Cutting assembly is equipped with two circular saws with a diameter of 700 mm, which overlap at the joint in a width of about 50 mm. The rotational speed of circular saws should be about 2100 rev/min (Spychala et al. 2010), which allows for a circumferential cutting speed of 100 m/s at the diameter of the saw of about 700 mm. This speed value is necessary to obtain a smooth cut surface and reduces the risk of splitting phloem under the bark, which could contribute to the snags putrefaction. Therefore, machines for willow harvesting use circumferential speeds of cutting saws

ranging between 63 and 118 m/s (Lechasseur and Savoie 2005).

The chipping assembly (Fig. 12a) is a constructional solution adapted from a wood cutter (Table 1) and is composed of two main units: feeder (1) and cutting assembly (2). The feeder comprises two shafts (3) on whose circumference toothed blades (15) are located. In the chipping unit, two heads (4) have blades (5) arranged uniformly at the heads circumference. The stem (6) is cut to billets (7) whose length depends on the ratio of the rotational speed of both feed shafts and cutting heads. As shown in Fig. 12b, the feeder of stems comprises two feed shafts, the driving (8) and the clamping (9), arranged one above the other. The lower driving shaft (8) is coupled to the feeder frame (10) by units of bearing and unidirectional clutches (11). In turn, the upper feed shaft (9) is connected to the feeder frame (10) and the lower drive shaft (8) by compression springs (12). The springs are slidably coupled with guides (13). The lower and upper shafts (8) and (9) have toothed blades (15), which protect hard wood from slipping, thus ensuring accuracy of cut to a predetermined length.

The cutting head (Fig. 13) has a body (1) with a shaft hole (2). A knife seat (3) is placed in the body. In the bottom of the knife seats, adjusting screws (4) are placed. Knives (5) are secured with wedges (6) bolted to the body with screws (7). Depending on the required length of chips, the chipping assembly has three, four or even six knives located uniformly on the head circumference. We cooperate with the following companies: R&D Centre Inventor Sp. z o.o. and SIP-MA S.A. – one of the leading manufacturers of agri-



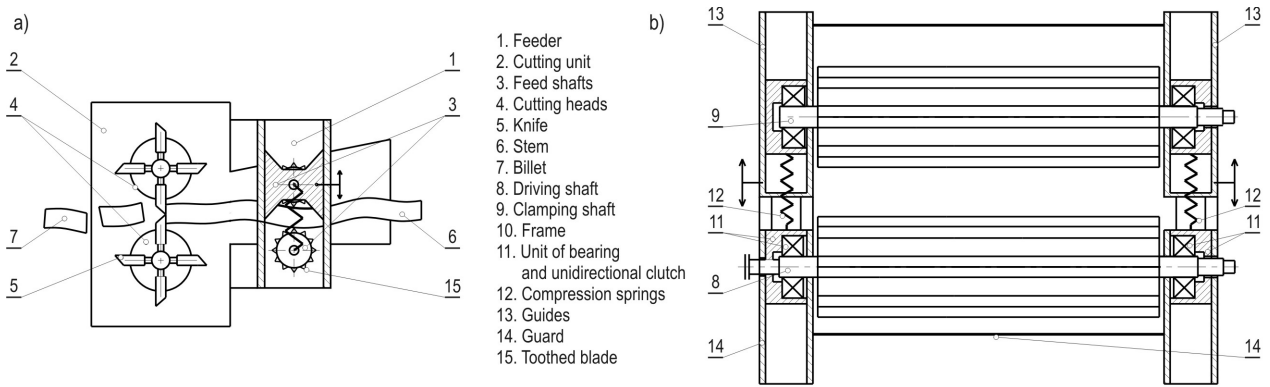


Fig. 12 Chipping (a) and feed (b) assemblies

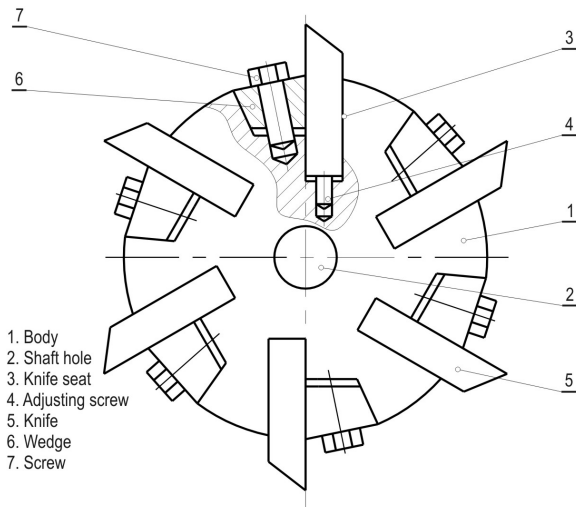


Fig. 13 Cutting head

cultural machines in Poland. The results of our collaboration are prototypes of chipping machines manufactured as electric motor driven (Fig. 14a) and PTO driven (Fig. 14b). These machines were manufactured by modification of the above mentioned harvesters. The field testing of machines indicates full usefulness of chipping devices.

In the alternative solution, the shafts of circular saws can be driven by hydraulic engines.

As the speed of tractor/machine arrangement can be changed depending on field conditions, the use of a hydraulic engine, controlled by electric-hydraulic distributor, will allow for optimum selection of the saws angular velocity so that the circumferential speed is higher than the speed of the farm tractor. The speed of the tractor will depend on field conditions, but the maximum speed cannot exceed the recommended



Fig. 14 Prototypes of chipping devices: electric motor-driven (a) and PTO-driven (b)

**Table 2** A qualitative and quantitative comparison of the harvest-and-chip and harvest-and-billet methods for harvesting SRC-willow, prepared on the basis of own experience and Kofman's study (2012)

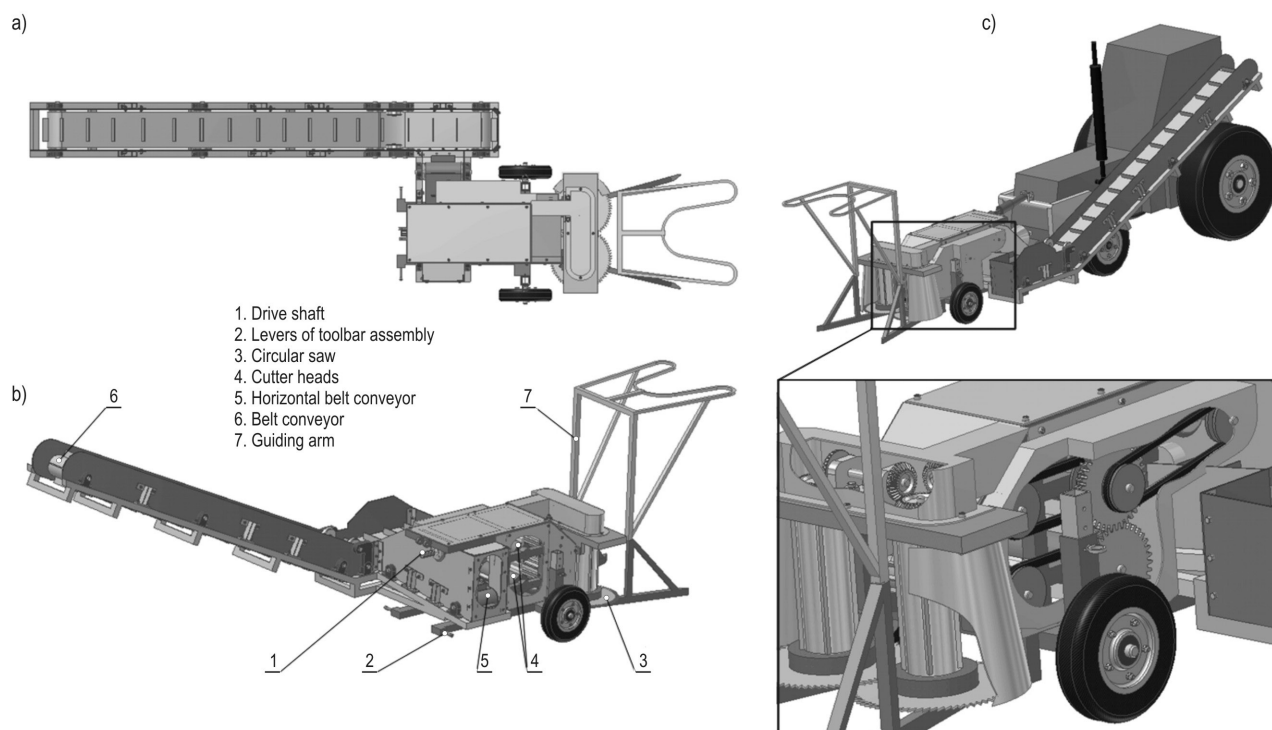
Factor	Area	Cut-and-chip <sup>(1)</sup>	Cut-and-billet <sup>(1)</sup>
Area	≤1 ha	–	–
	1÷5 ha	+	+
	≥5 ha	++	++
Harvesting productivity tonnes/ha	≤1 ha	<10	<12
	1÷5 ha	<25	<20
	≥5 ha	<25	<20
Drying possibility	≤1 ha	+	++
	1÷5 ha	–	+
	≥5 ha	—	+
Markets, ha	all	>5	1–5

8 km h<sup>-1</sup> (Lechasseur and Savoir 2005). Cutting height of stems of 100 mm above the ground is in the range usual in similar solutions i.e., 50–100 mm.

Characteristic features of the presented harvester are:

- ⇒ possibility of application of each typical agricultural tractor with a power above 60 kW,
- ⇒ multifunctionality: chipping on plantation or stationary chipping,
- ⇒ by the operating parameters, the harvester is adapted for especially small plantations of energy plants.

Both methods of SRC harvest are highly profitable in the case of larger plantations (Table 2). The harvest-and-billet method can be used because billets dry a lot easier than chips (Table 2). However, billets generally have to be re-chipped before being used as fuel or may be used as a whole in family households that use biomass for heating. Limited resources of energy, risks connected with emission of thermal gas and low efficiency systems of thermal energy transmission lines require exploration of other methods of generation, transmission and consumption of electric and thermal energy. One of the solutions of this problem is the idea of generating electric and thermal energy directly in a flat. Single-family homes especially use the system of combined heat and power for home (CHPH) in association with Stirling Engine supplied with billets or chips (Szewczyk and Trzepieciński 2012). It has been



**Fig. 15** Machine for harvesting and chipping of energy plants – the top (a), isometric (b) and tractor mounted (c) view

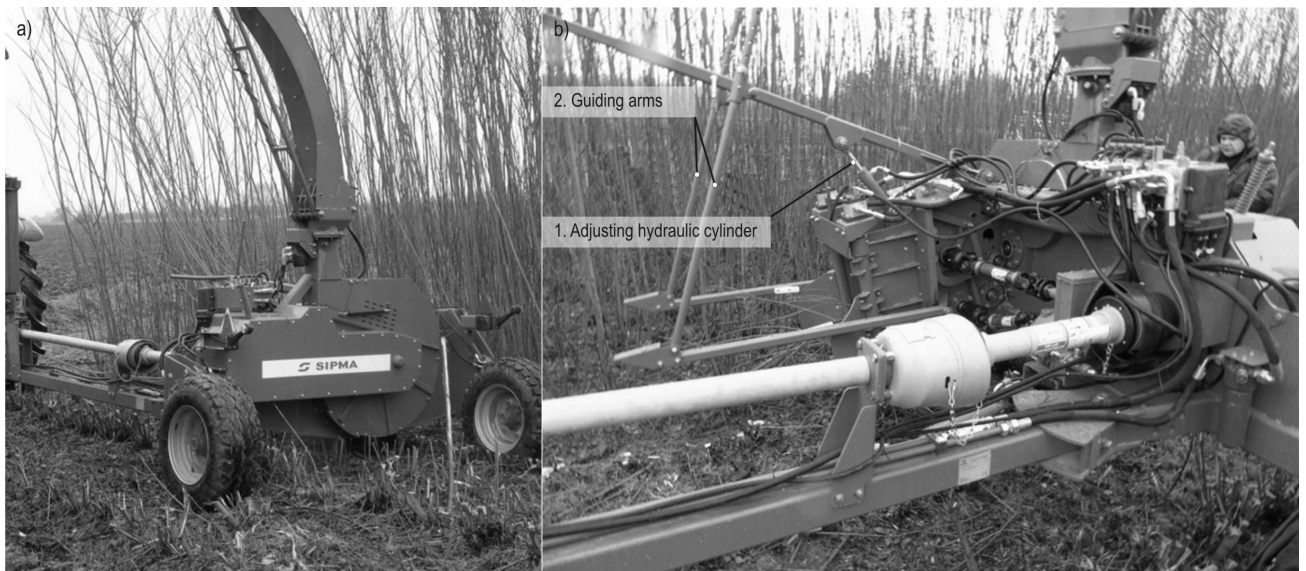


Fig. 16 Back (a) and front (b) views of prototype of one-row side-operating SIPMA SR 1010 HERO harvester



Fig. 17 Prototype of two-row side-operating SIPMA SR 2010 HERO harvester (a) and cutting system (b)

shown (Kofman 2012) that for a large-scale use, the harvest-and chip is the cheapest way of harvesting willow SRC.

### 3. Industrial application of harvesting technology

The result of cooperation of Rzeszow University of Technology and SIPMA joint-stock company, one of the

leading manufacturers of agricultural machines in Poland, are a series of harvesters for short rotation willow coppice. Both one-row (Fig. 16) and two-row (Fig. 17a) harvesters are side-operating and tractor-pulled single-pass harvest-and-chip machines. The harvester should be accompanied by an additional, separate tractor-trailer combination to collect the chips. The machines are intended to work on plantations with 0.75 m between rows. The header attachment for the »HERO« series





Fig. 18 View of the cut shoots

The two front rear feed rollers in the header grab the crop and draw it back toward the feed roller module of the harvester. The lower front feed roller in the header has deep paddles to help flip the base of each stem up into the two feed rollers behind it that are spring loaded. The harvesters are equipped with a *PTO* driven drum type chipper. Four knives are mounted on the rotor.

Many elements of both single and double-row machine are hydraulically driven, namely:

- ⇒ discharge pipe tilt mechanism,
- ⇒ lid tilt mechanism,
- ⇒ system of angular adjustment of bar position,
- ⇒ control system of cutting height,
- ⇒ circular saw drive.

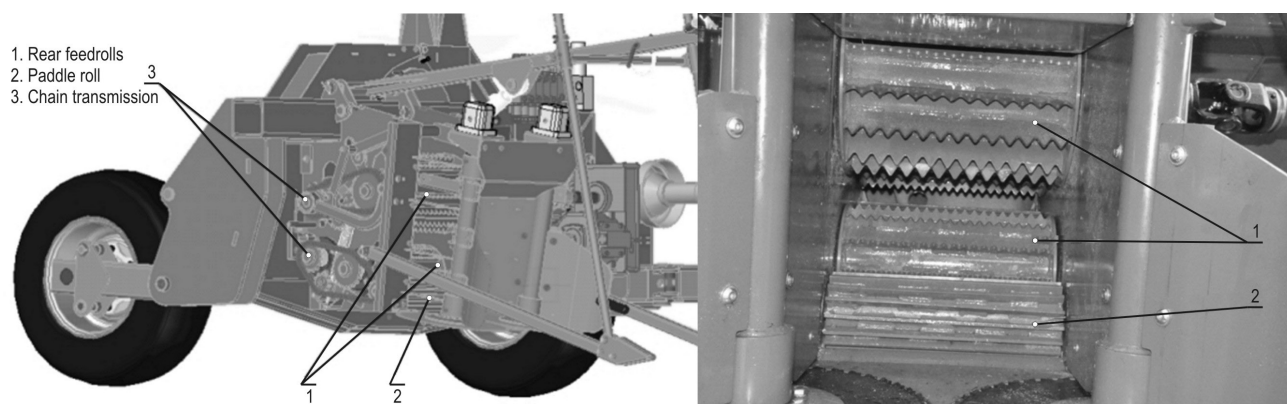


Fig. 19 Drive mechanism (a) and woody crop feeding system (b) of SIPMA SR 1010 HERO harvester

harvesters uses circular saws mounted in a horizontal plane to cut short rotation crops. The circular saws (Fig. 17b) with diameter of 0.4 m are driven by the HPL MA2 hydraulic engines controlled by electric-hydraulic distributor. The hydraulic engine drive of saws is much simpler than the structure of mechanical gears that transmitted the power from power-take-off (*PTO*) to circular saw. Hydraulic drive is characterized by high flexibility that fully eliminates failures due to overloading of the cutting head. Operating speed of the machine is  $6 \text{ km h}^{-1}$  and the rotational speed of the circular saw is  $n=2100 \text{ rev. min}^{-1}$ . The use of cutting system with carbide-tipped circular saw blades does not lead to negative tearing of fibrous tissue and stem bark (Fig. 18). However, the carbide blades were vulnerable to rocks and had to be replaced after approximately 10 ha. Feeder drums located vertically over the saw blades rotate at approximately  $160 \text{ rev. min}^{-1}$  to actively collect and feed the crop back into the harvester throat. The header has four horizontally mounted feed rollers (Fig. 19) that help feed cut stems back into the chipping unit.

All the mentioned mechanisms are controlled by waterproof mobile control panel located in the cab.

Chip size distribution is, therefore, the best indicator of how a chipper performs in terms of product quality. Dimensions of fuel wood chips are limited to 50 mm, however, at least 90% of the chips should not exceed 40 mm in size. In the case of storage, too exces-



Fig. 20 Example of willow chips

sive fragmentation of chips in combination with high humidity is disadvantageous because of the possibility of the digestion of stored chips. The presence of oversized particles may prevent the use in small and medium-size plants, those that generally offer the best price opportunity. However, very fine chips are known to store poorly. The size distribution of willow chips (Fig. 20) meets the geometric requirements of fuel wood chips. The major fraction of the crop are chips with length of about 35–45 mm. This confirmed the proper synchronization of feeding speed and rotational speed of the drum chipper.

Field tests confirmed that prototypes of willow harvesters meet the main design guidelines, i.e.:

- ⇒ machines provide handling of at least 3 year old willow with maximal stem diameter of shrub of 70 mm,
- ⇒ tractor power required to drive harvesters does not exceed approximately 120 kW,
- ⇒ drum type chipper can produce chips that are 35–50 mm long,
- ⇒ effective material capacity is 30 Mg per hour,
- ⇒ prototypes should meet the requirements of Road Traffic Act,
- ⇒ objectives of harvesting include the ability to harvest willow coppices containing stems of up to 120 mm in diameter,
- ⇒ harvesters are equipped with centrifugal discharge pipe allowing direct transport of chips into a trailer at the distance of 5 m.

#### 4. Conclusions

The proposed agrotechnical machines have original construction and take into account the needs of small producers of ligneous biomass. Machines intended for operation in small and medium-sized plantations of energy plants are characterized by simple construction and they do not require highly skilled workers. In the case of establishing protective treatments, logging and processing of biomass in plantations of energy plants, the farm tractors are the basic prime movers of specialized machines. The majority of developed machines are mounted on a farm tractor using levers of toolbar assembly. For a small-scale use, the whole-shoot cutting method is probably the best. Alternatively, for small-scale use, the harvest-and-chip method can be used but a special dryer is required for drying chips and it is very expensive. So, the harvest-and-billet method is more economic, because billets dry much easier than chips. Furthermore, the billets

can be used directly for heating in the single-family housings.

Considering the efficiency of application of the proposed machines for harvesting and chipping the biomass in small farms, a few factors should be taken into account. First of all, the size of a farm should be considered and in consequence the demand on manpower and the grade of accessibility of high power farm tractors. Considering the possibility of using the proposed machines, terrain hypsography and soil structure should also be taken into account.

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