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RFID IMPLEMENTATIONS IN THE WOOD SUPPLY CHAINS: STATE OF THE ART AND THE WAY TO THE FUTURE

The focus of this review paper is to present the state of the art regarding RFID implementations in wood supply chains, covering the tree marking stage till the transportation to the final processor. The easier than ever collection of data using sensors and the emerging ability to exchange information in the context of the Internet of Things (IoT) form a very promising new environment for the optimization of wood supply chains. Driven by currently enhanced, ability to store different layers of information per merchantable unit (tree assortments at final or semi-final form or containers of woody biomass), RFID applications can provide valuable solutions and revolutionize wood supply chains by warranting traceability, combating illegal logging, minimizing waste and offering detailed information of the wood products properties, among other benefits that are presented in the text. The benefits can be identified at the ecological, social and economic levels, addressing the sustainability concerns of modern societies. To make use of this huge potential, a continuous flow and fusion of information at all supply chain stages must be taken for granted, as well as the close cooperation among stakeholders.

Keywords: traceability, chain of custody, Internet of Things, sensors, optimization, precision forestry, digitalisation, tags

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Introduction

Radio-Frequency Identification (RFID) technology is a contactless interrogation method for the identification of objects [Finkenzeller 2010]. RFID has been extensively used in many industries worldwide in recent years [Zhu et al. 2012; Daya Priyanka et. al 2016; Das 2020]. Specifically, it has been frequently used in inventory and warehouse management systems [Wamba et al. 2008; Ozguven and Ozbay 2015], material flow monitoring and supply chain management systems [Zhang et al. 2012] among others. There is a growing interest in future implementations of RFID technology, especially in the context of Industry 4.0 [Elbasani et al. 2020].

Each RFID system works in a relatively simple way based on a signaling technology between the reader and the Radio Frequency (RF) tag. RF tags can be attached to different objects, including materials, commodities, logistics units, passengers, and living organisms like animals, and, in the case of forestry, unprocessed or processed tree biomass in various forms (seedlings, trees, logs, and wood chips). As a result, the considered objects, including forest industry products can be identified, positioned, monitored, and tracked [Attaran 2007; Finkenzeller 2010].

Nowadays, forest utilization faces considerably more complex challenges than it did some decades ago. Climate change, also referred to as climate crisis, stresses the need for forest sustainable management in a future with, largely unknown, weather modifications [Hawkins et al. 2020]. Illegal logging still represents a big challenge despite international initiatives and agreements [Hoare 2015]. Technological developments made possible a steep increase in computing power in the last decades and the emergence of new information technologies [Yamin 2019]. Big data collection is now, easier than ever, and its analysis may lead to significant insight and financial gains for forest enterprises. Finally, harsh competition demands optimization at all levels of the forest companies so that their supply chains are more efficient, at the environmental, social, and economic levels. Hence, new technologies that will satisfy these modern requirements are much sought after, in a new context where specific features of RFID technology are critical. RFID has been examined as a candidate for implementation in the selected wood industry and forestry applications. RFID can be an all-around carrier of information and data collector, once some of its weaknesses are bypassed.

This paper presents the state of the art of RFID technology and its perspectives on forestry supply chains. Initially, the major characteristics of the RFID technology and its applications in different areas and various industries are presented. Then the focus is on the need for traceability in wood supply chains as (re)defined by the international initiatives and policies such as the European

Union Timber Regulation. Past and current RFID applications in forest management are also described, starting from individual tree marking and harvesting, and extending to complete wood supply chains. Finally, the authors take the challenge to draft the prospect directions of RFID technology developments that could be implemented by forest industries in the era of Industry 4.0 and specifically its prospect connections to the Internet of Things (IoT).

Basic features of RFID technology and applications in different industries and supply chains

Introduction to RFID technology. Basic definitions and concepts

RFID technology is an electronic, wireless, sensor-based technology that uses electromagnetic fields (waves, electromagnetic signals) to automatically detect and track RF tags attached to different objects [Attaran 2007; Finkenzeller 2010; Zhu et al. 2012]. It is commonly used as one of the methods of automatic identification and data capture (AIDC) [Attaran 2007; Finkenzeller 2010], as well as a tracking and tracing system [Glover and Bhatt 2006]. As an alternative to bar code technology, the RFID system does not require that the object must be within the line of sight of the reader, which is an important benefit of the RFID technology.

A typical RFID system includes four components: an antenna or coil, a transceiver with decoder, frequently packaged as a reader, a transponder (RF tag), which is electronically programmed with unique information, and a computer system – application [Finkenzeller 2010]. The antenna emits radio signals for the RF tag to be activated and for data to be read and written to it. Antennas establish the communication between the RF tag and the transceiver, which is responsible for the data acquisition. The reader emits radio waves in different frequencies and corresponding ranges, referred to as low frequency (LF), ultra-high frequency (UHF) and microwave frequency (MF). The range of readers (from 10 cm to 200 m) strongly depends on the radio frequency and their power output.

An RFID tag consists of three elements [Glover and Bhatt 2006]: a microchip or integrated circuit (IC), a tiny antenna and a substrate – the foundation of the RFID tag. Tags are available in various sizes, designs, and forms. They can be standardized or customized for a particular application. Standardized tags, usually kept in stock, are relatively cheap (around $1 apiece) while customized tags can be very expensive (up to $100). In general, there are two types of RFID tags [Finkenzeller 2010]:

- passive tags, which are not equipped with their batteries and that are powered by energy from the RFID readers interrogating radio waves, must be read at a limited range,
- active tags, that are powered by their battery and thus can be read at a greater range from the RFID reader, up to hundreds of meters.

The passiveness or activeness of RFID tags has a strong impact on their prices. Passive tags are much cheaper than active tags. Usually, a standard passive tag can be priced at the level of $0.1 to $1, while the active tags can cost around $5 to $20 [Finkenzeller 2010; Das 2020]. In some cases, active tags can be 100 times more expensive than their passive equivalents.

The typical shape of the tag is cuboid with dimensions 1 cm by 3 cm by 5 cm. In recent years substantial research and manufacturing effort have been made to miniaturize RFID tags made of silicon, as in the case of Hitachi whose dust-sized mu-chip with dimensions of 0.4 mm by 0.4 mm in 2007-2008, was further squeezed to the size of 0.05 mm by 0.05 mm [Glover and Bhatt 2006; Finkenzeller 2010]. Furthermore, a terahertz frequency identification (THID) tag was developed in 2010, which was reduced to 1 mm^2 in size at MIT in 2020 [Zewe 2021]. The ultra-small-sized tags can be used for specific applications. In 2009 micro-transponders were glued to live ants to monitor their behavior [BBC 2009].

In regular daily logistics operations, often more than one RF tag responds to an RF tag reader. This happens when many individual products (e.g. logs) with RF tags are shipped together in a common pallet or chest. In such cases, possible collision in data transmission may happen and the proper identification of products may be disturbed. Thus, the detection of interfering data flows generated by different RF tags and their separation is important to allow the reading of source data and identifying reliably the individual products. Two different types of protocols including “Slotted Aloha” (SA) and “Adaptive Binary Tree” (ABT) are used “to singulate” a particular tag, allowing its data to be separated from the data generated by other tags and read transparently and without errors [Glover and Bhatt 2006].

The role of RFID technology in different industries and supply chains. Strengths and weaknesses of RFID

Many studies and reports are showing the worldwide variety of RFID applications across different areas/fields, industries, and supply chains [Attaran 2007; Finkenzeller 2010], including the automobile industry; logistics and supply chain, transportation, agriculture and green energy sector, all associated with the transfer of wood and forest products.

The RFID technology is commonly used in the automobile industry in such manufacturing – assembly plants as Toyota, Volkswagen, Ford [Schmitt et al.

2006] to mention a few only. In all these cases the RFID tag is attached to an automobile, a body, a chassis, an engine of a vehicle and/or its other components and subassemblies during the manufacturing process. Thanks to that, all the vehicle’s elements moving along the technological lines of the manufacturing plant can be tracked and the progress of the automobile’s assembly can be monitored [Schmitt et al. 2006]. In addition, good practice in the automobile industry is to use an RFID technology to track and trace test vehicles and prototype parts during their piloting and examination tests [Schmitt et al. 2006].

As indicated above, RFID technology is widely used in logistics, including yard/warehouse management, inventory control of goods, monitoring of the movement of materials (raw materials, components, subassemblies, and finished goods) within distribution centres and whole supply chains and/or control the deliveries of the shipments [Finkenzeller 2010; Attaran 2007; Jones and Chung 2007]. RFID-based solutions are frequently used by express delivery companies, such as DHL, UPS, and FedEx [Kirch et al. 2017]. At the last link of the supply chain, i.e. in retail stores, RFID is used for item-level tagging which protects articles against theft by customers (shoplifting) and employees (“shrinkage”) through the application of electronic article surveillance (EAS) systems. Naturally, RFID technology also allows inventory control and automatic customer service (self-checkout process) at the exit counters of the retail stores (e.g. Wall-Mart, Ikea).

RFID technology is also applied in various areas of transportation, including ITS (Intelligent Transportation System). RFID readers are deployed at intersections, toll gates, or highway exits to track RFID tags as a means for monitoring the traffic flow, calculating average speed and average car flow level on each road. The collected data is transmitted through the wireless infrastructure (usually broadband) to one or several traffic management centres equipped with high-speed servers with database systems. Such an RFID-based system is used to control congestion on the roads and perform adaptive traffic control on different roads. It can be also interfaced with the dynamic navigation system that assists drivers in finding the shortest path through the transportation networks, including the rural and afforested areas. The system can also trace criminal or illegal vehicles such as stolen cars or vehicles with illegal wood loads [Floyd 2015]. These solutions could be also applied in the rural and afforested areas provided the RFID infrastructure is available there.

The rail and road transportation industries have also adopted RFID technology. RFID tags mounted on locomotives, wagons, passengers’ cars trucks or tractors and trailers are used to identify the owner, number, and type of equipment and its characteristics as well as the material/commodity being carried, including raw and processed wood. The technology helps identify the landing/consignment, origin, and destination of the trips/ movements, routes of materials/commodities being carried, and means of transport being used for transportation. In addition, it controls the utilization of the fleet and optimizes the movements of empty vehicles [Floyd 2015].

RFID technology is widely applied in agriculture for different purposes [Ruiz-Garcia and Lunadei 2011]. Classically, various agricultural products (e.g. bales of hay, boxes of tomatoes, or pallets of fruits) are tagged to capture the following data: date and the field of harvesting, product characteristics, such as the temperature, weight, moisture level, and the nutritional information. All that information is forwarded through the whole supply chain to monitor the condition of many perishable food products. The RFID technology is also used in agriculture for special purposes. Customized RFID tags and readers, resistant to humidity and high temperature are applied to control the operations of greenhouses. New technological developments based on RFID technology allow for the control of irrigation systems, specialty crops cultivation, and farm machinery technical diagnostic and maintenance. RFID is applied for plant health inspection, monitoring disease, and the resulting agrochemical management to reduce the proliferation of plant pathogens (e.g. grapevines, cypress trees). It is also used in many fields to avoid theft (e.g. cactuses) and develop cloning strategies (e.g. fruits, vegetables). RFID tags integrated with gas sensors (O_2, CO_2, ethylene) are used to monitor and evaluate the freshness and quality of fruits and vegetables (e.g. apples, broccoli).

An important and probably one of the oldest sub-components of the application of RFID technology in agriculture is the identification of animals [Ruiz-Garcia and Lunadei 2011]. The RFID tags implanted in animals (herds of cattle) were originally developed for large ranches and rough terrain in the USA, Canada, and Australia to monitor the cattle moving on grasslands. The importance of RFID technology has been noticed since the outbreak of mad-cow disease when RFID has become crucial in animal identification management. Since then the implantable RFID tags or transponders, often called PITs (Passive Integrated Transponders) tags have been extensively used in all continents. Currently, Australia is the leader in RFID applications for cattle, sheep, and goats.

As indicated by Sundberg et al. [2018], RFID technology can be also applied in the green energy sector, including the monitoring of biomass fuels throughout a supply chain. As proven by the authors the RFID tags attached to the wood pallets transporting the biomass can monitor the flow of material and capture all the logistics information associated with the transfer of the biomass. In addition, RFID tags can be used to transmit vital information concerning the fuel properties directly to the energy plant. The information about fuel composition and condition is critical to managing the combustion process in the furnace. It can be used to improve energy efficiency, reduce emissions and limit problems with fouling and slagging. In the study, the authors examined the detection of pallets containing 5% and 100% of peat in the biomass by the RFID technology.

It was concluded that the RFID tags can be indeed used to monitor the flue gas composition resulting from the different input materials. They also indicated that the marginal cost to implement an RFID system would be less than 1% of the total production cost of wood pellets.

Summing up, RFID technology is very popular in various industries and supply chains. It is perceived as an identification technology with many strengths and benefits. The following features of the RFID technology are highly appreciated:

a. non-contact data capturing,
b. high identification rate,
c. mass memory,
d. secured access,
e. increasing affordability,
f. ability to be easily integrated with the existing computer-based systems.

They constitute the major strengths of the RFID technology. On the other hand, there are also certain problems and concerns associated with RFID technology. The following characteristics are considered as its critical weaknesses:

a. relative high costs of the tags and the whole RFID system (compared to the barcoding system),
b. personal location privacy concerns and possible corporate/military security violation,
c. induction of certain health problems (e.g. tumors in animal tissues),
d. sensitivity towards material contamination, which might be essential in wood applications
e. relatively simple deliberate destruction (for instance in a microwave oven) generating in some cases side effects, such as fire,
f. limited universality of the RFID technology for different environments (metal detection, water – humidity).

Major characteristics of the RFID market. Comparison with alternative communication technologies

In the last 10 years, the monetary value of the world RFID market (both passive and active RFID) more than doubled. In 2010 the RFID market, including tags, readers, software development, and supplementary services for RFID labels, cards, fobs, and other form factors accounted for approx. US$ 6 billion and has grown since then at an average annual growth rate of 5% - 6% reaching the level of US$ 11.6 billion in 2019 and 12.2 billion in 2020 [Das 2020]. The further market extension is expected in the next years. It is forecast that the global RFID market should rise to US$ 13 billion by 2022 and US$16 billion by 2029 [Das

2020]. In the last several years the major contributors to the worldwide RFID sales are as follows: passive RFID tags – 45%, passive RFID interrogators (readers, transceivers, antennas) approx. 25% - 30%, passive RFID services, networking, software - approx. 20%, active RFID/RTLS (Real-Time Location Systems) – approx. 5%. As far as geographical structure is concerned the most attractive RFID markets are: North America with around 44% of total sales, Asia Pacific – 30% of total sales, and Europe with 20% of total sales [Das 2020]. Asia Pacific is expected to be one of the most lucrative regional RFID markets in the coming years with an annual growth of approx. 17%. In all the regions the key factors contributing to the market growth are safety and security, tracking of expensive products, and assets control. There are more than 50 worldwide major suppliers of the RFID technology, including CoreRFID, Globe Ranger, Impinj, and RFID4U.

The concept of RFID generated a series of new technological developments, including Near Field Communication (NFC), Bluetooth (BT), and Bluetooth Low Energy (BLE) [Finkenzeller 2010; Das 2020], all of which are considered to be short-range, high frequency, radio, wireless communication. These technologies allow for reliable wireless transfer of data between electronic devices (in particular mobile) at a distance of several cm (2-3 inches) up to 100 m. RFID is variable range technology (10 cm - 200 m), while NFC belongs to short-range communication technology available on mobile phones (< 20 cm). At the same time, BT and BLE constitute medium-range technologies (from 50 to 100 m). RFID technology speed varies. The slowest versions (~100 kbit/s) are slower than NFC communication, while the fastest versions (2 Mbit/s) are comparable with BT [Finkenzeller 2010; Das 2020]. RFID technology offers a wide range of frequencies (~150 kHz - 10 GHz), while NFC operates at mid-level frequencies (13,56 MHZ) and BT and BLE at high-end frequencies (2.4 - 2.5 GHz).

Wood Supply Chains and the Need for Wood Traceability

Specific Features of Wood Supply Chains

In a forestry context, the wood supply chain may be regarded as a series of handling and processing stages that begin with standing trees in the forest and end with final wood products [Dykstra et al. 2002]. As compared with other supply chains, wood supply chains do not seem to be very complicated. However, they are featured by a large number of assortments being produced in the same harvested area, and a large number of forest products originating from various sources being transported to various distributors and manufacturers of wood products. Forest operations result in the production of wood assortments ranging from large-dimensioned logs to energy wood originating from small branches or even parts of the root system of the harvested trees. Three basic wood supply chains can be identified: high-grade timber for the veneer and sawmill industry, industrial timber for the board, pulp and pellet industry, and energy wood for power plants [Erhardt et al. 2010]. These three different supply chains focus on wood biomass of very different dimensions, which suggests the usage of different handling methods, equipment, and processing installations.

The above-described basic supply chains refer to the generic forms of woody biomass procurement from a logistics point of view. However, realistic wood supply chains are more complicated and take into consideration logging and transport operations, together with diverse stages of wood processing towards end products. Given that wood products are transported in unimodal or innovative multimodal systems [Kogler and Rauch 2019] in large volumes and from various locations to a large number of intermediate and final users, organizing and maintaining an efficient chain of custody is a very difficult and costly task [Dykstra et al. 2003; Chiorescu and Grönlund 2004; Sperandio et al. 2017]. Theoretically, the manager of a wood supply chain (or of any link in that chain) should be able to determine where the wood supply is coming from, where it is at any point in time, where it is intended to go, and when it is scheduled to arrive there [Dykstra et al. 2002]. This knowledge is of special interest, given the complex nature of wood supply chains, where a large number of products are delivered to various interested parties. Data on tree species, volumes, and wood quality classes is essential, so that the manager may be able to trace the wood and wood products back to their forest origin.

In the case of the highly diversified wood chains, data records are gathered with different levels of generality. Hence, the high-grade timber process chain is highly individualized, due to its high monetary value. Every single log is recorded and marked with a single tag with information on its dimensions and quality characteristics [Murphy and Cown 2015]. On the contrary, the procurement of industrial timber differs in many aspects; it is sold in large quantities of pre-arranged stack wood (the typical length of approx. 2 meters), where individual marking is out of the question. Information is usually gathered from 1-2 tags on truckload (depending on how many stacks of wood were placed on the truck) arriving at a mill and later on it is used for delivery, inspection, and invoicing purposes. The smaller dimensions of the industrial timber of lower monetary value are suitable for other uses, such as mechanical or chemical pulping and subsequent processes into pulp, pellets, or more complex products such as composite wood panels. The least advanced wood marking occurs in the energy wood chain because the loose biomass structures impede tags' attachment and feasibility [Erhardt et al. 2010]. As a negative consequence of this fact, it is quite common that the direct origin of energy wood is largely unknown and its trade is subjected to increased control, particularly when energy wood is subsidized by national financial sources.

Nussbaum [2002] described the main principles of identification, segregation, and documentation that are necessary for any system designed to monitor the chain of custody of logs. According to these principles to set up an efficient traceability system:

a. the logs must be identified using some type of labelling technology,
b. at any point along the supply chain when logs from a known source could potentially become mixed with logs from unknown sources, the logs should be segregated and handled or processed separately,
c. labels affixed to the logs must be keyed to documentation so that information on species, volume, quality, and other attributes are available to managers of the supply chain.

An effort has been made and the above-mentioned principles have been implemented in log supply systems in Europe.

Need For Traceability

Hence, to have a good control of what is happening in a wood supply chain it is imperative that the respective "chain of custody" (COC) is well-known. More specifically, the term "chain of custody" refers to the custodial sequence that occurs as ownership or control of the wood supply is transferred from one custodian to another along the supply chain [Dykstra et al. 2002; Gilani et al. 2016]. It comprises a set of technologies, procedures, and documents that are used to provide information useful for managing the wood supply chain.

An important issue in the forestry sector is the legality of its basic product – wood - that is traded in the sector. Logging must be carried out correctly, following the forest management plan, in accordance with the law, and forest standardization schemes (i.e. PEFC). Unfortunately, the law may also be violated and timber from illegal logging may be placed on the market. Chain of custody systems can be used to expose log theft and prevent "log laundering" i.e. mixing illegally harvested wood with others of legal origin. Thus, the chain of custody systems can be essential components of any effort to reduce illegal logging, currently recognized as one of the major concerns among all countries worldwide with a total value of 100 bn € [Neslen 2015]. Fighting both illegal logging and illegal trade is very difficult and has important and adverse environmental, economic and societal impacts [Athanasiadis et al. 2013]. To meet the threats of dishonest players on the wood market, legal regulations have been introduced regarding timber trading [FLEGT 2003; Lacey Act 2008; EUTR 2010]. A way to recognize if a given batch of raw material has been legally obtained is wood traceability. Traceability is defined as the ability to trace the history, application, or location of an item or activity by means of recorded identifications [ISO 8402]. This involves two main aspects: on the one hand, identification of the product by marking; and, on the other, the recording of data regarding the product along with the production, processing, and distribution chain [FAO 2016]. Currently in numerous European countries, disposable plastic tags with some information are used to mark logs. For example in Poland on these tags, there are two numbers: one refers to the forest address from logs that were harvested; the second number is a consecutive number to ensure the uniqueness of the tag.

Further data on wood quality, dimensions, and origin of logs [Szaban et al. 2021] are included in a database that is managed by the forest managers/forest owners and can be accessed only after a special permit. Usually, the data is used to prepare the transportation documents which later are stored in paper form by the first raw wood buyers. However, the data transfer is often hampered, or even discontinued, along the further wood chain. The use of modern technologies allows for improving its operation. RFID - marking connects the physical objects - logs with their database counterparts thus allowing automatic tracking of the objects. Such an automatic traceability system makes it possible:

a. to utilize raw material information efficiently throughout the forestry-wood production chain,
b. to maximize the raw material yield,
c. to optimize and monitor the environmental impact, by linking the relevant information to the traced objects [Björk et al. 2011].

The wide access to information on wood and wood products as well as coordinated activities in the forestry sector, plus actions caused by the activities of third parties create a wood traceability system. In Europe a dominant role has two certification schemes – PEFC and FSC. These social and economic factors which vary regionally and among individual landowners further complicate managing a wood supply chain [Kelly and Germain 2020]. Modern consumers care more about the environmental impact of wood products than in the past. Various eco-labels have been introduced to consumers’ mistrust, however, there is some scepticism about whether these eco-labels truly deliver their purpose. On the contrary, there is evidence that wood product consumers find it easier to believe information based on traceability systems [Appelhanz et al. 2016]. When consumers come across information, which they value as ethical (e.g. wooden products coming from certified forests), their trust in the respective products is increased as well as their willingness to purchase them. Thus, traceability in wood supply chains seems to have the potential to be used as a marketing tool for capturing, processing, and provision of product information [Tzoulis and Andreopoulou 2013; Appelhanz et al. 2016].

The forest industry operates in a global market where effectiveness in all parts of the wood supply chain is crucial to stay competitive [Björk et al. 2011; Erlandsson 2013]. Still, efficiency gaps are detectable even in technologically advanced countries. It is estimated that wood raw material worth approximately 5 billion € is wasted annually in Europe [Sirkka 2008]. The major reason for this is that the raw material is not used most efficiently as information needed regarding the wood raw material is not available throughout the supply chain. Rauch and Borz [2020] examining the Romanian timber supply chain provided the basis for identifying the main weaknesses of insufficient electronic data processing support and set the stage for redesign to make processes faster, cheaper, or smoother. The lack of information on round wood quality thru the forestry wood supply chain has a monetary dimension: a better description of log quality and transfer of this information to sawmills may be of fundamental importance to produce more of the most valuable products, even adding the value of the product with 8.5€/m^3 [Nilsson 2009]. So, wood traceability can bring direct financial benefits to the forest industry because of the information it provides to the managers, both at the forest and factory level, effectively tracing raw wood from stump to mill as well as storing and managing properly a high volume of data [Picchi et al. 2022].

Current implementations and status of RFID technology in wood supply chains

The important characteristic of RFID-based tags is that they do not require a line of sight between the transponder and the reader (RFID antenna), which could be very decisive in overcoming the limitations of the conventional and automatic identification approaches, such as barcoding, which are widely used in the forestry/wood industry [Chiorescu 2003]. RFID systems can work effectively in hostile environments such as in forestry and sawmills, where excessive dirt, dust, moisture, and poor visibility would normally hinder rapid identification. On the contrary, fast response times of less than 100 ms, can be achieved, in most cases, given that the right combination of RFID equipment is set up.

Once this is done, the identification of wooden products can run from this point on without the need for more personnel responsible for the manual scanning of the products, saving significant costs to the companies [Chiorescu and Grönlund 2004].

RFID technology in different stages of wood supply chains (From marking to final product)

Tree marking

In the large majority of cases, tree marking is carried out to facilitate wood harvesting by providing safer and easier identification of the trees that will be felled. Conventional marking is carried out in various ways, including metal tags, or in some cases is limited to painting. Initially, the use of commercially available RFID transponders in the marking of trees has been experimented [Mohamed et al. 2009]. The conclusion derived from these trials was that the commercial transponders were not very well suited for large-scale tree or log marking as they were not designed for this purpose [Björk et al. 2011], suggesting the need for new designs with improved characteristics.

Long-term ecological studies in natural populations of tree species require marking techniques that enable the easy relocation of trees over time. Using GPS coordinates in combination with physical labels can be problematic, especially under difficult conditions. Marczewski et al. [2016] tested passive, semi-active and active RFID tags and readers as a means to relocate individual trees. Active RFID tags performed best and should be considered for use in conjunction with other marking techniques such as physical tags and GPS coordinates.

Tree marking can be also used to promote precision forestry by making possible the storage and easy retrieval of various information fields from standing trees. In this context, detailed tree profiles including data on tree location, size, species, age, growth dimension, growing environment, health status, and maintenance needs, vital to forest managers can be easily accessible. More specifically, RFID tagging can be used as a link between physical items (trees) and the information related to digital inventory systems generated with the support of aerial and terrestrial sensors [Pichler et al. 2017]. In this case, manual identification of trees may provide further support to precision forestry applications in the areas where the global navigation satellite system (GNSS) cannot be used with adequate accuracy, a condition relatively frequent in a forest, particularly in mountain areas [Zimbelman and Keefe 2018].

Apart from the obvious advantages, more practical aspects of RFID implementation have to be solved. Fixing the tags is the first depending on the system used. Stapling is easier and faster compared to a manual screwdriver, particularly when two screws are demanded, as in the case of larger tags. Also, flat and clean surfaces are suggested compared to the rough and unstable bark surfaces.

RFID tags fall into two large categories: non-rigid and flexible ones. RFID tags with non-rigid shells, suffer deformation when applied directly on a rough and irregular surface as the bark of a tree. This deformation alters the geometry of the transponder, and consequently its communication with the interrogating antenna. For this reason, before the application of the tag on the bark, the main irregularities should be flattened off. This issue will be more important on trees with thick and irregular bark (e.g. most conifers, oaks) than on species with smooth bark (e.g. beech).

Several flexible models, such as short dipole types, are typically elongated in shape. If applied adhering horizontally on the tree, the tags will suffer a bending effect, which is more pronounced in smaller diameters trees. Picchi [2020] during field tests observed that bent transponders were still operative, but by increasing the bending angle, as it happened in smaller diameter trees, the returned signal decreased strongly. For this reason, it is advisable to place tags vertically on the trunk, thus causing no or limited bending to the transponder.

Srinivasan and Ranganathan [2013] used RFID technology to monitor sandalwood trees continuously and to control the smuggling of this valuable species. RFID tags were placed on the trees and were continuously monitored by RFID readers. If a tree is cut by an unauthorized person, sensors will trigger the transceiver to transmit the tag ID with an alert signal to the control room. To make this possible, ZigBee, an open global standard for wireless technology developed to address the unique needs of low-cost, low-power wireless IoT networks, has been used in combination with GSM technology. It should be noted that this low-cost solution could be relatively easily implemented in developed countries but its cost would still be prohibitive for developing countries.

Raj et al. [2019] developed a system that can detect intruders into forests and also an alert system that can warn those officials who can further take action into arresting them. For this, they embedded a module of Object Python Programming in cameras installed in forests. As soon as a human figure was detected by the module algorithm, the RFID technology was used for the identification of authorized officials, all of which were previously provided with dedicated RFID tags. Humans entering the forest without a valid RFID tag were identified as intruders and photos and details of their location were sent to forestry officials using a GSM module. A second option included the transmission of an audio message to the walkie-talkie equipment of the forestry officials. During this project, solar power was used as the energy source that warranted the continuous operation of the camera and the GSM module.

During the manual identification of RFID tags on standing trees, positioning the reader at a minimum distance and perpendicular to the tag assures a 100% of reading rate. However, during the felling is performed, the initial RFID tag originally placed on the standing tree should be moved to the felled stem or paired with a new tag on it. In the case that multiple assortments are produced, new RFID tags should be attached to each wood assortment.

Tree felling and processing

The large majority of existing literature consists of RFID trials in wood supply stages that take place during tree felling and processing or the survival rate on processed logs. Using RFID under the harsh conditions of the wood supply chains sets good readability and long reading range as a precondition for further implementation. The RFID tags attachment in the crosscut section provides the most reliable reading conditions, by reducing the risk of accidental removal of the RFID tag from the tree [Picchi 2020]. For quite a lot of time, effort has been made that the above-mentioned principles/experience have been implemented in log supply systems. Thus, the high-grade timber process chain is highly individualized, due to its high monetary value. Every single log is recorded and marked with its dimensions and quality characteristics [Murphy and Cown 2015].

On the contrary, the smaller dimensions of the industrial timber make it suitable for other, lower monetary value, uses compared to those of the high-grade logs; such uses include mechanical or chemical pulping and subsequent processes into pulp, pellets or more complex products such as composite wood panels. The procurement of industrial timber differs in many aspects; it is sold in large quantities of pre-arranged cordwood (typical length of one or two meters), where individual marking would be out of the question. Information is usually gathered from truck loads arriving at a mill and it is later used for delivery, inspection, and invoicing purposes. Marking is least advanced in the energy wood process chain because the biomass structures impede attachment and feasibility [Erhardt et al. 2010], with the exception of slash bundling [Spinelli 2021a] where marking could be easily implemented. Also the origin of biomass for energy purpose is of various sources, both from forestry [Mihelič et al. 2018; Szewczyk and Polowy 2020], agriculture sources [Dyjakon et al. 2020], and urban tree resources [Nowak et al. 2019]. Hence, it is quite common that the origin of energy wood is largely unknown.

Wood products traceability must take into consideration the two distinct all methods the harvesting operations are carried out, motor-manually, semi-mechanized and highly mechanized [Spinelli et al. 2021b]. In the first case, the attachment of the RFID tag is done by means of a specially designed axe, hammer or tagging stapler and must be easy to operate [Häkli et al. 2010]. In highly mechanized harvesting, the deployment of RFID technology can be combined with multiple sensors resulting in large number of benefits. Picchi et al. [2022] equipped a wood processor with sensors that made possible the identification of surface defects, the estimation of timber density, cross-cutting resistance and branches number with their approximate position. This valuable information was then stapled in the form of a RFID tag in each log individually. The RFID tagging device was attached on the harvester head. This is the optimum position for tagging the logs, since even small delays during this highly automated process may have a large impact on the efficiency of forest operations.

A complete RFID system in forestry is expected to have the following IT architectural elements:

a. data generators (measuring devices), e.g. harvester, log/board scanner,

b. marking/reading information devices, e.g. RFID tag, barcode, printed code,
c. central and local databases for storing information,
d. software for processing, analysis, and simulations.

Readability rates of 99% are the acceptance threshold [Häkli et al. 2013] but such results have been reported only for relatively small-scale studies. Under real conditions readability rates are in the range of 95%, which, although high, entails a large error potential for the forest industry. This suggests that more research is necessary on this topic. Furthermore, the reading range is affected by the frequency range used [Finkenzeller 2010]. Low frequency (LF/e.g. 125 kHz transponder) has a reading range of up to one meter, high frequency (HF/e.g. 13.56 MHz transponder) may reach 1.5 metres whereas ultra-high frequencies (UHF/e.g. 868 MHz transponder) allows effective reading ranges of several meters in operative conditions with passive tags [Korten and Kaul 2008; Tzoulis et al. 2014; Kaakkurivaara and Kaakkurivaara 2019]. On the other hand, LF transponders are relatively resistant to metals and liquids, HF transponders are strongly influenced by metal environments and UHF transponders are strongly influenced by both liquids and metals in their proximity [Korten and Kaul 2008; Picchi et al. 2015]. Furthermore, wood attributes such as the humidity and amount of water in a log of wood decrease the RFID tag antenna efficiency, which requires a stronger radio frequency (RF) signal to operate [Santos et al. 2014]. Thus, the choice of RFID type should be done after considerations of the working environment and not only on the basis of a single performance factor.

To make use of the considerable potential of RFID tags in forestry applications, a precondition is that RFID tags have a high survival rate of the harsh conditions from the felling site to the processing facility (e.g. sawmill) [Kaakkurivaara and Kaakkurivaara 2019]. The results of current studies are very positive with survival rates in the range of 91% - 98%, depending on the type of equipment and harvesting methods used [Picchi et al. 2015].

Kaakkurivaara and Kaakkurivaara [2019] have developed a testing method for use as a decision-making tool by RFID users. Five tests that considered climatic aspects, mechanical stress, readability and survival in the field, were used to evaluate the applicability of eight kinds of tag housing for forestry applications. The method was found to perform well with the tested tag housings and was suggested by the authors to other potential RFID tag users who wish to determine the most appropriate tag housing for their forest applications.

Kaakkurivaara [2019] reported that RFID outperformed barcode or conventional hammer branding for marking teak logs and storing data on quality and assortment classification at the roadside log yard; RFID tags offered greater durability in logging operations compared with barcodes and were less time-consuming with fewer errors compared with hammer branding. This came as a result of the much higher tag readability compared to the other methods; RFID reading time ranged from less than a second to 5 seconds depending on the moisture and dirtiness level (low, medium and heavy) whereas in the case of barcode it ranged from 10 (low level) to 60 seconds (medium level) and was impossible under the harshest conditions (heavy level).

RFID implementations in wood supply chains

The adoption of RFID in wood supply chains is rather limited compared to other sectors. Nevertheless, research results have indicated the potential behind RFID implementation and in some cases, the benefits are considerable and outperform other technologies.

Zhao et al. [2011] presented the case of the MHG system, a Finnish supplier of ERP systems for biomass material energy production. They implemented RFID tags in the form of nails or buttons on processed logs, RFID readers for the input and output of logs, RFID readers for log stock regions and positions, hand-held mobile RFID readers and log stock plates attached with RFID tags. To guarantee precise information flow in the log circulation, all radio readers were connected to the internet. RFID information was coupled with information from other sensors, such as GPS positioning, tracking of vehicles, records of fuel consumption, and CO2 emission. The implementation of this system in Finland and Russia resulted in a 5 - 10% moisture content decrease of the transported biomass, and reduced fuel consumption and CO2 emission of vehicles by 8-15%.

Santos et al. [2014] reported a very interesting case of RFID implementation in a railway crossties supply chain in Brazil under the scope of examining the life cycle characteristics of the specific product. The use of RFID tags in sawn wood, even under the harsh conditions that crossties operate, can yield many benefits, both for logistic processes and traceability. However, there are many technological challenges to overcome due to the adverse conditions of use, especially moisture, impact, vibration, and wood deformation, e.g. [Kamaguchi et al. 2001]. More research has to identify the proper tags and the best ways to install them. For optimum results, all stages of their life cycle should be monitored, starting from the marking of standing trees to the disposal of all resulting products.

In timber supply chains, one of the main obstacles to the implementation of marking systems, in general, is the specific requirements of the end-users. Sawmills would not accept timber with attached elements that could damage the sharp tools used in the industrial process. Furthermore, tags attached to the log surface would end up in the stream of processed wood chips, the typical by-product of sawmills, which are used either for pulp or energy production. In both cases, the presence of contaminants such as plastic or metal could limit or even prevent the acceptability of this material [Picchi 2020]. Innovative materials can also be used that offer a combination of good protection to the transponders and are also pulping compatible and biodegradable, posing little danger to the expensive factory equipment [Häkli et al. 2010]. In this context, dedicated solutions as developed by Ali et al. [2020] in the form of an inexpensive, chipless RFID tag in a compact dimension of 2.6 cm^2 are suggested for biomass pellet tracking and monitoring. A lot of research effort has been undertaken to reduce the cost and complexity of the RFID tags by storing the information data without a storage device, which has resulted in chipless RFID tags. These tags store the data in its geometrical structure, which consists of backscatters or resonators. Moreover, the authors reported as future aims of their research the integration of ambient humidity, temperature, and CO_2 level sensors by using fully passive chipless RFID tags.

Sundberg et al. [2018] demonstrated that RFID technology can be used to enable traceability of bulk biomass fuel throughout a fuel supply chain. However, the RFID system has to be optimized according to the biomass fuel characteristics, by proper configuration of the type and quantity of RFID tags. The authors concluded that the physical characteristics of the tags are also important to trace the bulk pellet flow sufficiently along the supply chain. Finally, the marginal cost to implement an RFID system would be less than 1% of the total production cost of wood pellets, a reasonable result from a financial perspective.

Figorilli et al. [2018] used RFID and open-source technology to develop and implement a blockchain architecture for electronic traceability within the wood chain. The development of this digital ledger involved different kinds of open source devices and tags, which were coupled with a specific app that facilitated the collection and storage of information in a centralized database. Similar research efforts can reduce or even abolish lack of information, by enabling real-time visibility into supply chains [Picchio et al. 2019], increasing customer trust and combat illegal logging.

Cost considerations

The Auto-Identification feature of RFID technology may play an important role in the future for tracking standing trees to prevent illegal logging. However, the introduction of new technology in any industry is associated with multiple changes and new cost factors which include all equipment purchase and installation, personnel training, and also partial reorganization of the material and processes flow in an enterprise [Banks et al. 2007]. As production cost is of paramount importance to all production sectors, adopting RFID technology is an extra cost that should be well justified. This cost can be a big capital investment for small- and medium-sized companies and a cost-increasing agent for large companies. Gjerdrum [2009] estimated that the annual cost for a sawmill utilizing RFID technology would be US$60.000–US$450.000 depending on mill size. For this reason, RFID currently is still used, almost exclusively, in high-value products, e.g. utility poles.

A study in Calabria [Sperandio et al. 2017] showed that the combination of RFID technology and open-source technologies for wood traceability led to an increase in timber price by 8% under the worst scenarios (average market prices for timber ranging from 80-120 €/m^3). However, this increase can be economically sustainable, as 40% of private companies stated their willingness to pay a premium price (on average 3.25% higher) for purchasing certified local wood products. Moreover, it is expected that the price, power, and availability of RFID will improve rapidly in the future [Bhattacharyya et al. 2010].

The cost of tags reflects the complexity of the protective case. Heavier and more complex industrial tags have unitary costs always above 1 €, whereas, simple tags have a much lower cost than can be below 0.5 € in case of large quantity purchases (batches larger than 20,000 tags) [Picchi 2020]. Despite its benefits, there is still some skepticism about the economic benefits coming of RFID implementation [Tucker et al. 2014]. Kaakkurivaara [2019] reported an acceptable cost of 0.42 €/tag, which is consistent with previous studies by Timpe et al. [2012] and Hogg [2012], who concluded that a suitable cost per RFID tag is 0.39 and 0.56 €/tag, respectively. A lower tag cost equates to a greater profit per unit and reduces the timber volume that must be produced to break even [Kaakkurivaara 2019]. Developments in RFID technology leading to price reductions are expected to facilitate its adoption by the forest industry.

RFID seems to be the most promising method for marking logs. Unfortunately, there is a lack of Return-on-Investment (ROI) studies on RFID deployment in wood supply chains. ROI analyses can be a convincing tool for the wood industry by evaluating whether an investment is profitable over a while [Sarac et al. 2010]. According to Goel [2007], understanding the ROI of RFID implementation, preconditions that an organization must first understand RFID technology, then understand potential uses of RFID in their environment, and finally decide how to invest. The deployment of RFID in whole supply chains can also involve sharing the costs; this serves as a strategy to maximize the total supply chain profit [Gaukler et al. 2007]. Successful implementation of this cost-sharing strategy has been reported for Wal-Mart, which is 2005 asked its largest 100 suppliers to use RFID and shared the costs with them [Wang et al. 2008].

The future of RFID technology in the context of an information-based precision forestry

During the last decades, we evidenced an unprecedented collection, analysis, and usage of data in most production sectors. Wood supply chains are no exception although there are still many fields that require further effort and implementation. We still have a long way to go until the “virtual forest” target is reached [Rossman et al. 2009], where large amounts of information are gathered, and analyzed, to optimize forest management and utilization. In this context, RFID seems to be a good candidate for applications linking the real to the virtual forest [Picchi et al. 2022]. By being a mature technology in terms of implementation volumes and, at the same time, a technology under constant development, it combines two characteristics that can facilitate its wider adoption in forest applications to a much larger extent than is today. RFID technology can be implemented at various levels: at the tree level, during harvesting operations, and in the wood supply chain.

Two preconditions for successful implementation of the following suggestions include the undistracted flow of information streams and their fusion at all forest management levels. Once the flow of information is disrupted the implementation of information-based precision forestry including RFID technology cannot be expected. Furthermore, it is the fusion of information streams that will considerably upgrade our optimization potential in wood supply chains. It should be noted that these two preconditions are currently met only in a few parts of the world, such as the Nordic countries, where a) the wood origin is from local sources, and b) fusion of information is progressing but, still, is, especially at a commercial level, rather limited.

At the standing tree level, RFID can function both as an information storage and a data collection device (e.g. wood properties). The first application is well known and of benefit to WSC as a tool against illegal harvesting. Considering the large demands in RFID tag numbers and the respective cost considerations, passive tags should be used. Small tag dimensions can also be an asset, making them invisible to humans and fauna to minimize, among others, tag losses. By knowing the origin of tree logs or biomass we will fulfill the demand for traceability in forestry.

Furthermore, even at standing tree level, RFID has the potential to capture information on tree vitality and wood quality with the inclusion of special sensors. This option allows us to store information regarding the quality attributes as well, in addition to spatial information and quantity attributes of wood products on tags, which will be available to all further stages of the wood supply chains. As an optimization principle of taking the best decision the fastest possible, we can have traceability of wood quality through a continuous flow of information starting from, still standing, trees. Managerial decisions can be more effective, especially when forest health-related problems are timely reported, as in the case of bark-beetle outbreaks or mistle-toe in Poland. The implementation of such applications is now easier than ever through the IoT which allows cyber-physical systems through physical objects to collect and exchange data [Chen and Chen 2016]. In addition, the emerging networked tags [Gorlatova 2013] may fundamentally enhance RFID tags by enabling communication among tags

[Margolies et al. 2015]. Therefore, RFID technologies integrate data collection, storage, and simple communication, and provide a simple and cheap way of connecting physical objects to the IoT [Chen and Chen 2016].

Wood harvesting operations can also benefit from RFID applications at two levels, by communicating and storing information from sensors attached to forestry equipment [Mavridou 2019] and by including sensors, as well. Both aiming at the, currently missing, the inclusion of wood quality information, may replace and improve the visual inspection of logs and optimize timber grading and further processing. More specifically, RFID tags can be easily combined with sensors such as metal detectors attached to the harvester head to store the result of the scanning process for hidden objects. This is expected to improve wood quality assessment but also prevent damage from e.g. nails trapped in the wood to machinery both at the harvesting site (harvester head) and, later on, at the wood mill. Mechanized harvesting systems comprise very promising platforms for the expansion of RFID implementations, as previous research has shown.

Progress has been made concerning the digitalization of wood transportation, since the importance of good logistics in the complex forestry sector has been recognized [Carlsson and Rönnqvist 2005; Rönnqvist et al. 2015; Baghizadeh et al. 2021]. The main steps toward digitalization include the usage of GPS equipment and the usage of certain gates where the RFID-tagged wood freights can be scanned. However, almost all cases refer to truck payloads and not individual logs. RFID technology can contribute even to this stage by providing, in addition to location, a complete inventory of the transported biomass, enriched with important information on wood moisture and wood quality. As this information will be available before the harvesting operations the payload efficiency of wood supply chains can be further optimized. Thus, the wood traceability, often, among various transporting or processing companies can be guaranteed along with minimizing waste. The most demanding problem is the traceability of comminuted woody biomass. Theoretically, the origin of the woody biomass can be known if it is transported in separate containers according to their place of origin, however, this solution is not a practical one. A proposal for overcoming this shortcoming is the use of rewriteable RFID tags on which, all changes in the transported biomass will be recorded. Every time a change to the payload takes place, most notably, to reach the loading capacity of the truck, specialized sensors will monitor biomass weight and moisture and will store the respective data. By doing so, the origin of the transported material will be known and an estimation of the proportion can be done, depending on the accuracy of the sensors involved.

Conclusions

The advancing digitalization in the forestry sector is making use of Information Technologies and promising research results will facilitate this trend. In the coming years, RFID technology can be used in many more applications than it currently is, supported by technological advancements. Significant ecological and economic benefits are to be expected, including guaranteed traceability, more automatic and reliable timber grading, waste minimization, and higher payload efficiency, among others.

Whereas the future technological advancements are to a large extent still unknown, some can considerably enhance the economic and ecological efficiency of wood supply chains. Such advancements include the development of small-dimensioned, passive, or highly energy efficient RFID tags that encapsulate sensor technology and easy communication with IoT devices at low cost. Another problem that has to be solved refers to low-cost, automatic, tagging of trees and logs. The potential of RFID tagging has to be expanded to all types of forestry equipment, including e.g. feller buncher models. The development of biomass-based tags is another point of interest to forest management and should be also pursued in future research efforts. The latter topic of eliminating material contamination is of particular importance primarily to the pulp and paper industries.

The current situation could be described as having limited, both in terms of volume and numbers, forest RFID applications, in some parts of the world. This stresses the need for closer cooperation among forestry supply chain partners and academia. Whereas the high cost of RFID tags can always be regarded as the main obstruction to wider adoption of RFID technology, the need to communicate the benefits of RFID can be catalytic to overcoming this problem. As evidenced in other production sections, a safe way to reduce the costs of new technology is by increasing its usage and range of applications over time. The first step in this direction is to follow the „lowest hanging fruit approach” in which large benefits can be succeeded with, relatively, low-cost and not technically demanding RFID applications. This approach can differ country-wise, concerning the special attributes and needs in any case.

Finally, preconditions for having an information-based precision forestry and supply chains are the continuous flow of information and the fusion of information at all levels. The emergence of trees, tree logs, or woody biomass quantities as units of reference, that are accompanied by various fields of information, can become a reality, with some restrictions, and, transform forest management and utilization. The analysis of such big data has to be continuous and will bring transparency to the forest supply chains. The above-mentioned proposal for wider RFID implementation could be described as basic considerations. Along with the technological development and wider implementation, more advanced problems may emerge such as security issues that will have to be properly addressed.

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List of standards

ISO 8402:1994 Quality management and quality assurance – Vocabulary

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