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RESEARCH ARTICLE

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Overview of MPC applications in supply chains: Potential use and benefits in the management of forest-based supply chains

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Abstract

Aim of study: This work aims to provide an overview of Model Predictive Controllers (MPC) applications in supply chains, to describe the forest-based supply chain and to analyse the potential use and benefits of MPC in a case study concerning a biomass supply chain.

Area of study: The proposed methods are being applied to a company located in Finland.

Material and methods: Supply chains are complex systems where actions and partners' coordination influence the whole system performance. The increase of competitiveness and need of quick responses to the costumers implies the use of efficient management techniques. The control theory, particularly MPC, has been successfully used as a supply chain management tool. MPC is able to deal with dynamic interactions between the partners and to globally optimize the supply chain performance in the presence of disturbances. However, as far as is authors' knowledge, there are no applications of this methodology in the forest-based supply chains. This work proposes a control architecture to improve the performance of the forest supply chain. The controller is based on prediction models which are able to simulate the system and deal with disturbances.

Main results: The preliminary results enable to evaluate the impacts of disturbances in the supply chain. Thus, it is possible to react beforehand, controlling the schedules and tasks' allocation, or alert the planning level in order to generate a new plan.

Research highlights: Overview of MPC applications in supply chains; forest-based supply chain description; case study presentation: wood biomass supply chain for energy production; MPC architecture proposal to decrease the operation times.

Keywords: biomass; forest; Model Predictive Control; planning; supply chain.

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Introduction

A supply chain is characterized by a set of inventory and entities, in which are included producers, suppliers, distributors and retailers, where materials are transformed in products and delivered to the final customer (Eshlaghy & Razavi, 2011; Al-e-Hashem *et al.*, 2012). Raw materials, intermediate or finished products flow between geographically distributed facilities, which acquire, transform, store or sell them (Mourtzis *et al.*, 2008), existing a direct flow of material and an inverse flow of information (Eshlaghy & Razavi, 2011; Al-e-Hashem *et al.*, 2012), as presented in Figure 1.

With the increase of economic globalization, competitiveness and need of quickly respond to customers demand, the management of supply chains is acquiring importance in many companies and sectors (Petrovic *et al.*, 1999; Eshlaghy & Razavi, 2011; Li *et al.*, 2010; Rong *et al.*, 2011; Al-e-Hashem *et al.*, 2012; Badole *et al.*, 2012; Li *et al.*, 2012; Park & Jeong, 2014). However, supply chains are complex systems and their management depends on the level of knowledge acquired about them (Janamanchi & Burns, 2013). Besides that, the control and management of a supply chain is an area with many and rapid changes, developing day by day, as is shown in the literature (Petrovic

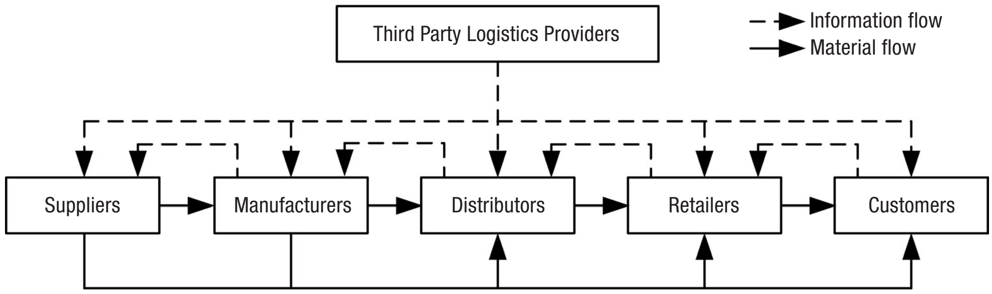

Figure 1. Supply chain flows (adapted from Min & Zhou, 2002).

et al., 1999; Eshlaghy & Razavi, 2011). The concept of uncertainty is also often related with supply chains, requiring more flexibility and so making the management more complex (Mentzer *et al.*, 2001; Vorst & Beulens, 2002).

The goal of a management system is to reduce the processing and delivery times, with the increase of products and services quality. The use of efficient management techniques will allow the reduction of production cost, inventory, supplying and service costs in each process (Eshlaghy & Razavi, 2011). In some companies, the incorporation of management techniques represented cost savings of 5-6 % (Huang *et al.*, 2009).

The functions performed in a supply chain are interdependent. In this sense, an entity's inefficiency implies a decrease in the overall performance (Stevens, 1989; Swaminathan *et al.*, 1998; Vorst & Beulens, 2002). In this way, the enterprises should integrate their objectives and activities to optimize the whole supply chain. If each enterprise tries to optimize its performance, the supply chain will become under-optimized (Vorst & Beulens, 2002; Eshlaghy & Razavi, 2011; Park & Jeong, 2014). Thus, in an integrated point of view, the flow of material must be optimized, i.e., the products must be produced and distributed in the adequate quantities, places and times, with minimized costs to satisfy demands. The information flow between supply chain members is also an important issue, as it influences the production schedules, inventory control and delivery plans (Lee *et al.*, 1997; Eshlaghy & Razavi, 2011; Park & Jeong, 2014). However, if the supply chain is multi-business oriented, this integration and coordination reveal themselves complex (Stevens, 1989; Parmigiani *et al.*, 2011; Park & Jeong, 2014). Furthermore, the previous goal of long-term optimization has been replaced for short term fluctuations in products' demand. Thereby, the supply chain management, in many cases performed by static models, needs to employ new dynamic and complex tools (Laurikkala *et al.*, 2005).

The sustainable management of supply chains is also receiving more attention (Parmigiani *et al.*, 2011; Seuring, 2011). The wood, as a natural resource, is integrated into this range of management. However, at the present, does not exist a common consensual definition of the forest sustainable management. This sector management should attend to aspects such as ambient preservation and future sustainability, always aiming profit maximization (Guinard *et al.*, 1998; Varma *et al.*, 2000; Alonso-Ayuso *et al.*, 2011). Besides that, requirements imposed by the industry, government, public, products, recreation, conservation, and preservation laws have increased the complexity of forest-based supply chain management (Beaudoin *et al.*, 2008).

The control techniques have been successfully applied to the supply chain management due to their ability to handle with systems dynamic behaviour. The MPC (Model Predictive Control), an advanced control methodology, has distinct characteristics that give it advantages in the treatment of such problems. Although this technique has already been applied to supply chains management in several areas, this has not happened in the forest industry. Therefore, this work proposes the analysis of the potential application of MPC to the forest-based supply chains management.

This paper is organized as follows: in section 2 is elaborated a review of the state-of-the-art of MPC application in supply chains, also presenting a brief overview of MPC concept. Section 3 presents the forest supply chain, describing its main processes, participants and faced problems. Section 4 describes the potential use of MPC techniques in the forest-based supply chain, particularizing for an use case in the biomass sector. Finally, in section 5 are drawn the main conclusions.

MPC application in supply chains

As previously mentioned, a supply chain management consists of a set of approaches that efficiently integrate the several entities involved in demand satisfaction at the lower possible price (Fu *et al.*, 2014). Thus, the global performance is highly dependent on the coordination and actions of each contributor (Perea-López *et al.*, 2003; Maestre *et al.*, 2009). In the current paradigm, enterprises do not compete with each other in the same supply chain. Instead, they act as a whole and are the supply chains that fight for leadership. The one that provides to the customer the intended products in the right conditions of quantity, time, place and price will stand out (Braun *et al.*, 2003). However, the supply chain is a complex system, where the influence of many factors should be studied and considered in its management (Fu *et al.*, 2014).

Traditionally, in supply chain management have been used heuristics or mathematical programming techniques (Li & Marlin, 2009). A common optimization method in supply chains is the individual analysis of the constituent elements. This ignores the fact that there are dynamic interactions between the several entities and that optimization should be performed as a whole. Control techniques are adequate to deal with these dynamic interactions of the system and, therefore, to optimize supply chains performance, often subjected to time varying demand conditions (Mestan *et al.*, 2006). In this sense, control theory has been used as a management tool due to its ability in dealing with uncertainty, delays and lack of information (Blanco *et al.*, 2008; Sarimveis *et al.*, 2008; Hai *et al.*, 2011; Ivanov *et al.*, 2012), which occur in supply chains.

The implementation of MPC (Model Predictive Control), also designated as rolling-horizon planning, receding-horizon control, dynamic matrix control or dynamic linear programming, in inventory control and supply chain management has revealed itself an interesting option (Braun *et al.*, 2003; Miranbeigi *et al.*, 2010; Wang & Boyd, 2010; Hai *et al.*, 2011; Fu *et al.*, 2013). Its main characteristics and advantages are: a cost function that measures the supply chain performance that can be maximized or minimized, MPC can be formulated to be stable and robust even in the presence of disturbances and stochastic demand (Wang *et al.*, 2007; Puigjaner & Laínez, 2008; Fu *et al.*, 2013). Also, it enables the integration of constraints in production, inventory levels and dispatch capacity, and defines operational objectives concerning how the following/monitoring of inventory goals and responses to customers' orders are achieved (Wang *et al.*, 2007), among others.

The operating principle behind MPC is based on the online optimization with a sliding prediction window that evaluates a cost function for the control action determination (Seborg *et al.*, 2004; Camacho & Bordons, 2007; Alessandri *et al.*, 2011). Namely, the MPC concept can be summarized as follows: a model of the system is used to predict, at each sampling instant k, the future outputs ($\hat{y}$) over a determined prediction time horizon P, as represented in Figure 2. The values of $\hat{y}$ depend on both the past inputs and outputs as well as on the past and future control actions. An optimization algorithm is used to maximize or to minimize a cost function to compute the future control actions, over a control horizon M, that will try to keep the system as near as possible to the set point (target), which can be constant or variable. From the evaluated set of control actions, only the first control action is effectively implemented. At each next sampling instant the whole process is repeated in order to update the model parameters and compute the next control action to

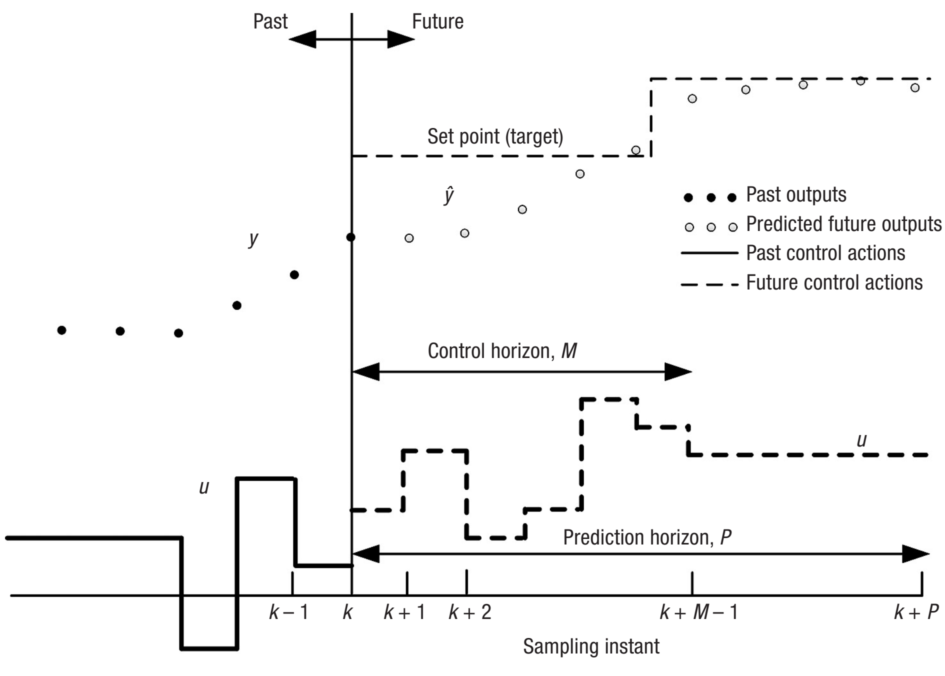

Figure 2. Basic concept of MPC operation (adapted from Seborg *et al.*, 2004; Camacho & Bordons, 2007).

implement (Perea-López *et al.*, 2003; Doganis *et al.*, 2008; Sarimveis *et al.*, 2008). The main advantages of MPC in supply chains are its ability to deal with variability in supply and demand and consider the future evolution of the setpoint and known disturbances.

In this context, a fundamental requirement of MPC is a supply chain model that adequately describes the dynamic behaviour of the system (Mastragostino *et al.*, 2014). Through this process model, the MPC will be able to react beforehand to possible disturbances (Wang, 2013).

The first application of MPC to inventory management was depicted in 1992, in the Kapsiotis & Tzafestas work (Kapsiolis & Tzafestas, 1992; Fu *et al.*, 2014). Afterwards, Tzafestas *et al.* (1997) applied MPC concept in decision support systems to solve integrated problems of planning and production in a stochastic environment.

In the Sarimveis *et al.* (2008) work it was performed a review of control theory application in supply chain management, considering its classical formulation and proposing other sophisticated methodologies, in which MPC is included. Follows the presentation of several developments made to this field.

In Bose & Pekny (2000), MPC was applied to planning and scheduling problems, enabling the integration of uncertainty in material processing time, random equipment breakdowns or uncertainties in demand. Unlike other techniques applied to these problems that fix a moment in time, MPC allows the time evolution monitoring of the system, i.e., allows its dynamic analysis. In this work, the predictive model calculates the goal of flow inventory while the scheduling model attempts to achieve the desired inventory levels in tasks. Thus, target inventory is the controlled variable and scheduling tasks the manipulated variables.

In the work of Braun *et al.* (2003) it was demonstrated the MPC applicability in supply chains management, emphasizing its robustness, flexibility and ability to reduce safety stocks. Its performance was proven in a problem with six nodes, two products and three echelons proposed by Intel Corporation, where existed demand uncertainty and model inaccuracies. Besides that, they showed the conversion of available information in the supply chain in MPC variables through an example of two nodes supply chain. With the application of MPC in the larger problem, the authors conceptually proved the efficiency of MPC handling with plant-model mismatch, constraints and information sharing.

To maximize profit in supply chains with multi-products, distribution networks with multi-levels with plants with multi-products, Perea-López *et al.* (2003) applied a predictive control strategy. In their work were compared centralized and decentralized management strategies, confirming increases of profit up to 15% on the centralized approach. The underlying methodology of their work encompassed a discrete dynamic model MILP (Mixed Integer Linear Programming) of the system with information and material flows, a dynamic optimization framework that considers all supply chain elements and respective interactions, and a predictive control approach that updates the decision variables when changes occur in the supply chain.

Seferlis & Giannelos (2004) applied the MPC principles in a control approach based on a two levels optimization of supply chains with multi-products, multi-echelons and independent production lines. As in a management system, the goal is to satisfy the customers' demands at the lowest operating cost. A penalty term is used to avoid abrupt changes. There were also used dedicated feedback controllers to keep the inventory of the several nodes between pre-set levels. The developed tool was tested presenting good performance for deterministic and stochastic variations in demand. In addition, was studied the influence of the delays in transport, the dimension of the control horizon and of the models quality in the control performance.

Dunbar & Desa (2005) demonstrated through a realistic simulation example the applicability of distributed nonlinear MPC to dynamic management of supply chains. This is based on local optimization of each subsystem and the corresponding result delivered to the adjacent subsystems.

Mestan *et al.* (2006) considered in their work a hybrid supply chain optimization through MPC, with continuous and discrete dynamics and logical rules. The system was modelled by MLD (Mixed Logical Dynamical) and the overall profit optimized by MPC. In addition, unknown but measurable changes were implemented in demands in order to examine the dynamic responses of the different nodes, i.e., assuming that at current instances demands are measured, but the future demands are unknown. Finally, were compared a centralized support decision scheme and two decentralized approaches. The results showed a better inventory management and production scheduling with the centralized configuration of MPC.

In Wang *et al.* (2007), the authors have implemented a MPC technique in tactical management problems encountered in the semiconductors manufacturing supply chain. Among the found problems, are emphasized the high stochasticity and nonlinearity in production times, demand and customer orders. The advantages of MPC were demonstrated using three benchmark problems. There were also tested the effects of model parameters synchronism by comparing robustness and performance metrics. Besides this work, in Wang *et al.*

(2004) and Wang & Rivera (2008), the same issue of MPC application in tactical decisions of semiconductor manufacturing supply chains management was also addressed.

Blanco *et al.* (2008) applied the MPC in the operational planning of a fruit industry supply chain. This choice was based on MPC's ability to deal with uncertain, multivariable and highly interactive systems. This type of supply chain, contrary to others, seeks to create a pre-delivery commitment, rather than respond to online demands. The work consisted in a computer aided decision tool that includes uncertainty and disruption episodes in short-term and medium/large term forecasts of important parameters (resources availability, costs, among others).

Doganis *et al.* (2008) developed a framework that integrates MPC and sales Time Series Forecasting for supply chain management. The data generated by the time series forecasts is used as inputs to the predictive control module. Several linear and nonlinear forecasting methodologies were tested, concluding that the time-series presented mostly a nonlinear behaviour. The results proved that the forecasting accuracy has impact in the control performance.

Given the need for competitiveness in the market and the need to deal efficiently with supply chain dynamics, Puigjaner & Laínez (2008) developed a supply chain integrated solution that incorporates design-planning and financial formulations. For this, it was used an MPC approach with stochastic optimization and an MILP model for problem representation. The developed solution was tested in a case study. The proposed control strategy proved to be efficient in dealing with uncertainty and incidences through the combination of reactive and preventive approaches. Also, this strategy may operate as a supervisory module contributing to close the information loop in the dynamic supply chain management.

Within semiconductors manufacturing supply chains, Huang *et al.* (2009) presented a testbed that integrates DEVS (Discrete EVent System Specification), MPC and KIB (Knowledge Interchange Broker) in a scalable and robust manner. The testbed was evaluated with different experiments, showing the benefits and challenges related to using and developing of manufacturing processes realistic models and processes control policies. The MPC control algorithm was based on a linear time-invariant model. Through simulations was proved that the MPC remains stable and robust even in the presence of uncertainty and nonlinear conditions.

To deal with real-time optimization of a supply chain with uncertainty, Li & Marlin (2009) developed a new robust MPC method. The method performance was proven by its application to a real industrial problem with multi-echelon, showing decreases in stock lacks without excessive inventories.

Integrated into the overall management of inventory at strategic and tactical levels, Alessandri *et al.* (2011) implemented an MPC approach in real-time decision in tactical transport. MPC was used to predict demand, in a reliable and short time manner. To maximize the supply chain profit, Niu *et al.* (2013) implemented an MPC method to predict demand and control the inventory in a single unit. As manipulated variables were defined the ordering and the pricing, with different dynamics in the supply chain. Ordering is seen as having a deterministic and a stochastic component. This strategy was compared to another without pricing dynamic policy and order-up-to-level showing its efficiency.

Subramanian *et al.* (2013) used distributed and cooperative MPC in supply chain inventory management. In this strategy, the local decisions of the several entities are taken based on the overall optimization of the supply chain. The solution was tested for an example with two nodes and compared with other conventional distributed operating policies. Still in inventory supply chain management, Subramanian *et al.* (2014) proposed the application of economic MPC with closed-loop properties. Besides that, demonstrated scheduling and control integration through an example of a manufacturing facility with multiproduct production.

Mastragostino *et al.* (2014) presented a support decision system for supply chain management based on a robust MPC strategy. This system was tested in two case studies with two processes and revealed a marked decrease in demands return. The work includes two uncertainty propagation mechanisms, one based on open-loop approach and other approximately closed-loop, i.e., a less computational expensive method to approximate the future closed-loop behaviour.

Besides the above-mentioned studies, many other works have been addressing this theme (e.g. Hai *et al.*, 2011; Fu *et al.*, 2013; Fu *et al.*, 2014; Han & Qiao, 2014; Kawtar *et al.*, 2014; Pannek & Frazzon, 2014). However, as far as is the authors' knowledge there is no example of MPC application to the forest supply chain. Based on the advantages presented with the application of MPC in other supply chains, it is proposed in this work the implementation of this technique in the forest supply chain, presenting a use case on biomass supply chain.

Forest-based supply chain

Forest planning problems are several and cover aspects from planting, cutting, construction of access roads to transportation, among others (Hachemi *et al.*, 2011). In these, it is necessary to attend to environmental and enterprise problems, as well as operation rules (Hachemi *et al.*, 2011). Furthermore, forest planning is performed in a stochastic environment without high quality information. This is due to the fact that information collection in this area, such as trees diameter, species, dimension and location of internal nodes, among others, is complex and expensive (Chauhan *et al.*, 2009).

At the beginning of the 70's, the forest management paradigm was mainly focused on stands and on trees, undergone a change with modifications of public perception about environmental issues. Since then, are being incremented management practices oriented to ecosystems (Heinimann, 2010), considering features such as wildlife, water, soil, landscape, etc. (Martins *et al.*, 2005; Marques *et al.*, 2011). Thus, forest planning, formerly simple and direct, become highly complex, with different planning levels, concerning large regions and small stands (Church *et al.*, 2000). This becomes even more complicated in multi-business environment (Bredström *et al.*, 2004; Beaudoin *et al.*, 2007). Besides that, with the new customer oriented forest supply chain approach, it is necessary to daily manage the ongoing operations (Palander *et al.*, 2005). This new approach aims to deliver the right products, at the right times and quantities (Carlsson & Rönnqvist, 2005).

Since the 60's, mathematical models have been used in forest-based planning problems (Goycoolea *et al.*, 2005; Beaudoin *et al.*, 2007). FORPLAN is probably the most well-known forest modelling system (Church *et al.*, 2000). Although many models have been developed, in many cases, the planning continues to be often based on intuition and experience (Beaudoin *et al.*, 2007). Even more, the commonly used approach is centralized, which is not the most indicated to multi-business contexts (Beaudoin *et al.*, 2010). The spatial component has also been present in forest planning because it has effects on wildlife, landscape and on other environmental issues. Among the common practices is the forbiddance, imposed by legislation, of large continuous clearcut areas (Goycoolea *et al.*, 2005).

Forest operations management deals with time scales ranging from a strategic level (decades) to an operational level (daily and hourly tasks) (Chauhan *et al.*, 2011). The highest levels of planning establish limits to the following levels. In particular, for example in the harvesting task, the strategic level set the volume of wood to cut in the next decades to achieve the forest management goal. At the tactical level are chosen which stands to cut in each period and which access roads to build based on the strategic goal. Finally, at the operational level are defined how many and which are the collection sites, roads are built and schedules are made (Clark *et al.*, 2000). At the tactical level are also defined the required production capacities. Through these, it is possible to the company determine whether to subcontract other companies for the year and define their work hours (Beaudoin *et al.*, 2008).

Figure 3 presents the generic processes of the forest supply chain. As can be seen, the first process to be considered is the harvesting in forest areas when trees are cut and branches removed. The species vary depending on the stands (Rönnqvist, 2003). By "stands" should be understood areas for forest harvesting at operational level. At the strategic level, these areas are called "macro-stands" (Cea & Jofré, 2000). Later, the forwarding process occurs, in which the logs are moved from the cutting areas to the proximity of access roads in the forest. Finally, the wood is transported to the desired site which can include sawmills, pulp-mills, paper-mills, heating plants and power plants (Rönnqvist, 2003).

The entities involved in this supply chain are several and can vary from country to country and depend on the addressed industry. Thus, as main actors can be mentioned: industrial forestry companies, public or private, which have forest lands and mills for processing; associations of forest owners, representing private entities and with their own mills, independent mills, without associated forest lands, and independent own-

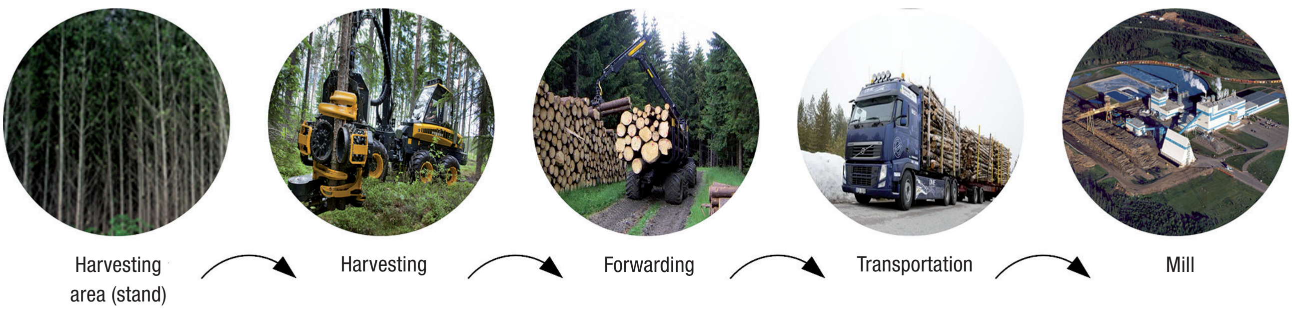

Figure 3. Generic scheme of the forest-based supply chain processes.

ers, not linked to any industry (Rönnqvist, 2003; Carlsson & Rönnqvist, 2005).

Harvesting planning aims to long-term tasks scheduling in order to maximize the cut volume and the profit respecting the imposed restrictions (Liu *et al.*, 2006). One of the restrictions of this problem is that some jurisdictions prohibit clearcuts, i.e., large areas cut (Brumelle *et al.*, 1998; Gunn & Richards, 2005). Moreover, stands adjacent to clearcuts cannot also be cut until the clearcut stand has regenerated to a certain level (Gunn & Richards, 2005). These adjacency restrictions complicated even more the process, partly nullifying the models previously used in harvesting planning (Brumelle *et al.*, 1998). This has increased the use of heuristics instead of mathematical programming in planning models development. However, with this technique it is difficult to find, with certain, the global optimum (Heinonen & Pukkala, 2004). Another relevant factor that also influences the annual planning of harvesting is the climatic conditions (Karlsson *et al.*, 2003; Karlsson *et al.*, 2004).

Another issue that must be taken in account is the increased use of mechanized equipment in the forestry sector. This is mainly due to the need for increase productivity, i.e., for economic reasons, and for increase security (Marshall *et al.*, 2006). There are two types of equipment used in harvesting: the harvesters and the forwarders. The harvesters cut the logs and let them in the forest, where the forwarders collect and pile them next to the access road. The trucks collect the logs from the piles and transport them to the desired destination. Because of this work sequence it is needed synchronization in tasks planning. The time and cost of moving equipment between stands will depend on the distance between them (Bredström & Rönnqvist, 2008).

The bucking is also a task sometimes associated with the harvesting. This is the cutting of the logs into smaller pieces that are then used in industrial processing. Due to its impact on the final product, and because it is an irreversible process, good planning should be performed, preferably integrated into the remainder supply chain planning (Dems *et al.*, 2013).

Transportation cost represents a significant parcel in the supply chain total cost (Rönnqvist *et al.*, 1998; Forsberg *et al.*, 2005; Carlsson & Rönnqvist, 2007). Since the 90's, this issue has becoming more relevant in forest sector companies, namely the control and scheduling quality of transportation systems (Hachemi *et al.*, 2008; Hachemi *et al.*, 2011; Hachemi *et al.*, 2013). This process planning is performed from the supply points, i.e., forest areas or terminals, to the demand points as paper mills, pulp, saw, heating plants or terminals (Carlsson & Rönnqvist, 2007). Therefore, the existence of an efficient road network affects the performance of the forest industry (Henningsson *et al.*, 2007). This problem is similar to the problem VRP (Vehicle Routing Problem) (Carlsson & Rönnqvist, 2007).

The different levels of planning imply different decisions on transportation. At the operational level are often determined the individual routes of trucks, and backhauling decisions if existent (Carlsson & Rönnqvist, 2007). This possibility of backhauling (see Figure 4) is an influence factor on transportation cost (Carlgren *et al.*, 2006). Through backhauling, instead of trucks make the return trip empties, and therefore with low efficiency, are found new charge points in the opposite direction increasing the load on its total trip (Palander & Väätäinen, 2005; Carlsson & Rönnqvist, 2007). However, backhauling possibilities are usually limited in forest (Forsberg *et al.*, 2005).

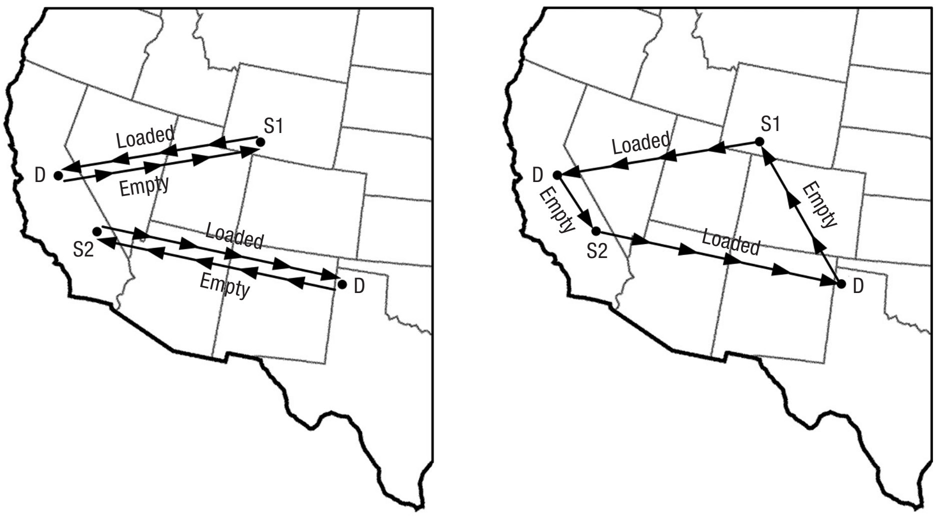

Figure 4. Transport possibilities: direct flow and backhauling (adapted from Carlgren *et al.*, 2006).

Also, it must be referred that there are two types of trucks, with and without crane. The main difference is that trucks without crane need other equipment to load and unload (Bredström & Rönnqvist, 2008). Thus, the occupation of the loaders when trucks arrive can be another cause of delay in transportation. Consequently, the truck has to wait implying higher transportation costs (Hachemi *et al.*, 2008). Rather, trucks with crane can manage these tasks autonomously. However, the crane weight withdraws from 5 to 10% load carrying capacity (Bredström & Rönnqvist, 2008). In addition, different materials have different densities and hence different weights. These factors will influence the amount of wood transported by a truck and consequently the cost of transportation (Carlgren *et al.*, 2006).

Although the transport is usually driven by trucks, in cases where the distances between supply and demand points are high, can be economically advantageous to use other means of transportation, such as train or ship. Still, the first part of the transport is done by trucks since the trains and ships collection points are fixed (Forsberg *et al.*, 2005).

It should be noted that although the described processes are transversal to the various branches of the forest supply chain, some processes, and specific considerations have to be included in particularized situations. For example for the pulp and paper industry other aspects must be considered such as the wood fibre (Carlgren *et al.*, 2006). In turn, in the biomass sector the chipping process should also be treated, which consists in the wood logs and harvest residues conversion in small pieces to be used, for instance, in power plants or heating plants.

MPC applied to forest-based supply chain

As stated in section 3, forest supply chain is complex since it generates a wide variety of products, integrates several processes and entities and attends to several problems of management and planning.

Although not known by the authors the application of control techniques, namely MPC, in this supply chain, the reviewed and discussed literature in section 2 shows the potential of this methodology for the forest supply chain management. Therefore, it is proposed the integration of MPC in the forestry industry, particularizing its implementation for a use case on biomass supply chain.

Use Case

This use case is integrated into the FOCUS (Advances in Forestry Control and aUtomation Systems in Europe) project. FOCUS is a 7 FP SME-target collaborative RTD project which objective is to “improve sustainability, productivity, and product marketability of forest-based value chains through an innovative technological platform for integrated planning and control of the whole tree-to-product operations, used by forest-producers to industry players” (www.focusnet.eu).

Within the FOCUS project, are involved the development and integration of several components, namely the planning, control, sensors, among others, showed in Figure 5, connected through a central component denominated FOCUS Core.

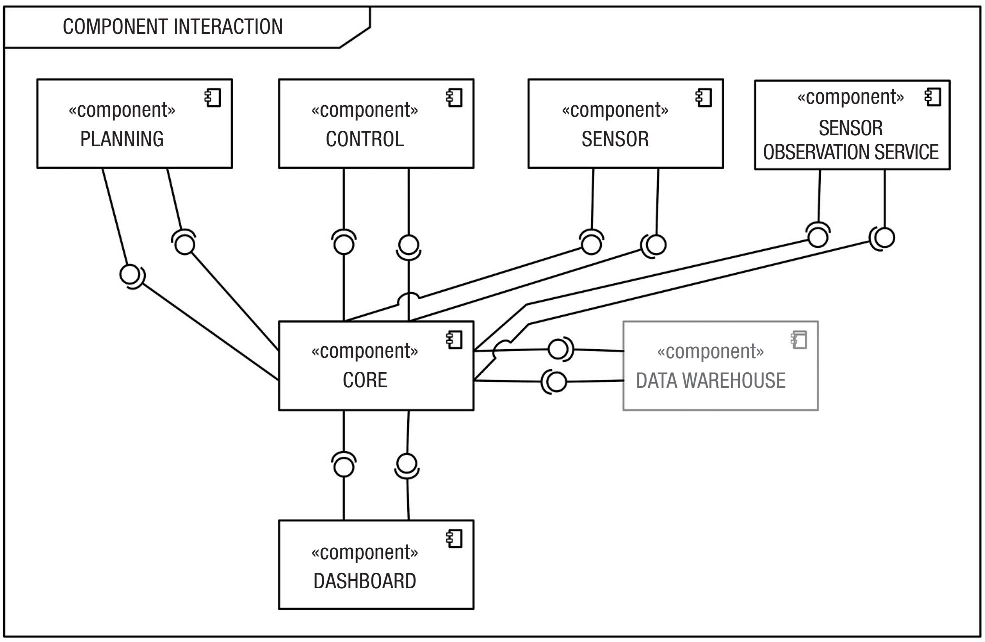

Figure 5. Components of the FOCUS architecture.

This European project encompasses four pilot cases, covering the supply chains of lumber, pulpwood, biomass and cork transformation. In particular, pilot case II, described in this work, is named "Control of biomass and transportation to energy conversion sites". It is located in Finland and involves a local company, which main objective is to optimize chips delivery in power plants aiming energy production.

Although biomass supply chain involves several processes as described in section 3, this pilot case will focus on the chipping and transportation processes, as depicted in Figure 6. The overall problem consists in wood logs transformation into chips by the chipping process and their subsequent transport to the power plants by trucks, for posterior energy production. The chips are directly loaded on trucks during the chipping process. In this context, may be involved several stands, with several piles each and several power plants. In a normal daily scenario can be considered about 1-6 chipping sites, 11 chippers, 20 trucks and 10 power plants. Each power plant demands the intended MWh on a weekly basis, and may also impose a daily minimum. It should be noted that the conversion of m^3 to MWh depends on the material density and wood moisture content. However, the moisture content of the wood pile is normally an unknown parameter. This parameter can be measured using sensors, which is a task associated with one of the work packages of the FOCUS project, or can be estimated through models, which depend on different factors, such as wood type, weather, among others, as presented in equation (1). In our case, the actual measurement of the moisture content is performed upon material reception at the mill. At the piles the moisture content is inferred from a model.

$$\begin{aligned}&\text{Moisture content}\,(\%) = \\ &= f\,(\text{wood type, meteorological data, } \ldots\,)\end{aligned} \tag{1}$$

Figure 7 presents the proposed control methodology. Considering the forest supply chain and the concept of MPC, the applied methodology will consist on the modelling of the processes through dynamic models that adequately describe the system behaviour, with information sharing across the whole system. This is because the processes are interdependent, and the one's results have influence on other processes results, and so in the entire supply chain.

The implementation of MPC in this pilot case also includes the coordination between the planning and control levels. Namely, the planning level involves two planning sub-levels, the tactical and the operational. The tactical level aims to maximize the net profit and, in this sense, define the number of equipment (chippers and trucks) needed to accomplish with the power plant demand. On the other hand, the operational level is responsible for the routing and scheduling of chippers and trucks in a synchronized manner, considering the minimization of operational costs, such as vehicles utilizations, distances, waiting times, fuel consumption, among other factors.

As previously mentioned the power plant demand consists in a quantity of wood material in MWh, con-

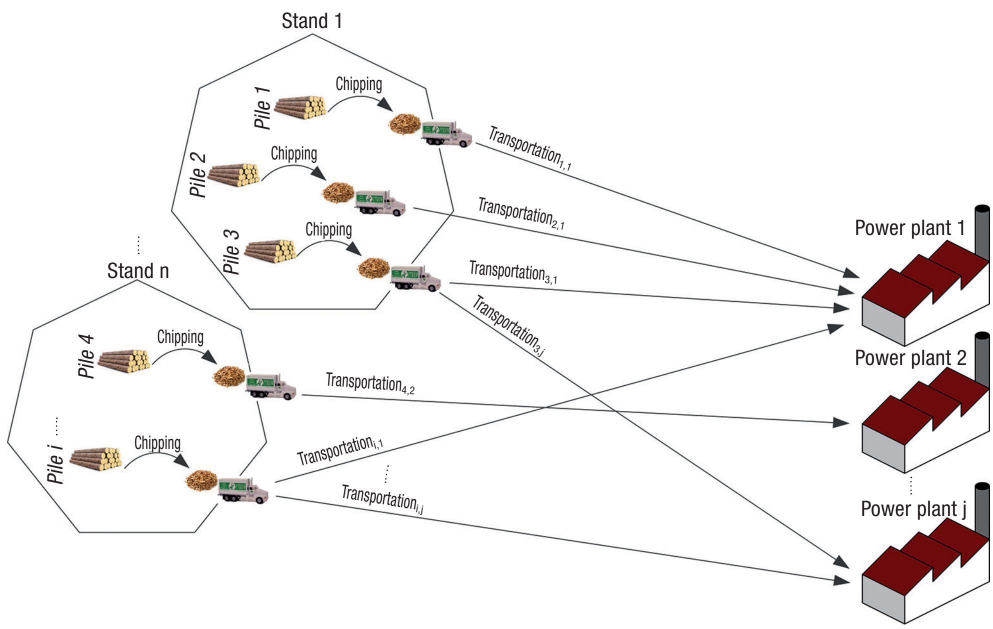

Figure 6. Considered processes in pilot case II.

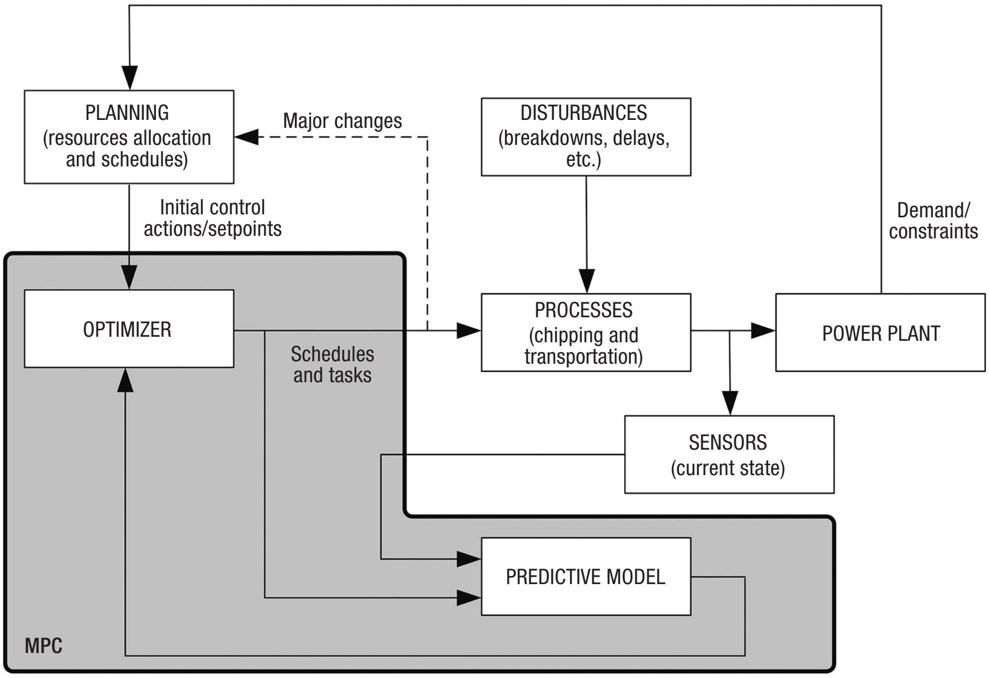

Figure 7. Proposed control methodology.

strained to moisture content thresholds and time windows in which the power plants accept the delivery of material. Chippers' and trucks' schedules, as well as the planned flows for the day, are used as inputs for the control level, which will verify if the plan is still able to be respected and react according that result. In detail, three control situations may occur: if the current state of the system is favourable to satisfy the plan within certain pre-defined limits, the initial control actions will be maintained; if the control detects the need to readjust the system, then actions related with schedules and tasks are directly performed to accomplish the plan; however, if these adjustments involve major changes in the system such as the hiring of new resources, the control will send an alert to the upper level of planning that will decide on the implementation of the suggested changes. Therefore, the coordination of planning and control levels will enable to plan the chipping and transportation processes and to insure the timely response to disturbances such as breakdowns of equipment and delays.

The initial operational plan provided by the planning level considers the synchronized routing and scheduling of chippers and trucks for a working day. In this way, it consists in a table with the tasks and schedules of chippers and trucks, indicating the origin and destination nodes with the corresponding loading and unloading services, as exemplified in Figure 8 for a small dimensional problem with two chippers, four trucks and six power plants. In this figure "p" represents the pile, "c" the client, in this case the power plant, and "d" the loading and unloading services at piles and clients, respectively. The "t" regards the terminal, at which the equipment stands during the

Vehicle \ Time	195	202	225	…	463	473	493	498	…	588	596	606	636
Chipper 1		p4d1	p4d1	…	p1d1			t					
Chipper 2	p2d1	p2d1	p2d1	…	p3d1	p3d1	p3d1	p3d1	…	t			
Truck 1		p4d1		…	p1d4				…				
Truck 2			p2d2	…		c1d3			…		c6d4		t
Truck 3	p2d1			…		c6d1			…			t	
Truck 4				…			p3d2		…				

Figure 8. Example of an initial operational plan provided by the planning level.

non-working period. To illustrate the information concerning this initial operational plan, the "p2d1", marked with a circle in Figure 8, regards the first loading service in pile 2 performed by the truck 3 at time instant 195.

As depicted in Figure 7, the information contained in this plan is loaded to the optimizer. In the case of disturbances, such as breakdowns, delays, bad weather conditions, etc., which imply the deviation or failure of the daily plan, the optimizer will compute the next control actions to be implemented in the processes in order to accomplish the initial plan. For instance in the occurrence of a truck breakdown, the optimizer can change the other trucks schedules and tasks to cover that truck work, without change the initial resources pool. The used optimization algorithm can be performed using techniques such as PSO or Genetic Algorithms, which is a method for solving optimization problems based on natural selection of organisms. In this technique, the optimization is based on concepts such as the evolution and the survival of the fittest organism.

Also, an essential component of the MPC are the predictive models, in our case concerning the chipping and transportation processes. With these models, the controller will be able to forecast the behaviour of the system based on the current state provided by the sensors. Due to the nature of the biomass supply chain, models will be based on Discret-Event Simulation (DES). In this technique, the systems are modelled through sets of queues and activities, and the changes in states are dependent on the occurrence of events at discrete points of time, such as, for our case, the truck's loading or unloading, the start of chipping, etc. The models were developed using a discrete-event simulation tool.

The predictive models will be used by the optimizer in the minimization of a specific cost function. This cost function consists in an estimation of the waiting and transportation times which are related with the operational costs, as represented in equation (2). In this sense, in a first instance if the verified disturbance consists in a delay, the algorithm will try to adapt the schedules or send alert to the planning level in order to comply with the daily deliveries to the power plants, at the lowest cost, i.e., minimizing the total trucks transportation time, the total chippers transportation time, and the total chipping time. However, if the disturbance consists in equipment malfunctioning and severe weather conditions, the algorithm will reallocate the tasks for that day, always aiming the chips delivery at the lowest cost.

$$\min J = \sum w_{vp} + \sum w_{vc} + \sum t_v + \sum t_k \tag{2}$$

Subject to:

$V \leq$ maximum number of trucks defined by planning

$K \leq$ maximum number of chippers defined by planning

Where:

w_{vp} = waiting time of truck v in pile p

w_{vc} = waiting time of truck v in client c

t_v = transportation time of truck v

t_k = chipping time of chipper k

V = set of v trucks

K = set of k chippers

Conclusions

Model Predictive Control has proved to be a successful technique in the process control applications. In this paper, it is provided an overview of its application as a management tool for supply chains. The mentioned works have demonstrated economic benefits for the involved partners through the MPC use since it enables the global performance optimization even in the presence of uncertainties and disturbances. Despite these facts, and as far as we know, MPC application is inexistent in the forest-based supply chain. This work has described the generic characteristics of the forest supply chain, and proposed the application of MPC in this area, in coordination with the planning level. The advantages of the proposed method were presented regarding a use case in the biomass supply chain. Therefore, by integrating planning and MPC, it will be possible to plan in a properly manner the involved processes, in this case the chipping and transportation, and respond in time to critical events and disturbances such as equipment's breakdowns or delays. At the present a set of tests is being conducted to evaluate the performance of the proposed methodology and, if required, redesign and/or tune the models and the optimization algorithms. From the performed simulations, it is possible to know in advance the impact of the occurrence of disturbances in the supply chain. This is a major contribution since it enables to correct beforehand or alert the planning level to generate a new plan.

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