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A novel decomposition and distributed computing approach for the solution of large scale optimization models

Yogendra Shastri*, Alan Hansen, Luis Rodríguez, K.C. Ting

Energy Biosciences Institute &, Department of Agricultural and Biological Engineering, University of Illinois at Urbana-Champaign, 1304 W. Pennsylvania Avenue, Urbana, IL 61801, United States

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ABSTRACT

Biomass feedstock production is an important component of the biomass based energy sector. Seasonal and distributed collection of low energy density material creates unique challenges, and optimization of the complete value chain is critical for cost-competitiveness. BioFeed is a mixed integer linear programming (MILP) problem model that has been developed and successfully applied to optimize bioenergy feedstock production system. It integrates the individual farm design and operating decisions with transportation logistics to analyze them as a single system. However, this integration leads to a model that is computationally demanding, leading to large simulation times for simplified case studies. Given these challenges, and in wake of the future model extensions, this work proposes a new computational approach that reduces computational demand, maintains result accuracy, provides modeling flexibility and enables future model enhancements. The new approach, named the Decomposition and Distributed Computing (DDC) approach, first decomposes the model into two separate optimization sub-problems: a production problem, focusing on on-farm activities such as harvesting, and a provision problem, incorporating the post-production activities such as transportation logistics. An iterative scheme based on the concepts from agent based modeling is adapted to solve the production and provision problems iteratively until convergence had been achieved. The computational features of the approach are further enhanced by enabling distributed computing of the individual farm optimization models. Simulation studies comparing the performance of the DDC approach with the rigorous MILP solution approach illustrated an order of magnitude reduction in computational time using the proposed DDC approach. Moreover, the solution obtained using the DDC approach was within ±5% of the rigorous MILP solution. This approach can be a valuable tool to solve complex supply chain optimization problems in other sectors where similar challenges are encountered.

1. Introduction

The importance of biomass feedstock production and provision in the success of the biomass based energy sector has been increasingly highlighted in recent times (Perlack et al., 2005; DOE, 2008). Low energy density, seasonal availability and distributed supply create unique challenges that need to be addressed effectively. Novel feedstock alternatives as well as new technologies for crop management, harvesting and post-harvest storage and handling are being developed and made commercially available. Moreover, since a number of independent farms supply feedstock to a single refinery, farm level decisions have direct implications on transportation logistics and refinery operations. This makes the selection of the optimal sequence of operations critical and non-trivial.

Shastri et al. (2009) emphasized the importance of taking a systems approach to overcome these challenges and achieve a system level optimal configuration that ensures seamless integration of various production tasks. BioFeed is an optimization model which has been developed as a first step towards such a systems analysis framework (Shastri et al., 2009, 2011). It is a mixed integer linear programming (MILP) model that incorporates various biomass production activities such as harvesting, packing, transportation, storage and handling, and determines the optimal system level configuration. An important unique feature of the model is the optimization of the operational blueprint for the whole system that can be used by farmers and managers. The model has been successfully applied to the case of switchgrass and Miscanthus production in southern Illinois (Shastri et al., 2009, 2011). However, the model simulation and optimization studies highlighted its computational complexity. This is primarily due to the large

* Corresponding author at: Energy Biosciences Institute & Department of Agricultural and Biological Engineering, 1206 W. Gregory Drive, Urbana, IL 61801, United States. Tel.: +1 217 333 1775; fax: +1 217 244 3637.
E-mail address: yshast1@illinois.edu (Y. Shastri).

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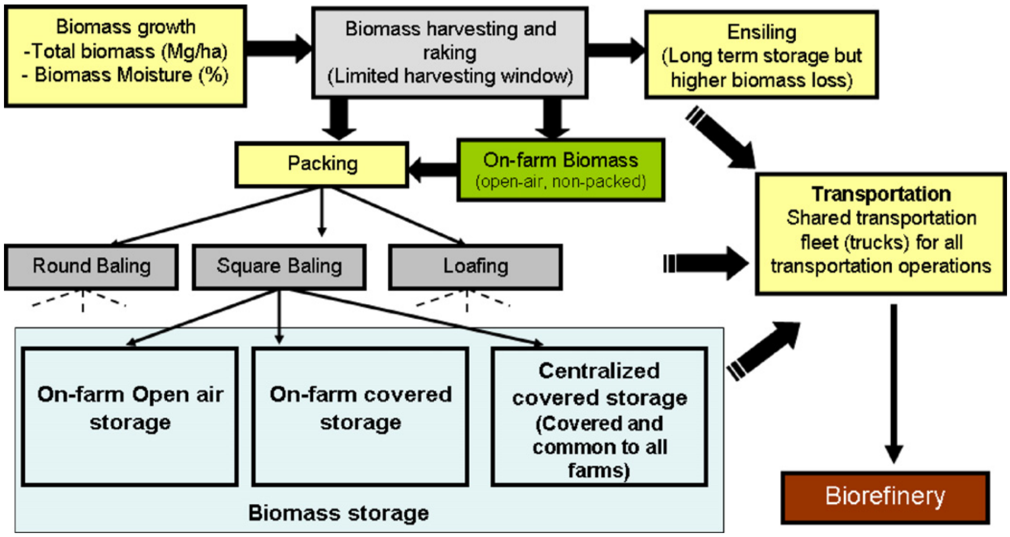

Fig. 1. Biomass feedstock production optimization model: BioFeed.

number of farms involved in biomass production as well as the simultaneous consideration of the design and management decisions for the whole system. Moreover, the BioFeed model will be significantly expanded in the future, and will be supported by an exhaustive database related to farm equipment that is being simultaneously developed (Domdouzis et al., 2009). These developments and enhancements are expected to further increase the computational demand for the future versions of BioFeed.

The objective of this work, therefore, was to develop a new computational approach to solve the BioFeed optimization model in a computationally efficient manner while preserving its original scope and objectives. It was intended that this new approach should reduce the computational requirements without significantly compromising the optimality of the problem solution. This article presents the development of such an approach which has been named as the Decomposition and Distributed Computing (DDC) approach. This new approach first implements problem decomposition and then develops an iterative scheme based on agent-based modeling philosophy to achieve solution convergence. The performance of the proposed approach is compared with the standard MILP solver in terms of accuracy and computational time for different scenarios of the BioFeed model.

The rest of the article is arranged as follows. The next section briefly describes the BioFeed model and highlights the important computational issues related to the original MILP model. Section 3 reviews the existing approximation approaches from the literature. Section 4 describes the proposed DDC approach in details, while Section 5 reports the simulation results for BioFeed model to illustrate the performance of the DDC approach in comparison with the rigorous MILP solution. The article ends with conclusions presented in the final section.

2. Background and motivation

2.1. BioFeed model description

Fig. 1 shows the overall scope and the important components of the BioFeed model. The model covers the important feedstock production and provision activities between the farms growing energy crops and the biorefinery. It is important to note that the model does not optimize the decision by farmers to convert agricultural land to energy crops which might be perennial. It is assumed that the cost–benefit analysis associated with land conversion has already been conducted by farmers. This leads to a known size and distribution of agricultural land growing energy crops, which is an input to the BioFeed model. The model assumes that standard crop-establishment techniques will be used resulting in known harvestable biomass on each farm. For each farm under consideration, the operations that are modeled include harvesting, raking, packing (e.g., baling), on-farm open and covered storage and/or ensiling. Biomass produced on each farm can be stored in one of the on-farm storage facilities for later use. Otherwise, the biomass can also be transported to the refinery for immediate processing or to the centralized storage facility that is shared by all farms. The transportation activities are carried out using a set of trucks that are independently owned. Each compartment in Fig. 1 is modeled using a set of linear algebraic equations that reflect the mass balance as well as the equipment capacity and availability constraints. The decision variables for the optimization model include equipment selection and their operating schedule for all activities on the farm (such as harvesting and baling), biomass distribution among various alternatives, on-farm storage selection and sizing, centralized storage selection and sizing, transportation fleet size selection and utilization of the fleet (logistics), and the biorefinery capacity. It is a mixed integer linear programming (MILP) problem where the equipment and storage site selection decisions are represented using integer variables. The design decisions such as equipment selection are one time decisions while the operational decisions are optimized for every time step of the simulation horizon. The simulation horizon consists of one year. Thus, biomass harvested during the harvesting horizon, which typically lasts for 3–4 months, must be stored and supplied to the refinery during the non-harvesting horizon. The smallest simulation time step is one day, and user can specify a larger time step consisting of multiple days. Although a smaller time step is desired for greater accuracy, reducing the size of the time step increases the simulation time significantly. The total production cost includes the capital as well as the operating cost for each operation. Since the objective of this paper is to describe the novel computational scheme developed to solve this model, a comprehensive discussion of the model is omitted here for brevity and interested readers are referred to Shastri et al. (2009).

It is important to note that the goal of the model is to determine the optimal feedstock production system configuration. Consequently, the objective function is the minimization of the total system cost rather than the maximization of individual stakeholder profit within the system. Such an integrated optimization model is extremely valuable to ensure a seamless integration of different operations within the feedstock production system. In addition