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Invited Paper

Systems Informatics and Analysis of Biomass Feedstock Production

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ABSTRACT

Sustainable biomass feedstock production is critical for the success of a regional bioenergy system. Low energy and mass densities, seasonal availability, distributed supply, and lack of an established value chain for the feedstock create unique challenges that require an integrated systems approach. We have, therefore, developed a Concurrent Science, Engineering and Technology (ConSEnT) platform integrating informatics, modelling and analysis, as well as decision support for biomass feedstock production. An optimization model (BioFeed) and an agent-based model, which are supported by an informatics database and made accessible through a web-based decision support system, have been developed. This article summarizes the recent advances in this subject area by our research team.

Keywords: Biomass feedstock, bioenergy, systems analysis, modelling, informatics, decision support

INTRODUCTION

Biomass based renewable energy will play a critical role in meeting the future global energy demands. A sustainable and competitive agricultural biomass feedstock production (BFP) system is critical for the success of a regional bioenergy system (Somerville *et al*., 2010). It provides the necessary material input for continuous operation of the processing facilities, and must do so by ensuring cost-efficiency, reliability and feedstock quality. Multiple tasks that comprise the BFP system include pre-harvest crop management, harvesting and handling, transport and pre-processing, and storage (Cushman *et al*., 2003). Our research programme at the Energy Biosciences Institute, titled 'Engineering solutions for biomass feedstock production', accordingly incorporates these four tasks, with the objective of developing new technological

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solutions to perform these operations efficiently. However, these tasks are highly inter-dependent, and it must be ensured that they work together in an effective, seamless manner. Moreover, low energy and mass densities, seasonal availability, distributed supply, and lack of an established value chain for the feedstock create unique challenges that pervade all stages of feedstock production, and require a holistic approach (Ting, 2009).

We have, therefore, taken a systems based approach and have constituted a fifth task of systems informatics and analysis (SIA). Using established and novel SIA techniques, we developed a Concurrent Science, Engineering and Technology (ConSEnT) platform by integrating informatics, modelling and analysis, and decision support for biomass feedstock production (Fig.1). A key outcome of this initiative has been the development of the BioFeed optimization model (Shastri *et al*., 2010; Shastri *et al*., 2011) and an agent-based simulation model (Shastri *et al*., 2011a). The article reviews our research on model development and application for decision support. We also discuss the role of informatics and decision support tools that complement the modelling and analysis work, and provide our thoughts on future challenges and opportunities.

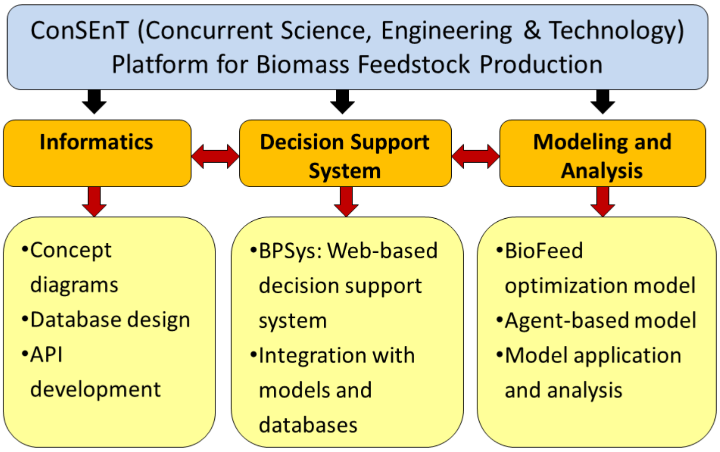

Fig.1: Concurrent Science, Engineering and Technology (ConSEnT) platform for the biomass feedstock production system

MATERIALS AND METHODS

Informatics and Database Development

The foundation of our work was first laid through the development of comprehensive concept diagrams for each stage of feedstock productions. The concept diagrams captured the scope of each task and were organized using an object-oriented approach to represent the tasks, sub-tasks, technologies, and equipment in a hierarchical format (Domdouzis *et al*., 2009). These diagrams were used as the basis to develop a MySQL database, along with user interfaces for data input and output. The models, described later, connected to the database in real time to ensure concurrency between latest scientific developments and model based analysis. This particular approach made the model generic, thereby allowing it to be used to study different crops in different geographical regions.

BioFeed Optimization Model

The overall scope and key components of the BioFeed model consider a scenario, where many farms are producing biomass feedstock for one or more regional biorefineries, considering the important operations along this value chain (Fig.2). For each farm under consideration, harvesting, raking, post-harvest processing, in-field transportation (roadsiding), handling, on-farm storage, and ensilage are modelled. Three storage options are modelled, namely, on-farm open storage, on-farm covered storage, and satellite covered storage. The satellite storage facilities are shared by all the farms, and they can include optional mechanical pre-processing of biomass such as size reduction (Shastri *et al.*, 2012). The transportation is carried out using a set of trucks bought and owned by the biorefinery. The impact of regional weather on the harvesting activities is modelled by incorporating the probability of working day (pwd) parameter in model equations (Shastri *et al.*, 2012a). The decision variables, which are simultaneously optimized during the model simulation, include on-farm equipment selection and their operating schedule, on-farm biomass distribution, on-farm storage method selection and sizing, satellite storage selection and sizing, transportation fleet size selection and utilization of the fleet (logistics), and the biorefinery capacity. The integration of design and management decision making is one of the unique features of this model. Several variables can be pre-specified to develop user specific scenarios. The simulation period consists of one year. The capital as well as the operating costs associated with each operation are included in the objective function, which is the maximization of the total system profit by assuming a certain biorefinery gate price. In addition to cost minimization, the model can quantify the systemic impacts of technological improvement, infrastructure limitations, management decisions, and conduct sensitivity analysis. A novel computational scheme, called DDC (Decomposition and Distributed Computing), is employed for a computationally efficient solution of the model (Shastri *et al.*, 2011b).

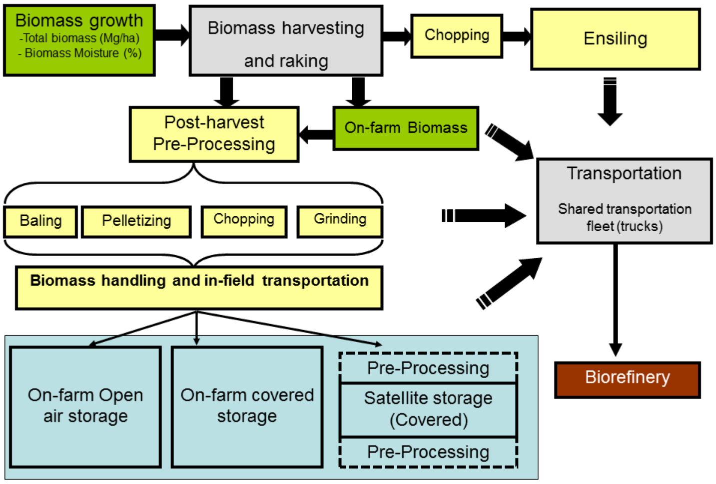

Fig.2: BioFeed optimization model - System level representation of the feedstock production system

Agent-based Simulation Model

The success of the lignocellulosic feedstock based bioenergy sector will require transitioning to an agricultural system that co-produces food, feed, and fuel crops. In addition to scientific and technological development, this transition will be driven by the collective participation, behaviour and interaction of different stakeholders within the production system such as farmers, biorefinery, transportation and storage companies, custom harvesters, and farm consultants. Conventional engineering and macro-economic models cannot be used to study such complex systems. We have, therefore, developed an agent-based simulation model using the theory of complex adaptive systems (Shastri *et al*., 2011a). The first version of the model focuses primarily on the farmer and biorefinery agents. Each agent class is characterized by a set of attributes such as farm size and location for the farmer agent. These attributes take different values for different instantiations to capture variability. The decision making of each agent is modelled using rules that incorporate social, personal, and regulatory factors of an agent in addition to economic cost-benefit analysis. Attributes and rules are parameterized using data from literature. During simulation, long-term monthly delivery contracts, valid over multiple years, are competitively negotiated between the farmer and biorefinery agents. The agents modify selected attribute values based on profits or losses during the previous year to model learning and adaptation.

Web-based Decision Support System

The true value of systems analysis can only be realized if it can lead to better decisions. Unfortunately, this does not always happen because decision makers either lack access to the systems based tools or do not have the necessary expertise to develop and use them. We, therefore, developed a web-based decision support system named BPSys (Liao *et al*., 2011) that provides user-friendly access to the database and the BioFeed model. It is programmed in Java and enables users to build production scenario in BioFeed, select and modify data, as well as perform simulation and analysis, and visualize results.

RESULTS AND DISCUSSION

The BioFeed optimization model has been used extensively to study the production of switchgrass and Miscanthus, two perennial C4 grasses that have been proposed as candidate crops. A collection region of 17,400 km^2 was considered. The collection region included 284 farms in 13 counties in southern Illinois. A biorefinery was assumed to be located at Nashville, IL. Crop harvestable yields and harvesting seasons were taken from the literature. The equipment performance data were adapted from previously published literature along with the ASABE machinery standards ASAE EP496.3 FEB2006 (R2011).

The optimal cost of switchgrass production was 45.1 \$ Mg^{-1}, which was almost evenly distributed among long distance transportation, harvesting, storage, and in-field transportation (Shastri *et al*., 2011). The on-farm baler selection varied based on farm size and storage requirements. It was found that 25% reduction in truck waiting time for loading/unloading, possibly through improved queue management, reduced the total cost by 22%.

The optimal production cost for Miscanthus was 44.7 \$ Mg^{-1} (Shastri *et al*., 2010). The optimal pre-processing technology recommended for each farm was either baling or grinding (hammer mill or tub grinder). In contrast to switchgrass, pre-processing accounted for 37% of the total cost, reflecting the lack of efficient equipment. The production cost increased substantially for farms smaller than 100 ha. A supply chain configuration incorporating distributed storage and pre-processing at satellite storage was also studied for Miscanthus using three different pre-processing alternatives, namely, hammer milling, tub grinding, and pelletization (Shastri *et al*., 2012). Mandatory pre-processing at storage increased the total cost by 16-53% as compared to the base case, but reduced the farmers' share of the total cost by 13-39%. The exact values depended on the pre-processing technology installed at the storage facility. The simulation results, therefore, recommended distributing the pre-processing operation between farms and storage facilities.

When the impact of weather in Illinois was quantified (Shastri *et al*., 2012a), the results showed that using a production system designed assuming 100% probability of working day (pwd) would incur an increase of actual production cost by 37% for Miscanthus and 12% for switchgrass. If the systems were instead optimized for typical pwd values for Illinois, the cost increase was less than 3.3%, but required higher investment in farm machinery by 34% for Miscanthus and 12% for switchgrass, respectively. Extending the Miscanthus harvesting season is, therefore, an option that must be rigorously evaluated.

The agent-based simulation model was used to study the establishment of Miscanthus production in Illinois by considering a set of 100 farmers currently growing corn and soybeans (Shastri *et al*., 2011a). The results showed that it took up to 15 years to reach stable regional production of Miscanthus, which was still only 60% of the maximum possible. Such a profile would have a significant impact on the capacity expansion, investment, and feedstock procurement decisions by the biorefinery. Meanwhile, a 25% reduction in the land opportunity cost led to a 63% increase in the stable production, suggesting that a region less attractive for conventional crops would be more suitable to establish Miscanthus.

CONCLUSION

In the study, the ConSEnT (Concurrent Science, Engineering and Technology) platform was developed by integrating informatics, modelling and analysis, and a decision support system for biomass feedstock production. The BioFeed optimization model and an agent-based simulation model constitute two key elements of this platform, and have provided valuable design and management recommendations for Miscanthus and switchgrass production. Such a decision-making platform would be extremely valuable in the future for large-scale deployment of the bioenergy sector. Various stakeholders that can benefit from this platform include biorefineries operators and investors, researchers, technology development engineers, regulators, and university teachers for educating the industry's next generation of human capital. Incorporating uncertainty in decision making and studying the full life cycle impacts of decisions are key future modelling challenges. The ConSEnT platform must also be further enhanced to achieve true concurrency between research and application.

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Dr. Yogendra Shastri is an Assistant Professor in the Department of Chemical Engineering, at the Indian Institute of Technology, Bombay in India. He has a B.Tech. in Chemical Engineering, M.Tech. in Systems and Control Engineering, and Ph.D. in Bioengineering. He conducts research in the area of systems theory including optimization, optimal control, and stochastic analysis, with applications in the field of energy, sustainability, and process design.

He was a post-doctoral research associate and a research assistant professor at the Energy Biosciences Institute (EBI), University of Illinois at Urbana-Champaign, where he participated in the research programme entitled, 'Engineering solutions for biomass feedstock production'. His research focused primarily on the development and application of model based tools for decision making, including the BioFeed optimization model, which has been heavily published and presented at various international meetings. In the past, Dr. Shastri also worked on the topic of applying engineering methodologies for sustainable management of complex systems, leading to several publications and citation by the Stanford Social Innovation Review. He has also made methodological contributions through the development of novel optimization algorithms.

Dr. Shastri has published 22 journal articles, 5 technical reports, and 3 book chapters. He has also given several presentations at international meetings. He is also the lead editor of a book on biomass feedstock production to be published soon by Springer. One of his research papers was awarded the best graduate student paper award by the AIChE (American Institute of Chemical Engineers) Environmental Division. He also received the DAAD (German Academic Exchange Services) scholarship to conduct his M. Tech. thesis research at the University of Stuttgart, Germany.