Risk advantages of platform technologies for biorenewable chemical production

Sampath Gunukula^a, Peter Keeling^b, Robert Anex^{a*}

^aBiological Systems Engineering Department, University of Wisconsin, Madison, WI, 53706, USA

^bThe Center for Biorenewable Chemicals, Iowa State University, Ames, IA, 50011, USA

Abstract

Recent investments in bio-based chemical development are financing the construction of commercial production facilities, often designed to produce a single biorenewable chemical. Investments in technologies targeting a single biorenewable chemical are subject to significant technological and market risks. Platform technologies that can convert biomass into a range of related biorenewable chemicals can reduce these risks significantly. Researchers are now developing platform technologies that combine bio-and chemical-catalysis, such as a process of converting glucose into fatty alcohols of specific carbon chain length. The financial risk and profitability of investments in platform technology producing fatty alcohol of different chain length were analyzed. A techno-economic model to evaluate single- and platform technologies was developed. A platform technology that can produce two products: 1-decanol and a blend of dodecanol and 1-tetradecanol reduces financial risk of investment by 23% and increases profitability by 55% compared to production via single-product technologies. This financial advantage of two-product technology is eliminated as the cost of switching between products rises above \$4 MM for a 14 metric-ton/yr plant. Investments in technologies that can produce a larger number of products provide higher returns lower risk. Other less quantifiable risk advantages of platform technologies that nonetheless important are also discussed.

Key words: Platform technology, biorefinery, biorenewable chemical, financial risk, biocatalysis, chemical catalysis

*Corresponding author. Tel.: +1 (608) 890-3839

E-mail address: anex@wisc.edu (Robert Anex)

1. Introduction

Most industrial chemicals used as materials, plastics, surfactants and solvents are currently derived from petroleum feedstock. Depleting non-renewable petroleum feedstock and environmental considerations have been drastically changing the prospects for renewable biomass as a raw material for industrial chemicals (Brehmer et al., 2009). In order to transform the petroleum-based chemical industry to a bio-based chemical industry, a substantial amount of research is ongoing throughout the world targeting one biorenewable chemical at a time. For example, Burk et al., (2011) describe a biological process for converting sugars into 1, 4-butanediol; bio-isoprene can be synthesized by genetically modifying microbial cells to overexpress levels of an isoprene synthase polypeptide and a mevalonate kinase polypeptide (Beck et. al, 2010); and biobased chemical company Rennovia, Inc. is commercializing a catalytic process for the production of adipic acid from carbohydrates (Boussie et al., 2014).

Unfortunately, this approach of developing single-product technologies is slow and costly, as it requires all the investment in time and money for one chemical. Moreover, investing capital for producing biorenewable chemicals via technologies that yield a single-product magnifies a variety of the technological and market risks that characterize the highly competitive chemicals industry. Volatility in prices of feedstock, energy, and the market demand for chemicals are just a few of the sources of market and financial risk of investment in the biorenewable chemical business (Curtis, 2010). Since biorenewable chemicals can either structurally or functionally replace existing petrochemicals, renewable chemicals compete for market share with existing petrochemical products. Thus, there is a risk of reduction in market price as supply is increased by new market entry and a risk of aggressive price reduction by incumbent petrochemical companies, whose capital investments are already partially or fully

depreciated. During the scale-up of pioneer renewable chemical technologies, there is risk of process failure due to technical barriers, characterized as technology risks (Edwards and Eng, 2015). Furthermore, lack of economies-of-scale may create a barrier to market entry for low profit margin biorenewable chemicals synthesized via single-product technologies.

The various risks to the investments in the biorenewable chemical business may be reduced by producing biorenewable chemicals via platform technologies. We define a technology as a platform technology when it meets following criteria: 1) it enables the synthesis of multiple chemicals; 2) the technological investments made in the synthesis of each chemical are at least partially used in the research and development of one or more other chemicals; 3) the production of each chemical in the platform uses at least 60% of the same plant equipment as the other products in the platform - in other words, it should enable the plant to make multiple chemicals by slightly modifying existing production equipment; and, 4) the products made using the chemicals platform can be sold in different market segments. The platform concept fits into one class of biorefinery identified by Sadhukhan et al., (2014) in which a portfolio of products are derived from a single biomass feedstock using flexible conversion processes. Thus, the development of platform technologies can expedite the development of a biorefinery that operates similarly to an oil refinery.

The recent development of a reverse β -oxidation pathway in *E.coli* as reported by Cintolesi et al., (2014), for example, facilitates the synthesis of a range of di-carboxylic acids with varying carbon chain length from glucose. This technology is considered a platform technology for the following reasons: Of these di-carboxylic acids, medium chain di-acids such as adipic acid can address the needs of the nylon industry (Taylor et al., 2015), and the long chain di-acids such as octadecanedioic acid have applications in polyamide, polyurethanes,

lubricants and adhesive industries (Greenwood, 2013). Since the mechanism with which the reverse β -oxidation pathway in *E.coli* that makes medium and long chain di-acids is similar, the technological advancements made in the development of bio-catalytic technology to synthesize medium chain di-acids are applicable to the synthesis of long chain di-acids. Although separation and purification processes are somewhat different for medium and long-chain di-acids, the production of these di-acids will utilize a substantial portion of the same equipment including the seed and product fermentors.

Platform technologies for biorenewable chemical production can be developed using purely biological, purely chemical, integration of biological and chemical processes, or thermochemical processes. The above mentioned reverse β -oxidation pathway in *E.coli* to synthesize various di-acids is considered as an example of a purely biological method. Similarly, synthesis gas from the thermochemical conversion of biomass can be used to synthesize a range of products, including paraffins and olefins using the Fisher-Tropsch process (Ng and Sadhukhan, 2011) and methanol using Cu/Zn/Al catalyst (Hamelinck and Faaij, 2002).

One example of a purely chemical approach is the oxidation of glucose over a platinum catalyst which yields glucaric acid (Boussie et al., 2010). This glucaric acid subsequently undergoes selective dehydration to lactones or selective esterification to polyglucaric esters (Werpy et al., 2004). Another example is the catalytic dehydration of fructose to 5-hydroxymethylfurfural (Pagán-Torres et al., 2012), which can be further transformed catalytically into various bio-fuels and bulk chemicals (Boisen et al., 2009). As an example of an integrated approach, triacetic acid lactone is produced biologically from sugars through overexpression of 2-pyrone synthase in *Saccharomyces cerevisiae* (Cardenas and Da Silva, 2014)

and this biological intermediate is catalytically upgraded to sorbic acid, hexenoic acid, and γ -caprolactone (Chia et al., 2012).

The concept of a platform technology is somewhat related to, but different from platform chemicals, as described by Werpy et al. (2004), who identified the most promising building block chemicals that can be derived from biomass. Among the building block chemicals identified by Werpy et al. (2004), most of chemicals can be produced via microbial technology, and subsequently upgraded to yield a diverse portfolio of biorenewable chemicals using a chemical catalyst (Shanks, 2007).

The NSF engineering research Center for Biorenewable Chemicals (CBiRC) is currently developing three platform technologies by integrating bio- and chemical- catalysis (The Center for Bio renewable Chemicals, 2008). One of these three technologies is the carboxylic acid platform technology (Liu and Jarboe, 2012). In this platform, microbial strains such as *E.coli* are engineered to synthesize various carbon chain lengths of fatty acids from glucose via the fatty acid biosynthesis pathway (Zhang et al., 2011), and these fatty acids are subsequently upgraded to yield fatty alcohols of different carbon chain length using a chemical catalyst (Gervajio, 2012) (Fig.1). The medium- and long-chain fatty alcohols are used in perfume, fragrances, cosmetics, pharmaceutical, and surfactant and lubricant industries (Noweck and Grafahrend, 2006).

In this paper we analyze and compare the risks of investment in technologies for producing fatty alcohols of different chain length via both single-product and platform technologies. We quantitatively analyze financial risk and the profitability of investment, and qualitatively evaluate other risks of investments in developing single and platform technologies. Financial risk is quantified by assuming all the risk due to variation in prices is captured in the

standard deviation of the probability density function of net present value (NPV) of irreversible capital investment¹ in biorenewable chemical production (Amigun et al., 2011; Damodaran, 2008). The expected values of the probability density function of NPV are used as an indicator to measure the profitability of an irreversible investment: as the expected NPV increases, provided it is positive, the profitability of an irreversible investment will increase (Amigun et al., 2011). Technology risk is quantified by estimating the likelihood of process failures that occur during scaling-up a novel bio-renewable chemical technology. Such an estimation of process failures requires a very large amount of process performance data from commercialized renewable chemical technologies (Edwards and Eng, 2015). Unfortunately, at this point in time these data for biorenewable chemical technologies are limited, because the biorenewable chemical industry is still in its infancy. It is also very difficult to predict risks of scientific breakthroughs and competitive market behavior. Thus, we qualitatively analyze these other risks and advantages of platform technologies that are currently impossible to quantify.

We quantify financial risk and profitability of investment by simulating single-product and platform technologies for producing fatty alcohols of different chain length using process simulation software. We create a techno-economic model by estimating capital and operating costs using simulated material and energy balances. The prices of feedstock, energy and products are modeled as a mean-reverting process. A switching rule based on cost of switching between products is developed and used in the economic model to represent profit-seeking plant operation. A Monte Carlo simulation is performed to predict the probability distribution of NPV of investment in fatty alcohol production. Comparison of the expected value and standard deviation of distributions NPV for technologies that can reach one or more products has shown

¹ The capital invested in a chemical plant cannot be fully recovered when the plant is retired or retrofitted, thus investment in a chemical plant is characterized as an irreversible investment (Dixit and Pindyck, 1994)

that the carboxylic acid platform technology can reduce the financial risk and increase the profitability of investment. The influences of product carbon chain length and switching cost on the risks of investment in platform technologies are investigated. Finally, we qualitatively evaluate other risk impacts of platform technologies.

2. Methodology

2.1 Description of fatty alcohol production process

The process flow diagram for fatty alcohol production from glucose is shown in Fig. 2. The annual plant capacity and plant life are taken to be 40,000 metric tonnes of glucose conversion and 20 years, respectively. The process flow diagram is similar for both the single-product and platform technologies for fatty alcohol production. However, in the platform technology the versatility of the fatty acid biosynthesis pathway makes it possible to produce fatty acids with varying carbon chain lengths. The versatility of this pathway is achieved by introducing a unique acyl-ACP thioesterase gene into a microorganism for the synthesis of a specific chain length of fatty acid. For instance, expressing class I acyl-ACP thioesterase genes into a microorganism can terminate fatty acid chain elongation and produce the myristic acid (C14:0), whereas expressing class III acyl-ACP thioesterase genes into a microorganism enables the synthesis of octanoic acid (C8:0) (Jing et al, 2011). In this production process, the biologically produced fatty acid then undergoes hydrogenolysis over a copper chromite catalyst to yield a fatty alcohol (Gervajio, 2012).

The fatty alcohol production process starts with adding preserved genetically modified *E.coli* seed culture to the first bioreactor in the seed fermentation train which consists of series of bioreactors that increase incrementally in size by a factor of 10 (Humbird et al., 2011). Once the *E.coli* cells are grown to a fixed concentration, the entire cell culture is transferred into the

subsequent bioreactor in the seed train. This process is repeated until the cell count and concentration required for the fatty acid production process is achieved in the final bioreactor of seed train. Glucose and other nutrients are added at each stage as necessary for *E.coli* growth.

The *E. coli* cells from the final bioreactor in the seed train are sent to the aerobic production fermentor, operating at 37⁰ C in fed-batch mode, to synthesize fatty acid from glucose under M9 minimal media. During product fermentation, CO₂ is evolved as a gas and fatty acid is produced as an extracellular product. The separation of *E.coli* cells from the fermentation broth containing fatty acid, *E.coli* cells and other impurities is achieved using a rotary vacuum filter. Fatty acid from the clarified fermentation broth is extracted using solvent extraction column with the aid of the extracting agent chloroform (López-Garzón and Straathof, 2014). The extractant phase of the solvent extraction process containing chloroform and fatty acid is separated into pure fatty acid and chloroform using distillation. Vacuum distillation and decantation processes are used to recover solvent present in the raffinate phase of solvent extraction process.

The purified fatty acid undergoes a high pressure hydrogenation reaction to fatty alcohol over a bimetallic catalyst in a catalytic reactor. After high pressure hydrogenation process, the mixture of hydrogen, fatty alcohol, and catalyst slurry from the catalytic reactor is sent to the two-stage cooling/expansion system to recover unreacted hydrogen that is later mixed with the make-up hydrogen before recycled to the hydrogenation reactor. Using a basket centrifugal separator, the fatty alcohol/catalyst slurry stream is separated into a fatty alcohol stream with some traces of solids and a catalyst slurry stream. The catalyst slurry is recycled to the catalytic reactor, and the solid traces in the fatty alcohol stream are removed by the filter (Gervajio, 2012).

2.2 Process simulation

SuperPro Designer[®] Version 9.0, (2013) was used for simulation of seed and product fermentation, vacuum filtration, and countercurrent solvent extraction using rotating disc contactor column, because this software provides necessary models of these processes that are not available in Aspen Plus[®] Version 8.6, (2014). The biomass growth in the seed train was modeled by Monod kinetics with a maximum specific growth rate of 0.4 hr⁻¹ and a biomass yield of 0.4 g (dcw)/g glucose. For the modeling of production fermentor it was assumed that there is no biomass growth, and the product yield is 0.34 g fatty acid/g glucose. The information on operating conditions and other modeling parameters that are required for the simulation of the seed and product fermentors were obtained from personal communication with the CBiRC development team (Table S1). SuperPro Designer[®] process simulation software was used to simulate the seed and product fermentors for the fatty acid production.

The necessary area of the rotary vacuum filter to remove *E.coli* cells from the fermentation broth and number of stages, diameter and height of the solvent extraction column were estimated using the SuperPro Designer[®] process simulation software. The needed design parameters for the solvent extraction column simulation were determined as described in our unpublished work (Table S2).

Aspen Plus[®] was used for simulation of the overall process, excluding fermentation, filtration, and solvent extraction processes, because it is the accepted industry standard process simulation software that provides sophisticated models of vapor-liquid equilibrium separations and chemical reactions which allowed us to more accurately simulate distillation and catalytic reactions. The simulated extractant and raffinate material flows of solvent extraction process were imported into Aspen Plus[®] software, which were used as inlet streams to distillation columns. The RadFrac method was used to perform the simulation of distillation columns.

Distillation column simulation defined the required number of trays and column diameter for the particular separation. The Aspen Plus[®] shell and tube model was utilized to determine the areas of the condenser, reboiler, and heat exchanger columns in the fatty alcohol process.

For the design of catalytic reactor, we selected an operating temperature of 553 K and 30 MPa which yield nearly 100 % conversion of fatty acid with 95% selectivity to fatty alcohol (Gervajio, 2012). We could not obtain kinetic data related to the high pressure hydrogenolysis of saturated fatty acid so the catalytic reactor was modeled using the Aspen Plus[®] stoichiometric reactor model. The two-stage cooling/expansion, and centrifugal separator processes were also modeled using the Aspen Plus[®] process simulation software. Required design parameters and operating conditions for these processes were determined using standard engineering methods (Seider et al., 2010). In this work we did not model any wastewater treatment processes and utility production. Instead, utilities were assumed to be purchased from an external facility and wastewater was assumed to be treated by an external facility for a fixed price.

2.3 Economic model and key assumptions

An Excel VBA (Visual Basic for Applications) economic model was developed using discounted cash flow analysis (DCF) to determine the distribution for the NPV of an investment for both single-product and platform technologies. The simulated material and energy balances data were imported into Excel spreadsheet from SuperPro Designer[®] and Aspen Plus[®] models. The amount of raw materials, natural gas, cooling water, and electricity required for the fatty alcohol production were determined using material and energy balance data. The operating labor-related charges were estimated using a correlation between operating labor and plant capacity as described by Peters and Timmerhaus (1991). The maintenance wages and benefits (MW&B) were assumed to be 4.5% of total direct plant cost. The maintenance overhead and

other maintenance related costs were calculated as 135% of MW&B (Seider et al., 2010). The operating overhead and property taxes were assumed to be 23% and 2% of labor cost and total direct plant cost, respectively (Seider et al., 2010). Annual plant depreciation was computed using the Modified Accelerated Cost Recovery Systems (MARCS) method (Peters and Timmerhaus, 1991). Total general expenses were estimated as 10% of total revenues generated from fatty alcohols (Seider et al., 2010).

Equipment costs of seed and product fermenters, vacuum filter, and solvent extraction column were calculated using a built-in cost model in the SuperPro Designer[®] simulation software. Distillation column purchase cost was estimated based on the number of trays and diameter (Peters and Timmerhaus, 1991). The cost of the catalytic reactor was computed using a design equation from Peters and Timmerhaus (1991) based on the reactor type and volume. The condenser, reboiler, and other heat transfer equipment purchase costs were estimated using a cost correlation method based on heat transfer area (Seider et al., 2010). An empirical equation based on bowl diameter presented in the Seider et al., (2010) was utilized to calculate the purchase cost of basket centrifuge. The equipment costs were indexed to US \$2014 prices using chemical engineering plant cost indices (Chemical Engineering Plant Cost Index (CEPCI), 2015).

The fixed-capital investment for a fatty alcohol production plant was estimated using ratio factors based on the equipment purchase cost quoted in Peters and Timmerhaus (1991, pp. 182). The prices for glucose, nutrients, solvents, utilities, catalyst and product were obtained from market data. Future cash flows were projected over the plant life using incurred operating costs and sales of a fatty alcohol. After deducting taxes, at the rate of 39% on the gross profit provided it is positive, from gross profit gave us net profit for each operating day. These net profits were discounted to the year 2014 at the fixed internal rate of return of 10%. NPV of an

investment was calculated by subtracting the total investment cost from the summation of all discounted net profits over the plant life.

Variables in the economic model that cause uncertainty in fatty alcohol sales, operating costs, and ultimately NPV of an investment are the price of feedstock (i.e., glucose), price of product (i.e., fatty alcohol), price of hydrogen, price of catalyst (i.e., copper-chromite), price of electricity, and the price of natural gas. We assume that although input prices move up and down in the short run, they revert to the marginal cost of production in the long run (Dixit and Pindyck, 1994). Therefore, in the DCF analysis, price dynamics were modelled as stochastic mean-reverting processes (Dixit and Pindyck, 1994). The following mean-reverting process equation was used to model economic variables:

$$x_t = x_{t-1} + \eta(\bar{x} - x)dt + \sigma\epsilon_t\sqrt{dt} \quad (1)$$

Here, η is the speed of reversion; x_t is the commodity price at time t ; $\bar{x}$ is the long-run marginal price of the commodity or long term mean; σ the variance parameter; $x_t - x_{t-1}$ is the change in price over any time interval dt ; and ϵ_t is a random number with zero mean and unit standard deviation. Mean-reverting process parameters for the respective economic variables were estimated from historical time series data. We obtained historical glucose price data from the United States Department of Agriculture, (2014); fatty alcohol price data from ICIS chemical pricing, (2014); hydrogen, natural gas, and electricity price data from the United States Energy Information Administration, (2014); copper and chromium data from United States Geological Survey, (2014). Sample paths were generated for each economic variable over the plant life by calculating a trajectory for x_t with a time interval (dt) of one day using Mean-Reverting process equation.

The Monte Carlo simulation then randomly drew values from each trajectory of economic variable to generate a unique set of market prices and costs from which NPV was computed. The entire distribution of all draws (10,000) resulted in a NPV distribution for investment in a single-product technology as well as the platform technology.

2.4 Switching cost

In principle, with a platform technology a chemical company could switch products many times, but in practice this is unlikely. Whenever a chemical company switches its production from one product to another, it incurs the cost of process conversion (X_{sw}). We break this cost into one-time and recurring switching costs. When a change in technology, taken as an example for one-time switching cost, requires different separation equipment, chemical companies will have to invest only on one occasion to purchase this equipment. Once the firm has switched, they own the equipment. While in other cases, for example replacing an expensive noble metal catalyst with another in order to switch the production, an investment is necessary for each switching because chemical firms generally lease an expensive metal catalyst. Thus there is a cost associated with each switch between products that is characterized as recurring switching cost.

Since switching the production from one chemical to another requires additional investment (switching cost), a chemical firm will switch production only when the economic return generated from switching production is greater than the switching cost. Following this logic, a switching rule based on switching cost was developed to determine the possibility of switching among different products with platform technologies at any future time. The development of switching rule is explained in detail in the supplementary material of this paper.

We used this switching rule in the aforementioned Excel VBA model to determine the probability distribution of NPV of an investment for the carboxylic acid platform technology. At each time period t ($t=0, 0.25$ yr, 0.5 yr, ... 20 yrs.), the developed Excel VBA model compares the net profit from the current product production with the net profit from the alternative product production, and if the net profit from current product production is less than that of the alternative product production, then the decision to switch to an alternative product will be made based on the switching rule. When the decision to be made is switch to an alternative product at any future time t , the switching cost is discounted to the current time, $t=0$, at a rate of return (r) of 10% and added to the total capital investment.

3. Results and discussion

3.1 Quantitative analysis of platform technology

In this section, we quantify and compare the financial risk and profitability of an irreversible investment for the production of fatty alcohol via single-product and carboxylic acid platform technologies. We assume single product technologies produce blend of 1-dodecanol and 1-tetradecanol or 1-decanol from glucose, and the 2- product carboxylic acid platform technology can convert glucose into a blend of 1-dodecanol and 1-tetradecanol and has a flexibility to switch to 1-decanol with the switching cost of ≈ 0 . The switching cost is assumed to be zero because the production of one fatty alcohol to another fatty alcohol using the carboxylic acid platform technology is simply achieved by changing the bio-catalyst.

Both single and 2- product platform technologies are modeled using process simulation software to estimate steady state flow rates of products and raw materials. The capital expenses for the production of fatty alcohols via single and 2- product platform technologies are estimated using standard methods (Table 1). Future price trajectories of each stochastic variable (glucose,

fatty alcohol, natural gas, electricity, copper chromite catalyst, hydrogen prices) are generated over the plant life of 20 years following mean reverting processes. Parameters required for the mean reverting process are determined through linear regression using historic time series data (Table 2). With this information, an Excel VBA based-model was developed to determine NPV of an investment. Monte Carlo simulation is then performed to derive a distribution for the NPV of an investment for a fatty alcohol production via single and 2- product platform technologies.

The resulting probability density functions of NPV are graphed in Fig. 3. Deriving the NPV distribution of an investment in a project that employs a single-product technology to convert glucose into blend of 1-dodecanol and 1-tetradecanol, an expected value of \$12 million and standard deviation of \$25 million are estimated. The average value and the standard deviation of NPV distribution are found to be \$ 20 million and \$26 million respectively for the investment in single-product technology that can produce 1-decanol from glucose (Fig. 3). If the investment is made in the 2- product platform technology that has a flexibility to switch to an alternative fatty alcohol, the project mean and standard deviation of NPV distribution are calculated as \$ 31 million and \$20 million, respectively (Fig. 3). The difference between two mean NPVs, that is, \$ 31 million - \$ 12 million and \$ 31 million - \$ 20 million determine the increase in profitability of an investment by 2- product platform technology compared to single-product technologies. Comparing standard deviation of NPV distribution of investment for 2-product platform technology, that is, \$ 20 million with that of single-product technology, that is, \$ 25 million and \$ 26 million shows that financial risk due to volatilities in prices of product, feedstock, energy, and catalyst is reduced by the 2- product platform technology.

This reduction in financial risk and increase in profitability of investment with the 2-product platform technology will be explained as follows. For example, Fig. 4 shows the five-

year forecasted net profits that are generated from the blend of 1-dodecanol and 1-tetradecanol and 1-decanol production via single-product technologies. If a technology only makes one product (either blend of 1-dodecanol and 1-tetradecanol or 1-decanol), a chemical firm must live with the up and down swings of these net profits that are caused due to volatilities in market prices of product, feedstock, energy, and catalyst. However, suppose the chemical firm has the platform technology to produce multiple products. If the net-profits of an alternative product become more attractive, the chemical firm can consider switching. The expectation to switching is that market prices of product, feedstock, energy, and catalyst will revert toward their long-term means, that the net-profit difference may not justify the cost of switching production. This ability to switch between products with platform technologies reduces the impact of market volatility and increases value of the investment.

3.2 Impact of multiple products

In this section, we analyze how the increase in the number of products in the “product suit” of platform technology impacts the financial risk and profitability of investment. The product suit of single-product technologies contain only one product, and the product suites of two, three, and four product platform technologies contain two, three, and four products respectively.

The financial risk and profitability of investment for making 1-octanol, 1-decanol, blend of 1-dodecanol and 1-tetradecanol, and 1-hexadecanol via single-product technologies are determined by deriving probability density function of net present value (Table 3). The prices of 1-octanol and 1-hexadecanol are modeled using mean reversion process, and required mean reversion parameters are estimated from their respective historical data (Table 2). The estimated operating costs of 1-octanol production are slightly higher than the 1-decanol production, and of

1-hexadecanol production are slightly lower than the 1-decanol production. The results summarized in Table 3 show that as the profitability of investment for the fatty alcohol production via single-product technologies increases the financial risk to investment also increases. Among the four fatty alcohols analyzed in this work, the investment for the production of 1-octanol has high profitability and financial risk, and for the production of 1-hexadecanol has low profitability and low financial risk (Table 3). This high profitability is due to the high long term mean price of 1-octanol compared to other fatty alcohols, and the high financial risk is a result of high volatility or variability in the price of 1-octanol (Table 2).

In order to compare the economic value of investment for synthesis of fatty alcohols using 2-product platform technologies with that of single-product technologies, NPV of investment for all possible product suites of 2-product platform technologies with four fatty alcohols are estimated (Table 3). It is found from results that the profitability of investment increases and financial risk of investment decreases with 2-product platform technologies compared to single-product technologies (Table 3). However, the economic value generated from 2-product platform technologies with a product suit of 1-hexadecanol and 1-octanol, 1-decanol, or blend of 1-dodecanol and 1-tetradecanol is similar to that of single-product technologies making 1-octanol, 1-decanol, and blend of 1-dodecanol and 1-tetradecanol, respectively. This exception is because net revenues generated from 1-hexadecanol production over the simulated time period is always less than that of other fatty alcohols, and thus it is not attractive to consider switching to 1-hexadecanol production with a 2-product platform technology. Thus, the addition of low value product such as 1-hexadecanol to the product suit of platform technology will not improve the economic value of investment for the synthesis of biorenewable chemicals using platform technologies.

Since the product suit of 2-product platform technology having 1-hexadecanol will not add any value to the investment, we analyze product suit of 3-product platform comprising only 1-octanol, 1-decanol, and blend of 1-dodecanol and 1-tetradecanol. The probability distribution of NPV of an opportunity of investment for the fatty alcohol production via 3-product platform technology is calculated to determine financial risk and profitability of investment (Table 3). The results in Table3 show that the 3-product platform technology increases profitability of investment to \$45 million, which is higher than that of single- and 2-product technologies, and decreases the financial risk to \$16 million, which is lower than that of single- and 2-product technologies (Table 3). Thus, profitability of investment increases and financial risk of investment for the biorenewable chemical production via platform technologies decreases as the number of products in the product suit of platform technology increases. However, the extent of this impact on the economic value with the increase in number of products in the product suit of platform technology will depend upon the type of product in the product suit. For instance, as shown above the addition of low value product such as 1-hexadecanol to the product suit of platform technology can't improve the economic value of investment.

3.3 Sensitivity to switching cost

The production of fatty alcohols is a somewhat unique case. In general, there is a cost associated with platform technologies for switching from one product to another. In order to see how switching cost influences the economic advantages provided by platform technologies, profitability of investment for the synthesis of fatty alcohols via 2-product platform technology is computed for increasing one- time and recurring switching costs.

The profitability of investment for the 2-product platform technology allowing access to two markets 1-decanol and blend of 1-dodecanol and 1-tetradecanol for increasing recurring

switching costs is estimated by exercising the economic model nested with Monte Carlo simulation (Fig. 5). As shown in Fig.5, the profitability of investment decreases with increasing recurring switching cost. Similar behavior in profitability is observed with increasing one-time switching cost (data is not shown). This decrease in profitability is primarily because the 2-product platform technology will allow its production to switch less and less as the switching cost increases.

For the recurring switching cost of \$4MM (Fig.5) and one-time switching cost of \$6MM, the profitability of investment for making fatty alcohols via 2-product platform technology converges to the value provided by single-product technology. Hence, the economic advantage provided by the 2-product platform technology allowing access to two markets (1-decanol and blend of 1-dodecanol and 1-tetradecanol) vanishes when the switching cost is greater than \$4MM in the case of frequent investment and greater than \$6MM in the case of one-time investment.

One reason for the different maximum values for one-time and recurring switching costs is the dependence of profitability of investment on discount rates. While exercising the economic model nested with Monte Carlo simulation, switching cost is added to the total capital investment in the case of one-time investment and in the case of frequent investment, switching cost at the time of switching is discounted to the year of 2014 at the fixed internal rate of return of 10%, and then added to the capital investment. The application of discount rates that are less than or greater than 10% will result in maximum values of recurring switching costs that are less than or greater than \$4MM. In conclusion, the switching cost limits the commercial advantage provided by the platform technologies irrespective of the nature of switching cost. In the

following section, we will qualitatively state other advantages of platform technologies for biorenewable chemical production.

3.4 Qualitative risk analysis of the platform technology

We have so far considered market risk due to variation in the prices seen in the market. Another dimension of market risk results from depression of the market equilibrium or long-term mean price of a chemical as new producers enter into the market. This reduction in equilibrium market price is dependent on the price elasticity of supply and demand of a chemical. Such price depression will decrease the current equilibrium price of a chemical and set a new equilibrium price (Mankiw, 2012). If the equilibrium price is highly sensitive to market supply and demand, there is more risk to the investment, particularly to the ‘single-product’ technology. For instance, the market price of ethane in the US fell nearly by 50 percent since 2005 as its production has increased from 700,000 barrels per day in 2005 to 1,000,000 barrels per day in 2013, as a result of the shale gas revolution (Chamberlin, 2014). If a technology only made ethane, there would be a high risk of incurring financial losses to a company if profit margins were low, as is often the case for commodity chemicals. An advantage of a platform technology is that if the market for one target product collapses, such as ethane in this example, the investment is not lost because production can shift to another chemical with a relatively small additional capital investment.

Another source of risk to the investment in the biorenewable chemical business is associated with scaling-up a new technology. When an incipient technology is scaled up from laboratory- to pilot-, to commercial scale, there is a risk of short fall in technology performance due to insurmountable technological barriers that are not identified at the research and development stage (Edwards and Eng, 2015). If a single-product technology experiences such insurmountable technical barriers, complete losses of capital and technical investments are

likely. However, these losses are significantly reduced in the case of platform technologies. If development of a particular technology, the synthesis of fatty alcohols from fatty acid for example, fails to meet process performance targets during scale up, perhaps the chemical catalyst cannot achieve necessary levels of selectivity under production conditions, much of the technology of the carboxylic acid platform can simply be repurposed to target a different molecule within the platform, such as n-alkanes (Mäki-Arvela et al., 2007). Thus, the investments made in developing and commercializing the fermentation technology for fatty acid production from biomass and the separation of fatty acids from fermentation media are saved and redirected into another product line.

Platform technologies also provide an opportunity to deliver multiple commodity chemicals to the market with one facility thus reducing production cost. Werpy et al. (2004) have identified the most promising building block chemicals that can be derived from glucose. In addition, they identified a diverse portfolio of chemicals that can be subsequently produced from these building block chemicals. Most of the chemicals identified by Werpy et al. (2004) are commodity chemicals with relatively small markets; much smaller than ethanol, for example. This small market size limits the feasible capacity of a production facility if designed to produce only a single-product. The high production cost due to the diseconomies of scale may create a barrier for market entry for commodity chemicals, which generally have low profit margins. Having the ability to produce multiple products using the same equipment, platform technology makes it possible to capture the economies-of-scale possible from a large biorefinery– without over supplying any individual product market.

Investments in platform technologies for producing high-profit margin specialty chemicals may over time lead to the production of commodity chemicals. In general, it requires

large capital investment to construct high capacity plants for producing conventional commodity chemicals. The requirement of such high capital investments will create a barrier entering into the commodity chemical business. One strategy to overcome this barrier is to make a higher value chemical via platform technology. If production and marketing of the first, higher-value products is successful, technologies can be refined and de-risked. As technology risks decrease, it may be possible for firms to take on more market risk. Firms will have both technological and financial capacity to increase plant capacity as necessary to produce larger volume commodity chemicals from biomass. For example, when investments made by a company in the microbial production of specialty chemicals such as azelaic acid via reverse β oxidation (Cintolesi et al., 2014) are profitable; then there is an opportunity to expand plant capacity in order to make a commodity chemical such as adipic acid.

The inherent functionality of biomass also creates an opportunity for making novel chemicals with unique and improved properties. Such novel products can functionally replace existing petro-chemicals or create new opportunities in the chemicals markets. The risk to the capital investments for the synthesis of novel biorenewable chemicals via single-product technologies is high as markets for these products are not yet developed and there is high uncertainty associated with their market potential (Werpy et al., 2004). These risks can be reduced by making novel products via platform technologies as technical and capital investments of platform technologies can be spread over replacement, functional replacement, and novel chemical products. Moreover, with platform technologies a company can adjust production volumes of making drop-in and novel chemicals according to their market growth potentials.

4. Conclusions

There are several different types of risks associated with the production of biorenewable chemicals. These risks reduce the profitability of capital investments in single-product technologies and are a deterrent to investments in biomass conversion technologies. In this work, we have shown quantitatively how platform technologies can reduce financial risks and increase the value of investments in biorenewable chemical production relative to single-product technologies. Platform technologies that produce a large range of different chemicals generate higher returns with lower risk. The benefits of platform technologies are reduced as the cost of switching between products increases. Platform technologies also reduce the risk of introducing novel and low-market volume products to the market.

Biorenewable chemical companies may benefit from developing platform technologies, particularly if they already have appropriate technical and marketing expertise. However, bringing a product into a new market can be more expensive than developing the product and often requires specialized technical skills as well. Thus capturing the benefit of making multiple products from a single technology platform may significantly increase the total investment required and reduce the appeal of platform technologies, particularly to smaller firms.

Firms that already operate facilities such as biofuel plants or biorefineries built around corn wet or dry mills are likely to find it easiest to incorporate platform technologies to produce a range of chemical and fuel products for the obvious reasons that these plants have some of the requisite infrastructure and these firms have diverse technical talents. The exact type of technology platform that makes the most sense for any firm, however, will depend on that firm's endowment of technical and physical resources. Further research is required to define how characteristics of a technology platform such as number of products, range of product markets,

variability of market prices, correlation between market prices, and nature of separation processes benefit the unique circumstance of a particular firm.

In general, the advantages of a multi-product approach improve the prospects for developing biorefineries built around or incorporating platform technologies. Easing access to capital through development of risk reducing platform technologies can stimulate the growth of the biorenewable fuel and chemical industries. Targeting biobased chemical platform technologies in research and development funding may therefore accelerate the growth of a biobased economy.

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Figures

Fig. 1- The carboxylic acid platform technology: Synthesis of wide array of fatty alcohols by coupling of biological and chemical catalysis (Single column)

Fig. 2 (a) Fatty acid production process block diagram (adapted from Gunukula and Anex, unpublished work) (b) Fatty alcohol production process block diagram (adapted from Gervajio, 2012) (Double column)

Fig.3 - NPV distributions for 2-product platform technology making 1-Decanol & Blend of dodecanol and 1-tetradecanol and single product technology making either 1-Decanol or Blend of dodecanol and 1-tetradecanol (Single column)

Fig. 4 - Five year forecast of net profits of 1-Decanol (C10) & Blend of dodecanol and 1-tetradecanol (C12-C14) (Single column)

Fig. 5 - Effect of recurring switching cost on the expected NPV of 2-product platform technology making 1-Decanol & Blend of dodecanol and 1-tetradecanol (Single column)

680 **Tables**681 **Table 1- Total capital cost estimation for fatty alcohol production Process**

USD (in millions)

Total Equipment purchase cost (TEP)	9.2
Installed cost (32% of TEP)	2.9
Instrumentation (43% of TEP)	3.9
Piping (31% of TEP)	2.8
Electrical (10% of TEP)	0.9
Buildings (15% of TEP)	1.38
Yard Improvements (12% of TEP)	1.1
Service facilities (55% of TEP)	5.0
Total Direct plant cost (TDC)	27.18
Engineering and supervision (32% of TEP)	2.9
Construction Expenses (34% of TEP)	3.1
Legal Expenses (4% of TEP)	0.36
Contractor's fee (19 % of TEP)	1.17
Contingency (35% of TEP)	3.2
Total indirect capital cost (TIC)	10.8
Working capital (10% of TIC)	1.08
Solvent cost	0.04
Catalyst cost	0.2
Total capital cost	39.7

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683 **Table 2- Mean reverting parameters of economic variables**

Economic Variable	Long-run mean	Variance parameter	Reversion Speed (day ⁻¹)
Glucose	0.30 (\$/kg)	0.004	0.15
Natural gas	3.35 (\$/MMBtu)	0.014	0.018
Electricity	0.07 (\$/kWh)	0.001	0.18
Hydrogen	2.5 (\$/kg)	0.014	0.01
Copper chromite	8.5 (\$/kg)	0.023	0.18
1-Octanol	2.2 (\$/kg)	68.25	0.15
1-Decanol	2.0 (\$/kg)	9.14	0.0033
Blend of dodecanol and 1-tetradecanol	1.9 (\$/kg)	12.21	0.0017
1-Hexadecanol	1.6 (\$/kg)	7.83	0.015

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687	Table 3- Results for impact of increase in number of products in the product suit		
	Product suit of Technology	Profitability	Risk
	Single-product technology		
	1-Octanol	\$29 MM	\$31 MM
	1-Decanol	\$20 MM	\$26 MM
	Blend of dodecanol and 1-tetradecanol	\$12 MM	\$25 MM
	1-Hexadecanol	-\$01 MM	\$12 MM
	Two-product technology		
	1-Octanol & 1-decanol	\$38 MM	\$22 MM
	1-Octanol & Blend of dodecanol and 1-tetradecanol	\$37 MM	\$21 MM
	1-Octanol & 1-hexadecanol	\$29 MM	\$31 MM
	1-Decanol & Blend of dodecanol and 1-tetradecanol	\$31 MM	\$20 MM
	1-Decanol & 1-hexadecanol	\$20 MM	\$26 MM
	Blend of dodecanol and 1-tetradecanol & 1-Hexadecanol	\$12 MM	\$25 MM
	Three-product technology		
	1-Octanol, 1-decanol & Blend of dodecanol and 1-tetradecanol	\$45 MM	\$16 MM
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689			