Review

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Risk management consideration in the bioeconomy

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Abstract: In investing in a new venture, companies aim to increase their competitiveness and generate value in scenarios where volatile markets, geopolitical instabilities, and disruptive technologies create uncertainty and risk. The biobased industry poses additional challenges as it competes in a mature, highly efficient market, dominated by petroleum-based companies, and faces significant feedstock availability and variability constraints, limited technological data, and uncertain market conditions for newly developed products. Thus, decision-making strategies and processes for these investment projects must consider solid risk estimation and mitigation measures. Focusing on the biobased industrial sector, this paper critically reviews state-of-the-art probabilistic and deterministic methodologies for assessing financial risk; discusses how a complete risk analysis should be performed; and addresses risk management, listing major risks and possible mitigation strategies. © 2017 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: investment assessment; project evaluation; uncertainty analysis; financial risk analysis; probability analysis; biomaterials; bioeconomy

Introduction

Problem statement

Investing in new ventures is a pathway to increase a company's wealth and create long-term value.[1,2] Selecting among the most promising and robust alternatives increases the chances of the financial success of an investment. Furthermore, if the risks, uncertainties, and ever-changing circumstances associated with investment decisions are not fully addressed,[3,4] the likelihood that a high-risk and/or financially unsuccessful project is chosen increases.[5,6] The inherent complexities associated with the biobased industry and bioeconomy,[7,8] such as dynamic geopolitics, market conditions, and innovations in feedstock handling and processing technologies, exemplify the important role that risk management has when designing investment strategy. In this work, we refer to *biobased*

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industry as the industry that uses predominately renewable feedstocks that are generally a substitute for petroleum-based products.[9] The term *bioeconomy* refers to the 'set of economic activities related to the invention, development, production and use of biological products and processes'.[10] Another definition considers bioeconomy as the sustainable utilization of renewable resources for economic, environmental, social, and national security benefits.[11]

Investments in the bioeconomy unveil promising opportunities for the development of local and global economies. As an example, the implementation of biobased industries can trigger job creation, develop rural areas, and consequently local economies.[11,12] Similarly, the use of renewable materials decreases the dependence on petroleum and reduces greenhouse gas (GHG) emissions.[11–13] The creation of biorefineries can allow small facilities to generate additional and new biobased products while using the available feedstock in the region.[14] However, due to inherent innovation and uncertainties associated with the bioeconomy, chances of failure are always present and the application of risk assessment can potentially decrease them.

Although large-scale biorefineries such as corn ethanol in the USA and sugarcane mills in Brazil are well established,[15–19] as well as the pulp and paper industry, recent failure of ventures using lignocellulosic feedstocks can be attributed in part to an incomplete understanding of risks or the absence of robust risk-mitigation plans.[20] The following examples are for the biofuels industry, since the recent investments in industrial facilities were focused in this sector. For instance, Range Fuels Inc., initiated operations in 2010 with the goal of producing 20 million gallons of biofuel from wood chips; however, in less than one year and after spending $300 million of public and private funding, the company closed its operations due to lack of sufficient pilot plant data to prove the merits of the technology, a poorly functioning main reactor that was initially designed for coal and not properly redesigned for wood, and problems with the gasification catalyst performance.[20–22] Similarly, Kior Inc., a biofuels producer that initiated operations in 2012, closed down its facility after approximately one year.[23–25] Reactor bottlenecks, low equipment reliability, mechanical issues, poor catalyst performance, and the decrease of final products' market prices were listed as main reasons for the closure.[26]

Since investors are risk averse,[27,28] risk awareness and mitigation plans that consider both technological and process design as well as market conditions are essential to the expansion of the biobased industry. Unfortunately, data scarcity from long-term operations at industrial scale makes the evaluation of new technologies a challenge.[29] Moreover, the equipment and technology used to handle feedstock are often adapted from similar industries (such as pulp and paper and sugarcane mills), leading to unknown operating conditions and difficulties in predicting equipment costs. Other process uncertainties comprise variability between and within the chemical compositions of feedstocks that lead to different reaction yields, conversion technologies that are still under development, scale-up, and chemicals recycling at large-scale production.[30] Market uncertainties, such as feedstock cost and availability, petroleum price instability (that affects biofuels and commodities prices), and unpredictability of new products prices also strongly affect project feasibilities.[31] Finally, geopolitical instability, environmental concerns, societal acceptability issues, and issues associated with the project execution (such as delay in equipment delivery, lack of qualified labor work, among others) persist as with any other industry.

Risk analysis, including the assessment of technology and financial risks, can guide future research and development efforts that in turn minimize the potential for project failure. As techno-economic calculations consume a significant amount of time and resources, risk assessments must be performed at the early stages of project design to reduce costs and screen out the high risk and/or less attractive options. While assessing all associated risks is extremely complex, an analysis that elucidates and examines the primary sources of financial risk is essential for effective business planning because it allows for better mitigation strategies.[32] Despite its importance, numerous feasibility studies do not consider risk analysis and there is no publication that addresses the importance of risk analysis in the bioeconomy,[33] the tools available, and detailed analysis around mitigation strategies.

This work critically reviews concepts of uncertainty, risk, and risk analysis and addresses methods and risk evaluation tools used to assess financial risks of an investment. This work intends to fill the gap in the biobased industry and bioeconomy literature by (i) assessing quantitative risk assessment methods, (ii) elucidating what a complete financial risk analysis should include, and (iii) listing major risks and mitigation strategies.

Literature review

The first part of this section provides conceptual information on risk, risk analysis, uncertainty, and related concepts, followed by an overview on how financial risk assessment can be executed in the context of capital investment decisions. The second part critically reviews

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the main tools used for quantitative risk evaluation in projects related to the bioeconomy.

Methodology

Google Scholar, Scopus, and Web of Science were used to search for related literature, using keywords such as risk, risk concept, risk analysis, uncertainty, uncertainty analysis, biofuel, biomass, bioproduct, cellulosic feedstock, Monte Carlo simulation, sensitivity analysis, stochastic analysis, and techno-economic analysis. Studies that performed qualitative risk assessments were not included in this review. The literature search on the definitions was not exhaustive, since its purpose was to provide concepts for ease of comprehension. In addition, publications related to safety and hazards risks were screened out because we understand that this is a separate area of study. The structure of the review is according to the following rationale: identification of final bioproducts and project scopes evaluated with financial risk analysis, investigation of the inputs and outputs assessed, comments on information provided by risk analysis, illustration of the approaches used for risk assessment, discussion on the main gaps identified, and finally, a description of the tools used for quantitative risk analysis, including a case-study example.

Main definitions

The concepts of risk and uncertainty are not consistent in literature,[34–36] generating confusion even among specialists. Compilations of definitions can be found in several sources.[37–40] Some authors equate *risk* with *uncertainty,* showing how uncertainty can lead directly to negative impacts.[4,41,42] Others believe that the concepts are quite different, showing that risk relates to the confidence in the input parameters used for a cost estimation while uncertainty relates to the imprecision of the calculation in a model. Authors have related risk to probability distributions and claim that uncertainty exists when it is not possible to allocate probabilities to the results.[6,34,43] Others think that the concept of risk can be thought of as progressing from a narrow perspective of probability to a broader perception involving events, consequences, and uncertainties.[36,44]

Considering the context of investment evaluations and decision-making processes, the following definitions are suggested. Figure 1 illustrates how these concepts are related in the context of capital investment decisions and Fig. 2 presents the stepwise process for executing an investment analysis.

- *Uncertainty* (A) designates both the existence of more than one value or the absence of information and is also related to randomness.[37,45] Since uncertainty is intrinsic in any system, its characterization and interpretation is an essential element of the risk analysis.[46]
- *Risk* is a random event that negatively affects a company's goals.[35,37,41] If the impacts are positive, it is categorized as an *opportunity.*[35,41]
- *Risk analysis* (or *risk assessment)* (B) is a methodology used to estimate how often an event may happen and the extent of its consequences.[47] It comprises the identification of the source of uncertainty, uncertainty quantification, the formulation of uncertainty for risk

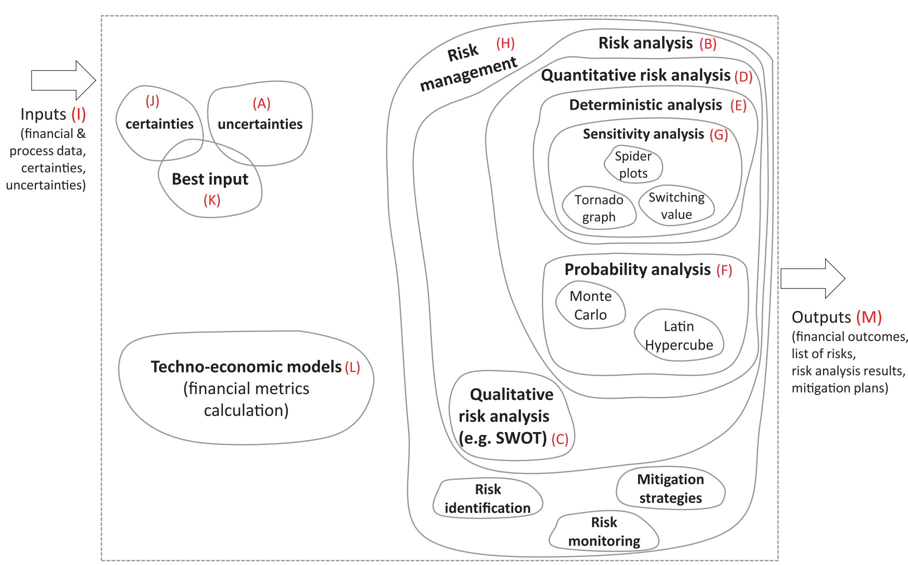

Figure 1. Risk concepts in the context of capital investment decisions.

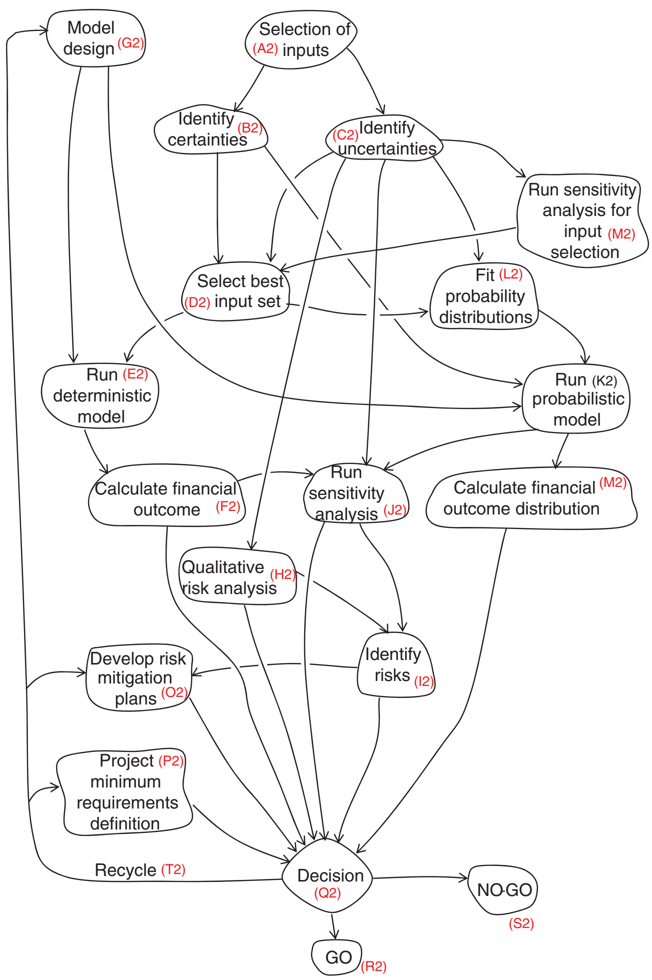

Figure 2. Stepwise process for investment analysis.

analysis, and finally the risk quantification.[30] Risk analysis can be conducted with either qualitative (C) or quantitative (D) methodologies.

- *Qualitative risk analysis* methods (C) classify the uncertainties that describe each scenario in terms of costs and benefits.[30] The risk evaluation is based on uncertainties assessment and usually contemplates prior experience, analogous situations, or even instincts or gut feelings.[47] An example of a well-known qualitative risk analysis methodology is the SWOT[1] analysis.
- *Quantitative risk analysis* methods (D) use numeric scales to quantify the uncertainties in a model.[30] The models for quantitative risk analysis can be deterministic – single output (E) or probabilistic – multiple outputs (F).[46]
- *Sensitivity analysis* (G) is a *deterministic risk analysis* method used to estimate the changes in model's outputs based on inputs variations.[3,30,45,48–50] The impact of changes are evaluated one input at a time and, consequently, the effect of simultaneous changes in two or more inputs cannot be assessed.[3,30] Tools to perform sensitivity analysis include tornado charts, spider plots, and switching value tables. Sensitivity analysis is widely used by the forestry industry,[51] probably due to its simplicity and easy interpretability of results.
- *Probability analysis* (or *stochastic analysis)* (F) is executed to estimate the probability distribution of the output values, based on the probability distributions of the inputs.[4,45,48] Although probability analysis is also identified as *risk analysis* or *uncertainty analysis* in the literature,[3,4,41,45,46,52,53] we believe that *risk analysis* is a broader concept that includes sensitivity and probability analysis methods, as shown in Fig. 1. Sampling methods for stochastic analysis include Monte-Carlo and Latin Hypercube, which will be discussed in detail later.
- *Risk management* (H) is a process that includes risk identification and analysis, development of mitigation strategies, and the monitoring of new events categorized as risks and opportunities.[35]

Profitability calculations are usually performed to provide information regarding the financial feasibility of a venture. Techno-economic models (L) have been used for this purpose, and use the best set of inputs (K), selected from inputs that are both certain (J) and uncertain (A). Due to associated uncertainties (A) of some inputs and unknown future circumstances, the investment can still follow a risky pathway that may lead to a less profitable output. To identify, understand, reduce, and mitigate potential threats, it seems reasonable to perform investment risk analysis (B) and risk management (H) during the capital investment evaluation process. The outputs from techno-economic model, risk analysis and risk management (M) can provide a better understanding of the investment profitability outcomes, possible risks related to the venture and the possible mitigation plans.

Figure 2 shows the stepwise process for financial risk analysis of an investment using the components presented in Fig. 1. The first step for profitability calculation is the input selection (A2), which consists of financial and process inputs. Examples of financial inputs are final product

[1]SWOT stands for Strengths, Weaknesses, Opportunities, and Threats. In this methodology the issues of a project, for example, are listed in the four quadrants of the SWOT analysis grid, helping to comprehend how the strengths can be monitored to achieve opportunities and how the weaknesses can evolve to threats [95]

price, interest rates, subsidies, inflation, and costs related to raw material, equipment, labor, and capital. Process inputs are usually related to reaction yields, production rates, feedstock composition, catalyst consumption, final product specification, flowrates, utilities consumption and process conditions (temperature, pressure, reaction time, etc.). Traditional techno-economic analyses select the 'best' estimate of inputs (D2) among certain (B2) and uncertain (C2) values to run a deterministic model (E2) and estimate financial outcomes (F2).[41,45,54] A single estimate from each input is used to generate a single value output.[41] Techno-economic models (G2) are commonly used for investment evaluation and are designed for each specific project. They are a combination of process models, which simulate the processes to convert raw materials into products with mass and energy balances, and financial models, which calculate financial outputs based on cash flow analysis.

As presented earlier, investment risk analysis can be carried out using qualitative and quantitative methods. Through qualitative methods (H2) the risks are identified (I2) based on subjective criteria. Sensitivity analysis (J2) is a quantitative pathway to assess the risks of a project. In this case, the financial outcome calculated (F2) is defined as the base value, and through sensitivity analysis it is recalculated for different input values (based on uncertainties in the input values (C2)).

Stochastic modelling (K2) is used to complement the deterministic model (E2). Similar to the deterministic model, the probability model is designed (G2) and the inputs are entered as the probability distributions of values (L2). As the number of inputs with probability distribution can be numerous in some situations, sensitivity analysis (J2) is used to select parameters with stronger impact in the output. In contrast to sensitivity analysis, the outcome of probabilistic models is the probability distribution of the financial outcome when all inputs (with their respective distributions) are iterating at the same time (M2). The probability analysis quantitatively exposes the venture's risks.

It is not necessary to perform all methods for risk analysis. The selection of the most appropriate method will depend on the phase of the project and on the information available. It seems preferable to execute qualitative risk analysis in the early stages of design and the stochastic risk analysis in subsequent phases, when more reliable information is available. Nevertheless, there is no established rule when applying a methodology.

After the identification of specific risks (I2), mitigation strategies (O2) can be proposed to reduce their probability and severity. By having more information regarding the minimum financial and technical requirements for the project (P2), managers and investors can have a better understanding of the risks associated with the venture and the proposed mitigation strategies. With all this in hand, decision makers can decide (Q2) to initiate (R2) or reject (S2) the project or ask for additional details on the models and inputs (for example, defining the impact of new plant throughput or process conditions), adjust mitigation plans or even alter the minimum requirements for project approval (T2).

Risk assessment for investments in the biobased industry

This analysis focuses on the application of quantitative risk assessment methodologies as well as commonly used tools and their respective advantages and disadvantages. There are a few dozen recently published articles (dating back to 2000) related to the application of financial quantitative risk assessment, with a greater share coming in the last 10 years. This is probably due to the relative novelty of biobased technologies, recent policies to develop an economy less reliant on oil, and the development of easy-to-use computational tools such as Microsoft Excel® add-ins.[33]

Final products and project scopes evaluated

As the United States and Europe have set ambitious targets for the use of renewable fuels,[55–57] it is not surprising that most risk analyses have been concentrated on investments for liquid biofuels production using different renewable feedstocks.[7,8,16,18,28,33,52,55,58–67] Other works have assessed financial risks for biopower generation from woodchips and co-production of ethanol and power.[15,68,69] Few papers performed financial risk analysis for chemicals and biomaterials manufacture.[17,31,70,71]

Quantitative risk analysis has been most commonly used to estimate the probability of financial success for a single conversion pathway or to identify the most promising option among different project alternatives (e.g. use of different feedstocks and conversion routes to produce different final products).[7,8,15–18,55,58,61,63–67,69,71,72] Other applications include (i) estimation of final product price,[62] (ii) investigation of the uncertainties associated with the production process[17] and feedstock supply cost,[60] (iii) evaluation on the impact of subsidies for an investment,[28] (iv) guidance to optimize the conceptual design of a project or the operating conditions of a facility,[52,68] and (v) assessment of risk for different biomass supply contracts considering the farmer and facility standpoints.[73,74]

Main inputs and outputs assessed

Quantitative risk analysis has been commonly used for the assessment of specific risks, rather than for understanding those inherent to the entire supply chain. For instance, the risks of financial loss can be minimized (for both the farmer and the producing company) if raw material contracts consider two combined metrics: one based on dollar per cultivated acre and one on dollar per ton of biomass.[73] Similarly, the risks of feedstock cost based on cultivation location are lowered when sourcing from irrigated areas due to yield stability.[60] Finally, it has been shown that the impacts of feedstock composition variability on project profitability are profound, with small changes (around 3 %) altering the investment's NPV (Net Present Value) by tens of millions of dollars.[56]

The consequences of key financial parameters' variations have been the most common focus of risk assessment,[75] although in some situations the impact of reaction yield variability was also significant.[67] Final products and by-products prices, interest and inflation rates, and costs associated with raw materials, catalysts, utilities and capital investment, and contingency plans are the most common parameters analyzed.[7,8,16,18,19,28,33,61,62,64–66,68,69,71] The most common financial metrics used have been NPV, Return on Investment (ROI), and Internal Rate of Return (IRR).[7,8,16,18,19,28,33,55,59,61,65,66,68,69,71–73] Other metrics include the minimum revenue price for the final product,[8,15,28,55,62,64,67] and production costs.[52] While Zhao *et al.* (2015)[55] argue that breakeven price is a better measure than NPV in the decision-making process since it does not consider the uncertainties in the final product's price, we consider that the uncertainty in final product prices is highly important and should be taken into account in the evaluation of any investment, especially if the final product is a fuel or a commodity. In the literature review performed for this paper, we noticed that the variation in the final price of the product is among the most important parameters affecting the financial performance of a specific project.

Outputs from the sensitivity analysis have shown that feedstock cost and final product price are usually the financial parameters with greatest impact on a venture's profitability,[7,8,17,19,28,55,61–66,68,69] followed by capital investment.[15,17,19,64] For biochemical processes, enzyme price has also been found to be significant, depending on the final product obtained and the specific technology applied.[8,15,19,70] For processes that use hydrogen as a raw material, it has been shown that its price variation, or the technology used to produce the hydrogen, significantly affects project profitability.[55]

Variability in process inputs should be considered and can also have a major impact on investment risks. However, in many cases these parameters' impacts are not closely evaluated. Reasons for not including stochastic distributions on process inputs are related to data availability and the difficulty of performing several process simulations in parallel.[62,64] Major non-financial risks evaluated include feedstock availability, composition, input flowrate, and reaction yields.[8,15,52,55,61,62,64,67,68] In an unusual evaluation, Morales-Rodriguez *et al.* focused solely on uncertainties in process parameters and found that changes in reaction yields and feedstock inhibition were the most important risk factors for financial return from production of lignocellulosic ethanol.[52]

Another type of risk assessment includes the evaluation of the impact of subsidies and policies on project profitability. The probability of having a profitable investment is significantly lower when government subsidies are not taken into account,[72] or when tax rates increase or tax credits are not available.[16,58] Some studies have used probability analysis to estimate the value of the subsidy required to increase the probability of achieving the desired financial outcome.[59] Some risk assessment methodologies have been used to illustrate that inputs used in deterministic modelling may be too optimistic. For example, stochastic analysis results showed relatively low probability of having IRRs higher than the calculated deterministic value.[17] Likewise, it was found that deterministic analysis results can underestimate the manufacture cost of biofuels when compared to the estimation using probability analysis.[67]

Risk assessment approaches

Quantitative risk assessments for biobased industry investments have two main approaches: studies that employ only probability analysis, and studies that consider both sensitivity and probability analysis. The first approach has been less common in literature, where the desired output is solely the distribution curve of the financial output.[28,59,60] The second approach provides a deeper understanding of the outputs, and sensitivity analysis was commonly used to (i) identify the parameters with high impact on the model output,[8,15,17,19,52,55,61,62,64–67,69] (ii) help select inputs to assign stochastic distribution,[7,52,68] (iii) identify major input parameters to be modified for conceptual design optimization,[68] and (iv) reach cost-effective operating conditions.[52]

It is imperative to carefully define uncertainty limits when performing risk assessment. These limits can be sourced from historical records, forecasted trends, literature data, reference cases, and expert interviews.[7,8,16,18,19,28,33,52,55,59,61,63–69,71,72] Usually, the probability distributions for raw material costs and final product prices have been obtained by adjusting a distribution curve on real historical data.[8,15,16,18,61,65,66] Common adjusted curves are triangular, pert, normal, and lognormal shaped.[7,17,28,58,62,64,71,76] Uniform distributions have been used when there is high uncertainty on a parameter value, lack of information on the input mean value or unavailability of data distribution. Some examples where uniform distributions have been used are capital investment,[8] reaction yield and by-products prices.[17,61]

Main gaps identified

Main gaps identified in the execution of this review are related to the underestimation of different types of uncertainties during the risk assessment process. Most of the previous publications have considered only specific uncertainties when performing risk analysis, mainly related raw material costs and final product prices. To the best of our knowledge, consideration of uncertainty across the whole supply chain has not been documented in literature. In addition, there are few studies on the impact of the shape of the probability distribution curves, since in many cases there is little data available. Finally, previous research has failed to analyze the development and role of mitigation strategies, a crucial step when evaluating investments. The chances of an endeavor's techno and financial success can only increase when risks are adequately addressed and feasible plans for risk minimization or contingency are available.

Tools used for quantitative risk analysis

This section provides a short description of the tools used in sensitivity and probability analysis, and shows how these tools can be effectively used for financial risk assessment. Following, a case study is presented to better illustrate how the tools are used and the major differences between them.

Sensitivity analysis tools

Sensitivity analysis, occasionally called *what if* analysis, evaluates impacts on a given outcome based on changes in the input variables. It is a fundamental concept for the decision making process and simple to implement.[77] The independent variables are modified, one at a time, and the outcomes are recorded. A Microsoft Excel® spreadsheet can be used to perform sensitivity analysis, and numerical results are easily evaluated in graphical presentations, such as tornado diagrams and spider plots,[8,15,17,55,56,61,64,66,67,69,70] although they can also be presented in a table format (switching value analysis). The main drawback of sensitivity analysis is that it does not consider interaction among variables.[28] In-depth information on sensitivity analysis can be found in literature.[30,41,77]

Tornado diagrams provide a quick overview of the most influential input model parameters.[41] In Fig. 3(a), the vertical axis of the diagram is the base-case output from the deterministic model. The model is then recalculated by changing each input, one at a time, to the upper and lower values and this is reflected in the length of the bars on the *x* axis: longer bar lengths show a greater impact of the respective input on the outcome.[50] More information on how to construct tornado diagrams using Microsoft Excel® spreadsheets can be found elsewhere.[78] Some authors developed an advanced configuration of the tornado diagram, named *uncertainty tornado chart,*[64] in which the bars have a boxplot format, enabling the analyst to identify outputs for the input ranges that are more likely to occur. The add-ins that perform Monte Carlo sampling usually express the tornado diagram in the form of a correlation parameter graph (Fig. 3(b)). The software uses each independent input distribution to construct the correlation diagrams, in which coefficient values vary between +1 / -1. The

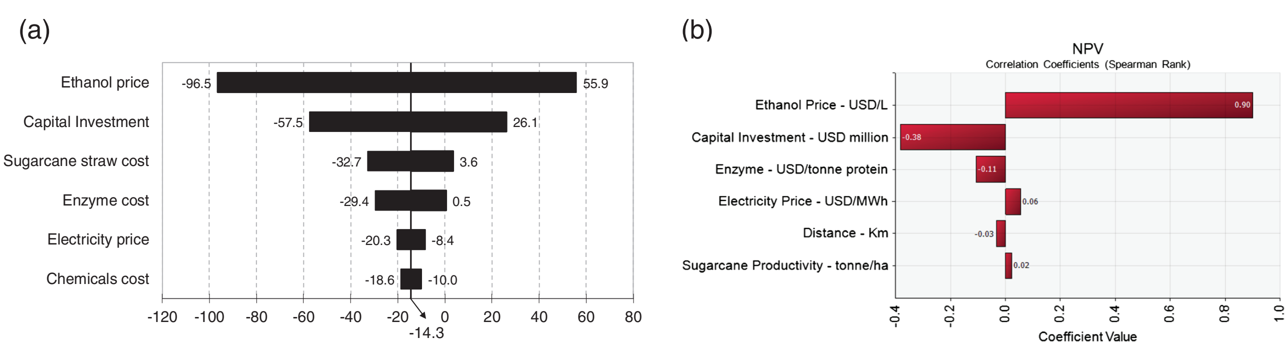

Figure 3. (a) Example of a tornado diagram. (b) Correlation parameter graph based on Assis (2016).[82]

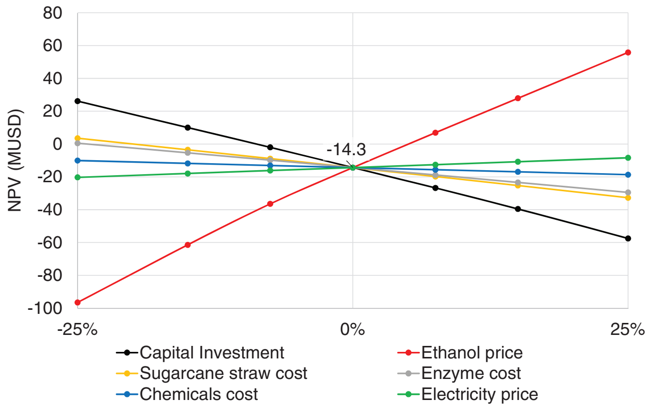

Figure 4. Example of spider plot (adapted from Assis, 2016).[82]

Table 1. Switching value table.

Input variable	Switching value (turns NPV to zero)
Ethanol	+5.0%
Capital investment	– 8.7%
Sugarcane straw cost	–19.9%
Enzyme cost	–24.1%
Electricity price	+60.8%
Chemicals cost	–84.3%

closer the correlation coefficient is to +1 or –1, the more the output is dependent on the input, whereas a value of zero indicates no influence of the input on the output.[41]

Spider plots (Fig. 4), like tornado diagrams, illustrate the impact of changing one input at a time on the output results. The spider plot is constructed by plotting the output against different inputs for each independent variable on an *x-y* plot. Usually, the *x*-axis represents the percentage change from the defined base case scenario for each input.[50] The higher the absolute value of the curve slope, the greater the impact of input variability in the output value. The number of input variables should be restricted to four or five as visualization can easily become overcrowded.[78]

The **switching value method** (Table 1) expresses the percentage change of each variable, done one at a time, necessary to bring the project NPV to zero.[79] The smaller the switching value is relative to the others, the greater its impact.[65] The advantage of this methodology resides in displaying readily accessible numerical information to the analyst on how the inputs should be changed to achieve NPV zero.

Probabilistic analysis tools and computational add-ins

Computational add-ins are commonly used to perform risk assessment, mainly for probability analysis. The software package @Risk, from Palisade, has been extensively used for quantitative assessment of financial risks in bioprocess investments.[7,8,15,17,28,55,60,61,65,66,69,70] Other software used are Crystal Ball,[62,76] and Simetar©,[16,18,33,59,72] although some authors have developed their own routine models in Matlab® and Mathematica™.[52,64] Monte Carlo is a widely employed sampling method, in which the model normally runs between 1000 and 5000 iterations,[80] with random selection of input values generating a representative range of output values.[81] The result is a clearly defined distribution curve for the outputs. While less commonly used, Latin Hypercube is another sampling method in which the stratified probability distribution is divided in equal intervals and a random value from each interval is sampled, thus faster converging the simulations.[67,73,81] Historically, Monte Carlo simulation methods were considered to be complex and time-consuming, requiring considerable amounts of information regarding input values and their expected ranges.[68] However, Monte Carlo simulation has become more popular due to reduced computing costs and the availability of computational software.[33]

Case study: using quantitative risk analysis tools

In this section, results from a case study are illustrated to provide a better understanding of the risk analysis tools previously discussed. The techno-economic model is based on Assis (2016).[82] In this analysis, the financial risk of producing second-generation ethanol and electricity from sugarcane bagasse and straw in a facility co-located with an autonomous distillery is assessed. The financial output is the NPV (calculated at a 12% discount rate), and the inputs evaluated are ethanol price, electricity price, straw cost, enzyme cost, chemicals cost and capital investment.

Sensitivity analysis is performed to investigate how inputs' variation affects the NPV. The inputs are changed by ± 25%. The base NPV value calculated by deterministic analysis is –14.3 MUSD. In Fig. 3(a), the tornado diagram illustrates that ethanol price variation is the major cost driver (wider bar), followed by the capital investment. The diagram shows that a 25% increase in ethanol prices increases NPV to 55.9 MUSD.

The same set of data is used to build the spider plot (Fig. 4). All curves intersect in the base NPV value (–14.3 MUSD), and as anticipated by tornado graph, the ethanol price

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presents the higher curve slope, indicating that it is the major driver, followed by the capital investment.

It is worth mentioning that tornado diagrams show the major inputs in a clearer way when compared to spider plots. However, it can be challenging to identify if an increase in input increases or decreases the output in a tornado diagram. This information can be easily observed in the spider plot through the slope inclination. On the case study, the spider plot shows that the NPV increases for an increase in ethanol price while the increase in capital investment lowers the NPV. Additionally, spider plots illustrate how is the relationship between inputs and output (e.g. linear or non-linear).[50] Nevertheless, when several inputs are evaluated in parallel, it is recommended to construct a tornado diagram, since the spider plot can be overcrowded. In summary, tornado diagrams and spider plots provide complementary information: the first summarize the impacts of each input variable in a clear and simple way, while the second give a more comprehensive view on the input–output relationship.[45,50]

Additional information can be explored using the switching value method (Table 1). For the case study presented, the table shows by how much each input should be changed independently to reach NPV zero. As previously mentioned, the estimated NPV is –14.3 MUSD. Ethanol price, the input with major impact, need the smallest change (increase of 5 %), to turn NPV to zero. However, chemicals' cost – the input with less impact in the NPV — needs to decrease by 84.3 % to turn NPV into zero. As tornado diagrams and spider plots, the results of the switching value method consider the variation of one input at a time, so it is not possible to assess the impact of two or more inputs in parallel using this tool.

Probability analysis was performed for the same case study, using the software @Risk. In this case, distribution curves were adjusted for each input: ethanol price (based on historical data), electricity price (based on historical data), enzyme cost (from the literature), and capital investment (uniform distribution). Straw cost was calculated based in the sugarcane productivity (historical data) and the collection distance (information from the literature). The cost of chemicals was not considered in this analysis since it presented very low impact in the output.

The model was executed with the input distributions and the graph in Fig. 5 was generated. The results of the probability analysis show that there is a chance of 47.5% of NPV being positive. The mean NPV value, considering all the distributions, was calculated as 0.94 MUSD. Probability analysis provide additional information to the analyst, since the risk of a financial failure is assessed, based on the uncertainties provided. Nevertheless, the decision to proceed or not with the investment depends on the risk appetite of the decision maker. As mentioned earlier, @Risk software provides a correlation tornado diagram (Fig. 3(b)). From this result, it can be inferred, as the tornado diagram and spider plot pointed out, that the NPV is highly dependent on ethanol price (correlation coefficient of 0.9), followed by the capital investment. From this tornado correlation diagram, it is possible to see if the correlation input–output is positive or negative, as it is in the spider plot. Assis (2016)[82] used probability risk analysis tools to calculate what would be the minimum ethanol price that guarantees 99.9% probability of positive NPV, thus minimizing the investment financial risk. This information could be used to assess what would be the amount of subsidies needed to develop the second-generation biofuels industry, for example.

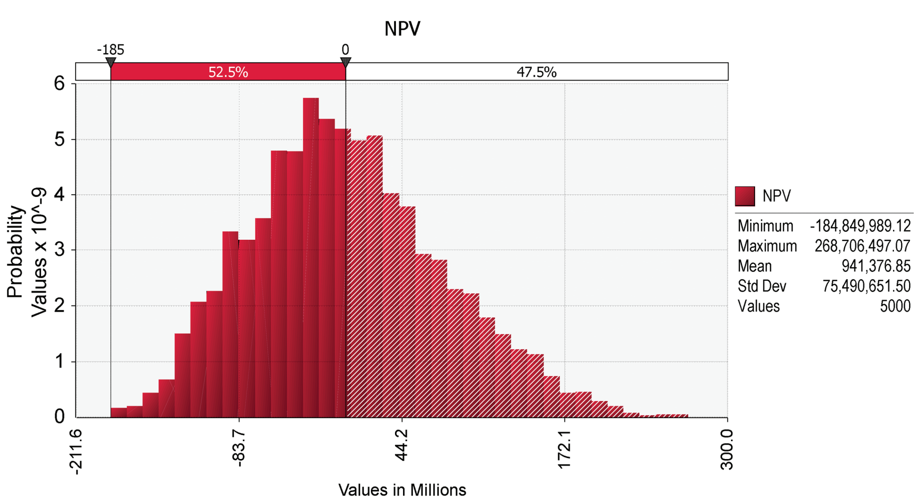

Figure 5. Distribution of NPV values for the case study (based on Assis, 2016).[82]

As was exemplified by the case study, sensitivity and probability analysis tools provide complementary information about the financial risks of the investment. The quality of the results is based in the quality of input information. These tools provide additional quantitative information for the decision maker and can point out where to devote efforts in order to minimize the chances of project failure from a financial perspective.

What a complete financial risk analysis should include

In this section, we discuss how a complete financial risk analysis should be performed, considering the literature and tools reviewed. The following guidelines can be applied for any investment assessment. We believe that the use of quantitative financial risk analysis is especially beneficial for bioeconomy investments, due to the inherently uncertainties previously outlined.

Initially, one should identify the required amount of detail for the analysis considering the current project phase and level of information available. For example, when information about process conditions, equipment design and costs are not available, typically in the early stages of a project, a sensitivity analysis may be sufficient to determine whether to move forward on a project (often termed as GO/NO-GO).

A further step is to identify and define the inputs and their associated minimum and maximum values. The number of inputs included should be sufficient to cover the entire supply chain, and feasible minimum and maximum values for each input should be considered in order to have reasonable analysis results.[50] Sensitivity analysis is one available tool to select inputs for probability analysis. The probability analysis evaluates the effects of manipulating inputs simultaneously and is usually presented as the distribution of financial metric's values.

The outcome of the deterministic model (single output result) should be evaluated in conjunction with sensitivity and probability analyses to have a relatively complete picture of the risks. However, the combination of deterministic and stochastic models can be problematic (for instance, using a mean value calculated through the probabilistic analysis as an input for deterministic modelling can generate misleading results because the probabilities are not taken into account).[37] Since the numerical precision of probability analysis results does not provide important information about their sensitivity to changes in the inputs,[83] combining them with sensitivity analysis provides synergetic risk assessment results.

Figure 6 provides an effective way of selecting tools to use when performing quantitative risk analysis, which will depend largely on the information available. If there is no uncertainty in the input data, a deterministic model is sufficient to give a single-point output. However, a situation free of uncertainty is very unusual. When uncertainty exists, the tools used will depend on the requirements and on the approach defined by the project team. A qualitative risk assessment may be sufficient if there is no need to quantify the outputs and in the very early stages of a project when no quantitative inputs are accessible. If quantitative inputs are available, the use of tools will depend on the type of uncertainties present. For instance, if one has only the maximum and minimum values for the uncertain inputs, a sensitivity analysis can show how the model outputs vary with each individual input change, and probability analysis can be performed considering uniform distributions. In addition, consideration should be given to how results are presented when selecting specific tools. For example, as spider plots can become crowded, it would be more appropriate to use a tornado diagram for graphical outputs and a switching value for table outputs if there are more than five input variables.

Stochastic analysis is recommended when the distribution of uncertainty is available or it is possible to adjust distribution curves to historical records, forecast trends or literature data or even if there is a large uncertainty in the input values. The stochastic analysis results show the combined impact of including several uncertainties simultaneously and provides information on the probability of a successful investment, from the financial point of view. There is no significant difference between Monte Carlo and Latin Hypercube models, and their use can be subjected to the software and models available.

The results of sensitivity and probability analysis provide meaningful information for investments in the bioeconomy sector. For example, stochastic analysis outputs show the probability of having a profitable investment (e.g. 30% chances of positive NPV). Moreover, sensitivity analysis results elucidate which parameters should be investigated and changed to improve the probability of financial success (e.g. composition variation of a feedstock). The outcome from this analysis provides guidance on where to devote efforts to improve efficiently the financial performance of the investment.

  | *Biofuels, Bioprod. Bioref.* **11**:549–566 (2017); DOI: 10.1002/bbb

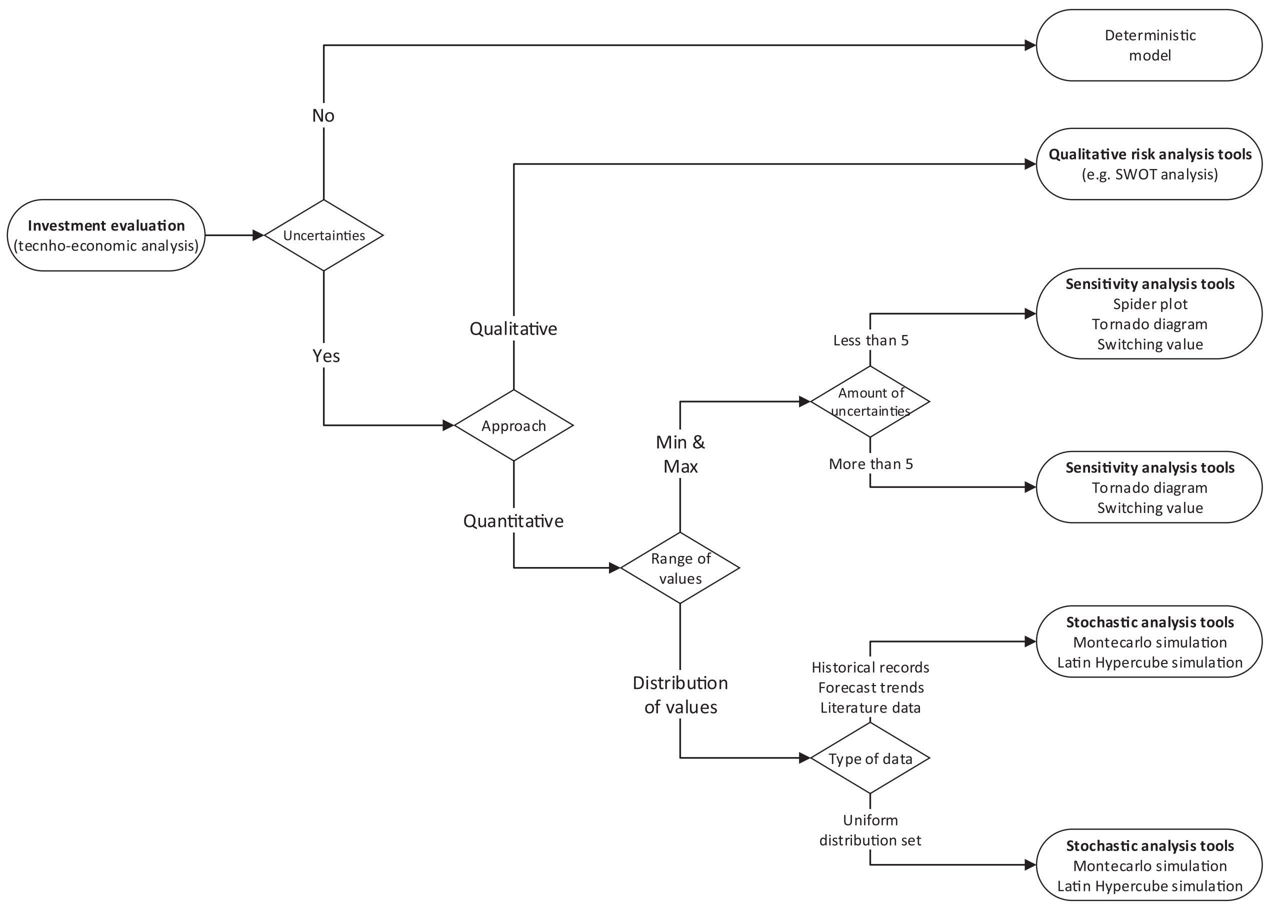

Figure 6. Decision tree for selection of qualitative and quantitative risk analysis tools.

In addition to risk assessments, any comprehensive analysis should address risk management, including ranking and illustrating major risks according to their probability and severity in a numerical scale. For example, a scale from one to four can be used, where one represents low probability/severity and four high probability/severity. Risks with the highest impact and likelihood demand the most attention.[84] Risk severities, risk likelihoods and probability distributions can be inferred and/or estimated by sensitivity analysis, probability analysis, prior experience, or subjective evaluations by the project team. Major risks can be easily illustrated in a risk heat map,[37,84,85] as shown in Fig. 7. In this example, risks 3, 4, and 7 are the most impactful and should thus be the focus of mitigation strategies.

Mitigation plans are the final step in in the risk-management process. In many cases, mitigation plans require additional data, which may be resources and time consuming. Risks will always be a part of any investment, but risk awareness and mitigation strategies plans are essential for minimizing the chances of an investment failure.

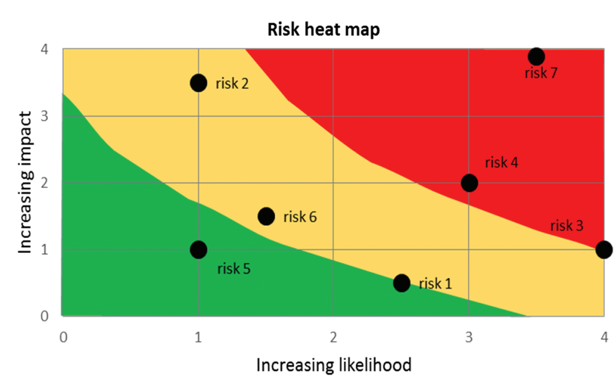

Figure 7. Example of a risk heat map (adapted from Branson, 2015).[84]

With a complete financial risk analysis and risk management, investors can have a more comprehensive view of a project and its uncertainties, making it possible to develop effective mitigation strategies and bring better technical information to support the decision-making process.

Major risks for the biobased industry and proposed risk mitigations

Biobased industries have unique risks, in addition to those found in any venture, which must be systematically identified and mitigated.[86,87] Table 2, while not exhaustive, provides an overview of the major risks in the biobased industry and possible mitigation strategies. This table illustrates the major risks identified from the literature review and from information related to recent biobased industry project failures. Critical risks primarily relate to feedstocks, processes, products, market and technology,[27,29,68,87] in addition to operation, financial, legal, regulatory and environmental.[68]

As previously mentioned, feedstock cost uncertainty can harm the development of the bioeconomy. While their prices will likely rise over the long run due to increased demand,[87] it will be accompanied by significant volatility due to weather conditions, diseases, pests, and/or competition from alternative land uses. Feedstock supply and plant size tradeoffs are another consideration. Although the increase in processing scale reduces operating costs per unit of product, larger collection areas can increase transportation costs of feedstocks.[14] Likewise, commodity processing plants scaled to typical forest biomass supplies can be too small to be economically viable whereas those at an economically-sensible size will face higher feedstock costs.[14,88] Establishing mid- to long-term contracts and diversifying suppliers can help mitigate risks concerning raw material supply and cost volatility. Finally, contracts between farmers and companies can be modified to minimize risks of biomass supply and prices.[73,89]

Final price volatility is another major known market risk and is common when the final product is a commodity or a substitute for a product derived from petroleum. Prices for liquid biofuels are dependent on the price of gasoline, an inherently price volatile commodity.[33] This helps to justify policy support for biofuels, which are exposed to political and social changes. Bioproducts (such as biochemicals and biomaterials) that have unique characteristics compared to the petrochemical derived products, will be less challenged by oil prices,[14] and can present fewer risks than commodity biofuels. A company can increase profitability and reduce risk by diversifying the final product portfolio as it would reduce exposure to price volatility in a single market.[15] However, this should be carefully evaluated from technological and financial perspectives as relevant studies vary their results. For example, Mariano *et al.* observed that the introduction of the butanol and acetone production via ABE fermentation in a first- and second-generation ethanol from sugarcane mill increased and diversified the revenue.[19] In another analysis, although a techno-economic evaluation of butanol and ethanol production showed higher revenues than a single ethanol facility, NPV and IRR were decreased due to higher capital and operating costs.[17]

High production costs can lead to low project profitability. For example, bioethanol and biobutanol production costs using sugarcane bagasse as feedstock are strongly impacted by the enzyme cost whose prices are inherently volatile.[7,70] If enzymatic technologies become widely available, the risk of an increase in enzyme cost due to higher demand is real, but at the same time the overall production costs should decrease as manufacturers become more skilled. These trends will affect the financial return for a new venture, and both price scenarios should be considered during risk assessment.

High capital costs can limit the development of bioindustries. The shape of distribution curve of the capital cost values can highly affect the profitability calculation results, so the uncertainty of the values should be carefully assigned.[76] This risk can be minimized by evaluating the main components related to capital costs, such as investment scope and main equipment costs. Several strategies can be employed to reduce capital costs. For instance, co-locating with existing mills and pulp and paper industries utilizes existing infrastructure, such as roads, buildings, and processing equipment. Further, including higher 'capital contingency' (an amount of money to cover known-unknown costs) is common for these new ventures because unmitigated risks may need extra expenses; however, higher contingency plans also lead to higher financing costs.

Government policies such as excise tax credits or accelerated depreciation should help the biobased industry development by increasing profitability and reducing risk.[17,67,87] However, most of the policies are temporary and subject to shifting social and political landscapes and, unless officially approved for the project, should not be considered as a permanent fact when conducting long-term financial projections and early stage scenario comparisons.[7] Policymakers generally echo this sentiment and argue that biorefineries should be feasible without subsidies or unique incentives.[87]

Technological risks are among the greatest sources of concern in the bioeconomy because of its relative nascent state. Information on lignocellulosic-based technologies is usually scarce and being developed by small and medium enterprises who lack the capital needed for prolonged development and testing.[86] In addition, equipment and

Table 2. Main sources of risk and risk drivers for the biobased economy.

Risk category	Risks	References	Proposed mitigations
1 – Market	1.1 Uncertainty on raw material cost	15,17,56,69,87	Identify feedstock cost variability based on past data. Establish mid to long-term contracts. Diversify suppliers to avoid one-to-one dependence. Consider cheaper feedstocks options (such as rejects and wastes).
	1.2 Volatility on final product price	8,17,69	Establish mid to long term contracts.
	1.3 High enzyme cost and variability	7,70	Develop R&D plans to minimize enzyme consumption. Consider Mid to long-term contracts on enzyme supply.
	1.4 Competition with commodities / petrochemical industry	14,92	Find products with unique characteristics to have less price competition.[14] Diversify production,[15] preferably with value-added products.[14,87]
2 – Technology	2.1 Scale-up	93	Perform pilot trials, and, if possible, do scale-up in steps.
	2.2 Technology risk - general	27,29	Perform pilot trials, especially for the reaction section. Identify risky process conditions.
	2.3 Use of genetically modified organisms (GMOs) for fermentation	93	Identify regulations and restrictions for GMOs in the region where facility will be constructed. Perform bench scale experiments to have enough data for yields.
	2.4 Technology use feedstock specific enzymes or microorganisms	93	Investigate restrictions of specific organisms and the impact on financials.
	2.5 Feedstocks flexibility	29; 93	Perform pilot trials with several feedstocks. Preview operational margins on equipment design.
	2.6 Level of sterility demanded by the equipment	93	Perform pilot trials, and, if possible, do scale-up in steps Investigate the trade-off between having several smaller scale equipment (cost implications) and difficulty to sterilize big equipment. Preview cleaning and sterilization conditions for equipment.
	2.7 Low or variable reaction yields	15,56,70	Develop R&D plans focusing on reaction yields optimization.[55]
3 – Financial	3.1 High capital costs	8,13,15,17,70,87	Consider low complexity technologies, if available. Explore co-location options.[15,72] Calculate the trade-off capacity vs. feedstock cost. Evaluate the impact of capital cost uncertainty.[76] Perform pilot and/or demonstration scale trials to provide design information for new technologies.[67]
	3.2 Low investment return	87	Improve margins through product diversification[87] Mitigations for risks 1.2, 1.3, 1.4 and 3.1 also apply to this risk.
4 – Regulatory	4.1 Policies, subsidies	16,33,72	Carefully measure the impact of subsidies in project financials. Deep understanding on duration and values of subsidies.
5 – Supply chain	5.1 Feedstock growth yield and variability	60,89,94	Model the impacts of feedstock growth on delivered cost. Select the most suitable biomass species and varieties for the intended process.
	5.2 Feedstock distribution Biomass supply chains are on early stages of development	60,89	Evaluate trade-offs between feedstock yield and transportation cost (related to density) to define plant location.[60]
	5.3 Final product distribution		Identify how final product distribution can limit project profitability.

technology is often adapted from other industries and while they serve well as a cost saving measure, they cannot be used for certain bioproduct applications. Technological risk should be compensated by greater financial returns, or mitigated by using conservative start-up time and initial production volume estimates.[17] Running a large-scale pilot plant before commercial deployment of a specific technology is a crucial step for any venture in the biobased business, since it helps to mitigate risk and direct future R&D strategy.

The information available in the risk mitigation strategy literature is generally descriptive rather than specific, but is still useful for bioeconomy investments. For example, ASTM provides a guide for developing cost-effective mitigation strategies for new and existing facilities, although it focuses on hazard prevention.[54] This guide provides a generic framework to assess risks and develop risk mitigation strategies, using financial performance to identify the most cost-effective combination of risk taking and risk mitigation. Kaplan and Mikes[90] propose risk mitigation strategies based on their classification (preventable, strategic or external). Preventable risks should be avoided and the probability and impact of strategic and external (uncontrollable) risks reduced.[90] Partnering with other companies can be a good strategy to share risks, however this approach is not common in the forestry industry.[87] A midterm strategy needed to mitigate risks during the first few years of operation may be different than the longer term needed over the complete lifetime of the technology.[87] Finally, some industries are simply more risk averse than others and it is important to change risk perception and appetite in order to minimize and overcome the inherent risks for the biobased industries.[87,91]

Concluding remarks

While there is no consensus on the concepts of uncertainty, risk, and risk analysis, this review paper suggests the following definitions in the context of capital investments: (i) uncertainty can relate to randomness or designate both the existence of more than one possibility for a input value, or the absence of information; (ii) risk is a random event that can negatively affect a company's goals; and (iii) risk analysis is a methodology used to estimate the likelihood and frequency of an event and the extent of its consequences. Financial risks can be quantitatively assessed via deterministic and probabilistic analysis, and the tools available for this purpose were presented. Risk management is a broader concept and incorporates the ranking of risks and the development of risk mitigation plans. Investors can have a more comprehensive understanding of a venture when the uncertainties are known and risk assessment and risk management are applied.

The probability analysis approaches provide a more complete view of the expected project outcomes compared to deterministic models. Sensitivity analysis can help select the critical input parameters for subsequent probability analysis. Current risk analysis tends to focus on specific risks instead of evaluating them across the entire supply chain. Additionally, analyses are commonly focused on financial inputs and do not incorporate process inputs. Since technological issues are among the leading cause of project failures, investors should address the impacts of technical risk and uncertainty on the financial outcome of the investment.

Our findings suggest that a comprehensive risk analysis should evaluate the maximum number of inputs that have a critical impact in the output, including material composition variability, reaction conditions, consumption of feedstocks and utilities, uncertainties in raw materials costs, costs associated with utilities and capital, final product prices, subsidies and inflation rates, among other parameters. In addition, the analysis should follow several steps, including performing a sensitivity analysis, identifying the inputs with greatest impact on the outcome, analyzing them using a probabilistic risk assessment method, and applying risk mitigation strategies. This review provides the necessary resources and strategies to assist in developing a successful investment strategy, from a financial point of view, and a starting point for researchers and investors interested in the bioeconomy.

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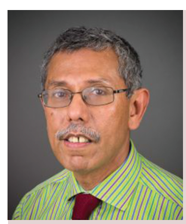

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