


# A market-driven algorithm for the assessment of promising bio-based chemicals

Agustín Helal<sup>1</sup> | Roberto Kreimerman<sup>1,2</sup> | Soledad Gutiérrez<sup>1</sup> | Ana I. Torres<sup>1</sup> 

<sup>1</sup>Instituto de Ingeniería Química, Facultad de Ingeniería, Universidad de la República, Montevideo, Uruguay

<sup>2</sup>Departamento de Inserción Social del Ingeniero, Facultad de Ingeniería, Universidad de la República, Montevideo, Uruguay

## Correspondence

Ana I. Torres, Instituto de Ingeniería Química, Facultad de Ingeniería, Universidad de la República, Montevideo, Uruguay.  
Email: aitorres@fing.edu.uy

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## Abstract

Actors willing to participate in biomass-based value chains need to screen through a vast number of product options to identify the most promising ones. This is challenging as (a) processes for biomass-based chemicals/materials are still in development stage, thus do not perform well in techno-economic evaluations, (b) factors as which and how many links of the value chain should be uptaken, are not fully addressed by techno-economic analysis. Inspired by the Five Forces framework for industry analysis, this work presents an algorithm-like approach for assessing the attractiveness of biomass-based products. The algorithm relies on market data to classify the different sources as posing a low, medium, or high threat to the profit of a company that is considering production of a certain chemical/material. The approach is exemplified by analyzing the attractiveness of the biomass-lactic acid-poly(lactic acid) route in the context of defining pathways for development of a biomass-based industry in Uruguay.

## KEYWORDS

biorefineries, Five Forces (Porter) analysis, PLA, product portfolio

## 1 | INTRODUCTION

Replacement of the traditional fossil-based chemicals by biomass-based chemicals has been in the spotlight since the early 2000s. As of today, a vast number of chemicals and processing routes have been proposed,<sup>1-4</sup> and identification of new bio-based chemicals is still a very active research area. Along these lines, Shanks and Keeling have introduced the concept of *bio-privileged molecules* which states that in order to be attractive bio-based chemicals must be “biology-derived chemical intermediates that can be efficiently converted to a diversity of chemical products including both novel molecules and drop-in replacements.”<sup>5</sup> Seeking systematization of the identification of the characteristics that would make a bio-based chemical a promising one; Wu and Marvelias have developed different analytical frameworks: in Reference 6, the authors propose a genome-scale metabolic modeling approach to identify possible products that can be produced by *Escherichia coli* and/or *Saccharomyces cerevisiae*; while in Reference 7, the focus is on the identification of the molecular characteristics

that would make a bio-based chemical a promising replacement chemical.

Still, screening through these options and identifying the ones that will make it to the market is a challenging task. Techno-economic analysis (TEA) is for Chemical Engineers the first choice for screening. However, it is of limited use in the biorefinery context, in which most technologies are still in development or nonoptimal stage and thus perform poorly when compared to the highly optimized fossil-based technologies. In addition, TEAs alone do not take into account factors that move the needle toward commercialization of biomass-based products. For example, the willingness of the general public to pay more for more sustainable goods.<sup>8</sup>

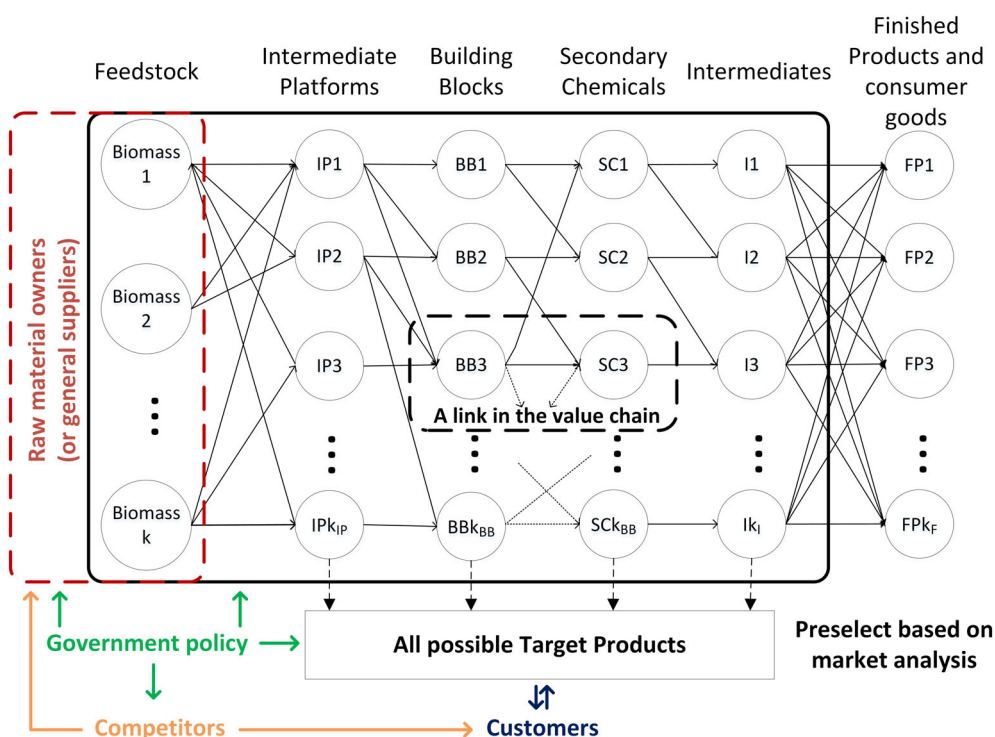
An aspect that is important to the screening process, and usually overseen, is the fact that many actors seek the development of a biomass-based industry, each have a different perspective, pursue a different interest, and thus have a different answer to the “what product should we make out of biomass?” question. Looking at the biorefinery development problem from a holistic perspective, we have

identified five classes of actors that have (potentially different) interests in the definition of a biorefinery product portfolio. Before discussing each, it is pertinent to introduce the biomass to chemicals value chain and some considerations that are important to this work. Figure 1 schematizes this value chain which starts with biomass-based feedstocks that are processed through different pretreatment steps into intermediate platforms (e.g., sugars), these into building blocks, which in turn are converted in secondary and intermediate chemicals before production of consumer products. In principle, any of these building blocks, intermediates or secondary chemicals is a possible target product for a future biorefinery. TEAs that analyze the overall conversion process from biomass to a specific compound, do not take into account that the chemicals' value chain is usually distributed among different companies (actors). Thus, implicitly assume the position of either (a) a single actor biorefinery in which the actor dominates all the processing steps up to the target product, or (b) that of an overarching entity that ignores internal interactions/restrictions among the different actors.<sup>9</sup> On the other hand TEAs that focus on a single conversion step, for example, fructose to 5-hydroxymethylfurfural<sup>10</sup> which is placed in the middle of the value chain, implicitly assume a distributed position in which the actor takes for granted the access to a certain chemical at a certain quality and price

(without caring about the original biomass feedstock itself), and sells the upgraded chemical to other actors for further processing. Analyzing the biomass to chemicals value chain as distributed and understanding where each actor "plays" in it and how it connects with downstream and upstream actors, is in our opinion a key point to address for advancing on the definition of a future biomass-based industry.

Below, we provide a brief discussion on the actors that we have identified as having an interest in the definition of a biorefinery product portfolio and hypothesize on their interests within the value chain:

*Chemical processing industries (CPI's).* These are the companies that will upgrade the biomass and/or biomass derived chemicals. Their interests lie in producing green products, that might be similar to the ones they already produce from fossil sources, or completely new ones. These companies may already be installed in the market or have a particular set of clients to whom they supply. Their decision will probably be more related in how to satisfy the needs of their clients, and how to fit in already existing chemical products value chains. Deciding how many links to capture is part of their decision. TEA as well as expertise and current position in the market are required inputs. They may also exploit the "greener" or "more sustainable"



**FIGURE 1** Scheme of the biomass to consumer products value chain: biomass is upgraded through a series of chemical compounds: intermediate platforms, building blocks, secondary chemicals, and intermediates. Classification coincides with the diagram in DOE "top ten" report.<sup>1</sup> In the most general case, all these chemicals are possible target products. Preselection of the product portfolio should be done based on a systematic market analysis and taking into account the place the actor occupies in the value chain, then economic indicators combined with superstructure optimization may be considered for final selection (see Figure S1). The scheme also shows interactions with other actors: the black boundary represents operations/decisions within the company; suppliers interact through the feedstocks (biomass in this case, but may be any starting chemical/material); consumers/customers interact through the chosen products; competitors interact directly by competing for the same raw materials, or producing the target product or its substitutes; the government may interact at several levels with all the actors [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

characteristic of their product/process to sell the product at a price above the non-green options available in the market.

*Biomass-based feedstocks owners.* In general, these actors already participate in the market, occupying a place at the very beginning of the processing value chain. They may produce the biomass as their main product (e.g., energy crops) or as a residue of another process (i.e., other crops, forest related activities, and food processing industry). In case of owners of residual biomass, development of a biorefinery is not usually the core of their business, but see in its development a venue for getting additional profit. This additional profit may come either from selling the biomass itself or by overcoming disposal and treatment costs. Forward integration to produce chemicals, might be a possibility in cases where they already know the market, already consume a product that could be obtained from biomass and/or the target chemical is just a step away in the processing value chain.

*Researchers.* Researchers are actors interested in solving problems. Depending on their particular expertise, they may focus on developing new chemicals/materials, overcome technological bottlenecks or develop new technologies, and so forth. Specific to the academic sector, there is an expectation of novelty and impact, which results in a publication. Researchers from nonacademic sectors may focus more on further developing academic based findings and scaling-up the technologies. Altogether, researchers span the overall value chain, some specializing in certain parts, some having a wide overview, some analyzing the effects of a biorefinery beyond the processes themselves, for example, their interaction with the environment, resources, and society. Their interest in market analysis and TEAs lies in the fact that if positive, they provide stronger arguments for applying to grants.

*Capital investors.* These actors are the ones who have the resources to materialize the biorefinery. They will take into account returns and risks, and most probably invest in one or a few (not necessarily connected) links at a time, if it is more advantageous than other investment alternatives. Market attractiveness as well as TEAs of the different options is inputs that they take into account for decision making.

*Politicians or government based entities.* These entities are the ones that have a wide overview of the biomass to products value chain, and for strategic reasons might pursue a design as if it were a single actor. Their objectives generally include generation of jobs, long-term development strategies such as expansion of the already existing value chains or establishment of new connections between the links, substitution of imports, promotion of a particular economic sector, and so forth. Placing funds for directed R&D is also at the core of their decisions. For them, TEAs play an important but secondary role as these entities have the power of placing subsidies to pursue a particular goal. Understanding the market, and in particular how to fit in worldwide value chains and attract investors, is a key aspect for policy makers. In order to do so, they may want to identify actors, their connections, the obstacles that they face, and the opportunities to improve the "link-ability" among them.

Definition of a biorefinery product portfolio using market-driven approaches in Chemical Engineering is uncommon but not unheard of in the Chemical Engineering community. Relevant examples include different contributions from the Stuart group who has studied Canada-based biorefineries<sup>11</sup>; summarizes the work related to the Forest biorefinery; while<sup>12-14</sup> present different analysis related to the triticale-biorefinery. These contributions have focused on the metrics that should be calculated to assess the different options and how to weigh them in order to represent the point of view of a decision maker. Although not fully developed, a pertinent contribution that combines the value-chain perspective mentioned above, with market-driven approaches can be found in Bomtempo et al<sup>15</sup> In this manuscript, the authors adapted the technological platform concept, as used within the business settings, to particular aspects of platform chemicals and proposed that the following six strategic dimensions must be met by a platform chemical to be considered attractive: intermediate position in the (chemicals) value chain, a flexible chemical structure, potential of being transformed in several cost-competitive derived products, capability of relate to innovation agents located in different positions of the value chain, governance of the value chain (at least in the development phase), and the ability to create value through scope (number of derived products) and scale economies.

In here, we have taken a complementary approach and base our decision-making strategies on the "Five Forces" framework proposed by Porter.<sup>16</sup> Porter analysis is a tool that is commonly used by managers and decision makers for the development of business strategies. The main concept behind the framework is that besides businesses that sell the same products (i.e., direct competitors), suppliers, customers, potential entrants to the market, and products that might substitute the ones sold by the company, will also affect the level of profits. The tool fits perfectly in our value-chain vision of the biorefinery as once decided how many links are we interested in capturing, downstream links become suppliers, and upstream links become consumers. Then, depending on the results of the analysis, the links to be captured might be changed. Apart from suppliers and consumers, the tool also analyzes the potential of attracting new entrants, product substitutes, and the rivalry with existing companies. In a sense, if TEAs screen feedstock/products combinations by looking at their connecting pathways (i.e., inside the boundaries, see Figure 1 and scheme in Figure S2), the Five Forces analysis screen by looking at how these feedstocks/products interact with external actors (i.e., across the boundaries in Figure 1). The intensity with which each force is expressed depends on sources that are commented in Section Systematic assessment of the competitive forces. If the forces are intense then, the company will not have high profits, or if entering the market will face low Internal Rate of Returns.

Contributions that have applied Porter's Five Forces analysis to biorefinery problems include the work from Stern<sup>17</sup> who evaluated the attractiveness of producing dietary fiber products (cellulose-based products, gum arabic, and arabinogalactan) from wood for companies operating in Germany, Switzerland, and Austria; the MSc thesis from Borgman<sup>18</sup> who utilized Porter's model to analyze the structure of the bioethanol market with the aim of formulating strategic options for

large scale European producers; and the MEng thesis from Bruce<sup>19</sup> who also analyzed the structure of the bioethanol market in order to assess advantages and disadvantages of bioethanol fuel in the United States.

The usual way to assess the strength of the each source considered in the Five Forces analysis is a qualitative description of what the source involves and an also qualitative argument stating how much this source affects or not the particular case that is under study. In some cases,<sup>18</sup> market data are used to backup the argument. However, the overall qualitative nature of the analysis and the multiplicity of actors (i.e., government, multinational corporation, already in the market, and trying to enter in the market) whose point of view could be taken to perform the analysis, makes it difficult for an engineer working on the assessment of priorities for bio-based products to (a) understand the rationale and follow the line of thought behind each assessment, (b) systematically compare the options, and (c) propose "what if" scenarios to analyze solutions that mitigate or enhance a particular source.

The objective of this work is to present an algorithm-like methodology for screening/assessment of promising bio-based products using Porter's Five Forces approach. The rationale is that the current qualitative expert-based assessment of the Five Forces analysis can be translated into a set of data requirements and a set of questions, that are pertinent to the development of a biomass-based chemical industry. Then, these questions can be put into decision-making trees and, based on the data and chosen parameters, be used to categorize and infer on the strength of the sources. We envision our methodology to be used by chemical engineers as a decision-making tool complementary to the traditional techno-economic and environmental analysis, which allows not only for the assessment of one's, but also other actor's positions.

We exemplify the systematic through the study of the biomass-lactic acid (LA)-polylactic acid (PLA) route in Uruguay: a country with no proven fossil feedstocks reserves but plenty of biomass and biomass-based residues that sees in the expansion of the biomass-based value chains a promising pathway for development.

## 2 | METHODOLOGY

This section is divided in two parts: the algorithm itself and its connection with Porter's original work<sup>16</sup> is presented in the second part; in the first part we provide an organized list of the data that needs to be collected for conducting the algorithm.

### 2.1 | Data needs

As the result of the analysis is highly dependent on the perspective of the analyst, the first need is to clearly define whose perspective is the decision maker taking. This is a key definition, as the decision maker might really want to know if her/his business will be competitive, or a decision maker, for example, a governmental entity, might be trying to understand which forces will another actor face and take actions to

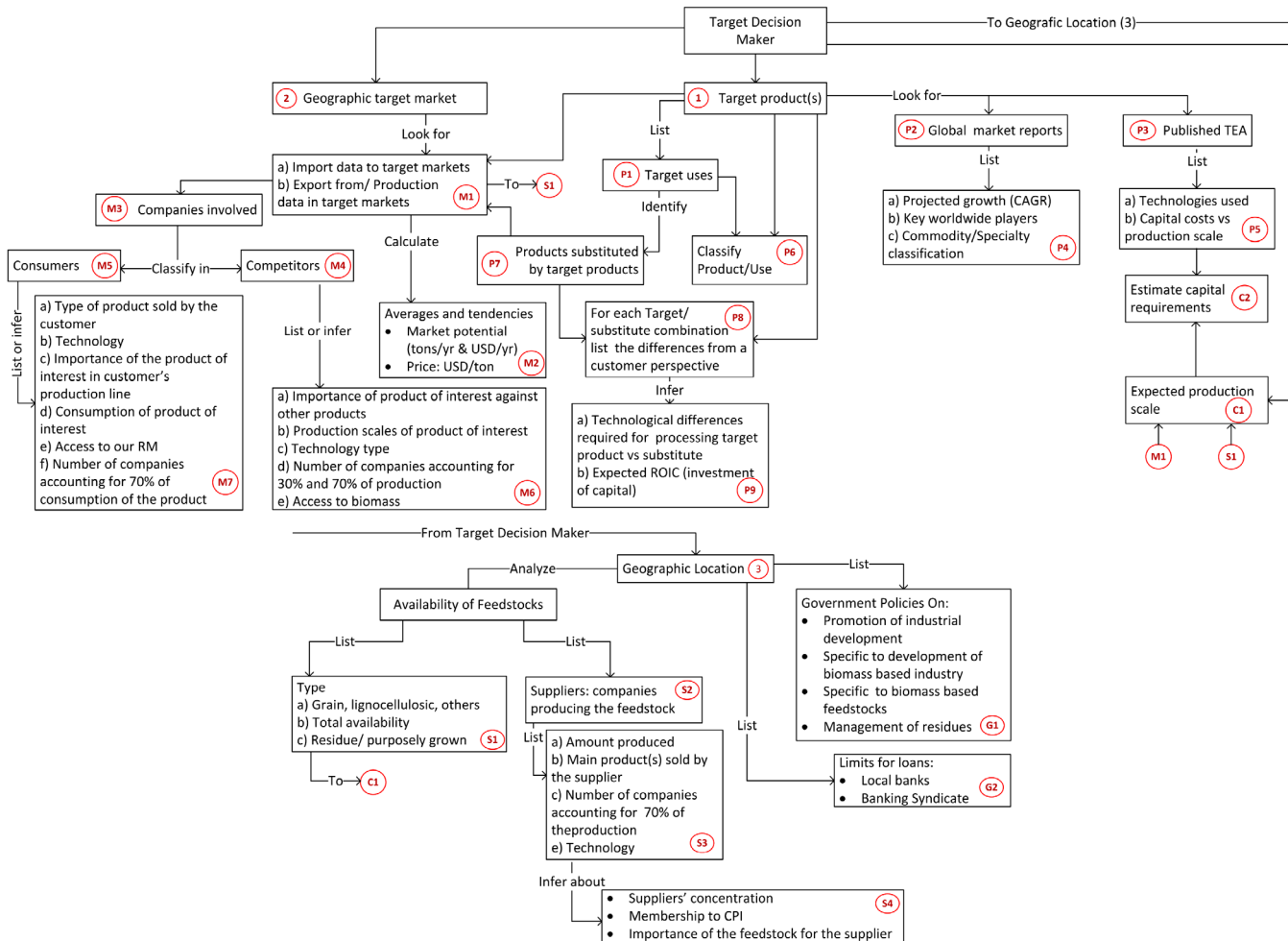
mitigate/intensify them. In this second case, we will distinguish between the *Decision Maker*, this would be the real actor, and the *Target Decision Maker (TDM)*, this would be the actor whose perspective is considered.

A summary and roadmap of the data required for the analysis are presented in Figure 2. To start the analysis the *TDM* selects (1) a Target Product, (2) a Geographic Target Market, this is the market where the product will be sold, that is, the location of the customers, and (3) a Geographic Location, this is where the processing plant is or will be located.

Once the Target Product is selected, its possible uses needs to be listed (P1) and data from global market reports (P2) and TEA (P3) be gathered. From these last two, the most important information is that of market growth (Compound Annual Growth Rate (CAGR) values) and an estimation of capital requirements for at least one scale of production. From the list of target uses, two things need to be done. The first one is to classify each product/use combination (P6); we propose (and have used throughout the text) the following categories: For the *Target Product*: (a) New: refers to a product that is not yet commercialized in the Geographic Target Market, (b) Existing from fossil feedstock sources: refers to a product that already exists in the market and the target product intends to act as a bio-based replacement of it, (c) Existing from biomass-based sources: refers to a product that is already obtained through a biomass-based pathway, and has attracted renewed interest in the context of a future biomass-based industry. For the *Target Use*, the categories are New and Conventional and are both self-explanatory.

The second one is to identify current products that might be substituted by the Target Product (P7), and the differences between them from a customer perspective (P8). This step is particularly important when the Target Product is a novel chemical as market/production data for it may not yet exist. In these cases, the key point is to consider substitution broadly, looking more at the needs of the customers rather than the chemistry itself, and to assess on the advantages that the novel chemical brings over the existing ways that customers are using to satisfy their needs. The goal of this exercise is to be able to infer about the cost incurred by the potential customer for switching from the product the customer currently uses to our proposed Target Product and if this extra cost will in the end result in a benefit for the customer (P9).

The choice of a Geographic Target Market allows the *TDM* to look for specific information for that market. The search should be done for both the Target Product (1) and the possible substitutes (P7). Relevant data in this case are import/export and production data (M1). Import/export data are collected by customs. Potential sources of production data are government departments and agencies, although some may only be available if physically in the territory. The data collected allow for the estimation of a market potential and the price of the product in the market (M2), and also for the identification of the companies involved (M3). All the companies involved should be further classified as *Competitors* or *Consumers*. Competitors (aka incumbents; M4) are the companies that produce or import the Target Product to the Geographic Target Market for distribution to other



**FIGURE 2** Roadmap of data needed for the analysis. CPI, chemical processing industry; TEA, techno-economic analysis [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

companies; Consumers (M5) are the companies that currently purchase from the Competitors or directly import for their own needs. Data needs required to analyze the competitors is listed in (M6), while that required for the consumers is listed in (M7).

Given the choice of Geographic Location, a list of policies (G1) that might favor or disfavor the venture in that region should be gathered. We have included here the access to banking loans (G2), assuming that the *TDM* will need to borrow money and the first choice is locally. Despite if the borrowing location coincides or not with the location of the facility, the important point in here is if the *TDM* will require a loan from a banking syndicate or international funds.

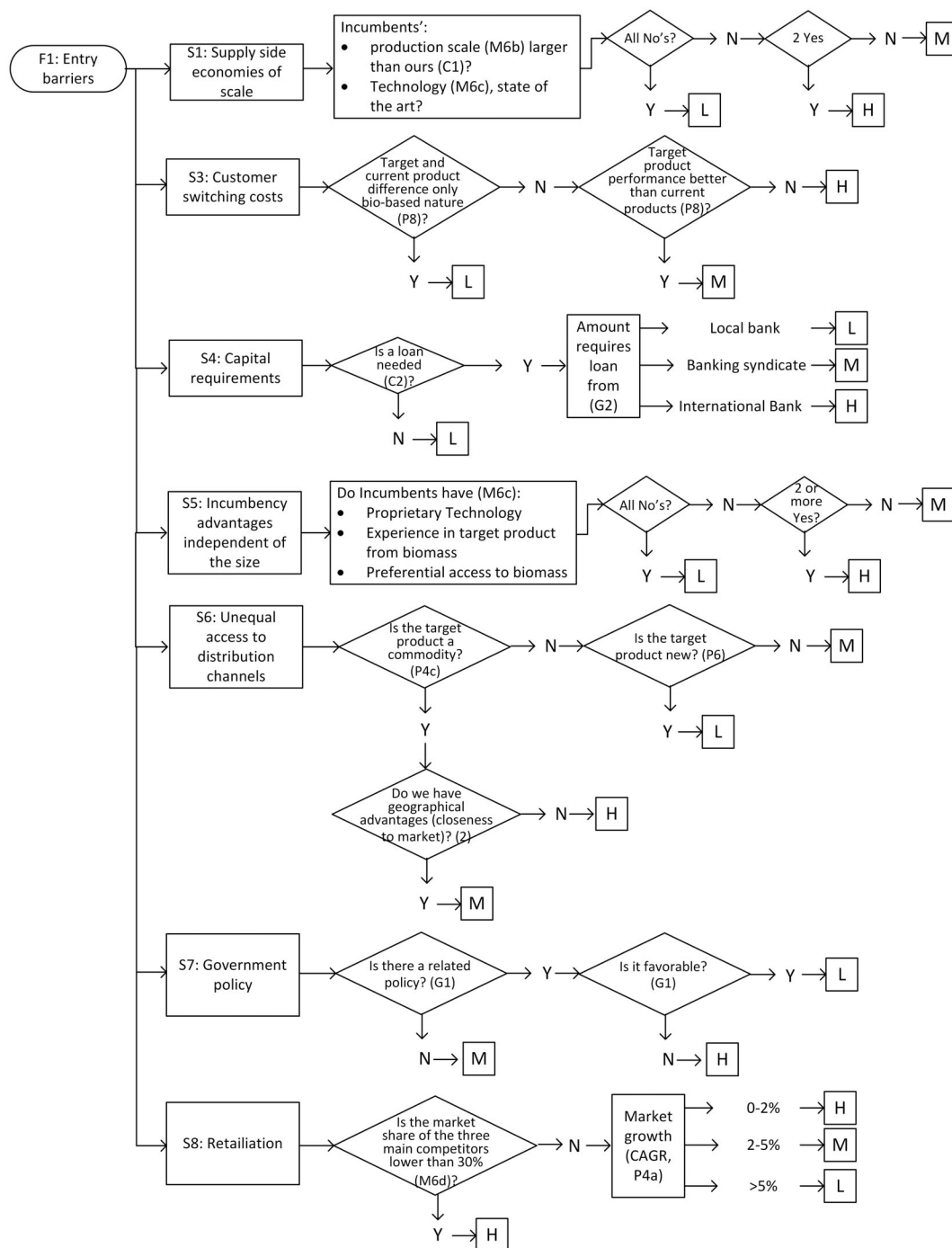
The choice of Geographic Location also affects the availability of feedstocks. In here, it is important to list the types of biomass (S1) and for each the total availability and whether they are residues from other industry or purposely grown (e.g., energy crops). In addition, for each raw material a list of the suppliers (S2) and the characteristics listed in (S3) should be prepared. As will become clear later, the importance of this step is to be able to infer about the concentration of the suppliers, the importance of our feedstock (their product) for their profitability and whether or not the supplier possess the technological

knowledge to forward integrate and start producing the Target Product. This information is compiled in (S4).

Finally, given consumption and feedstock availability data (in M1 and S1, respectively), the *TDM* can infer lower and upper limits for its production scale (C1), and roughly estimate capital cost requirements (C2) by combining these limits with already available TEAs, prior updating using the six-tenth rule and the Chemical Engineering Plant Cost Index.<sup>20</sup>

## 2.2 | Systematic assessment of the competitive forces

The systematic in here proposed “translates” the generic statements in the Five Forces framework<sup>16</sup> into decision-making trees that categorize each source as low threat (*L*), medium threat (*M*), or high threat (*H*). We do so by postulating questions that are relevant to the production of biomass-based chemicals, and can be answered/inferred using the data gathered before. It is important to remark the *threat* characteristic, as this implies that if a large amount of sources is classified as *H* production of the Target Product will *not* be attractive. The opposite is true if a large amount of sources is classified as *L*.



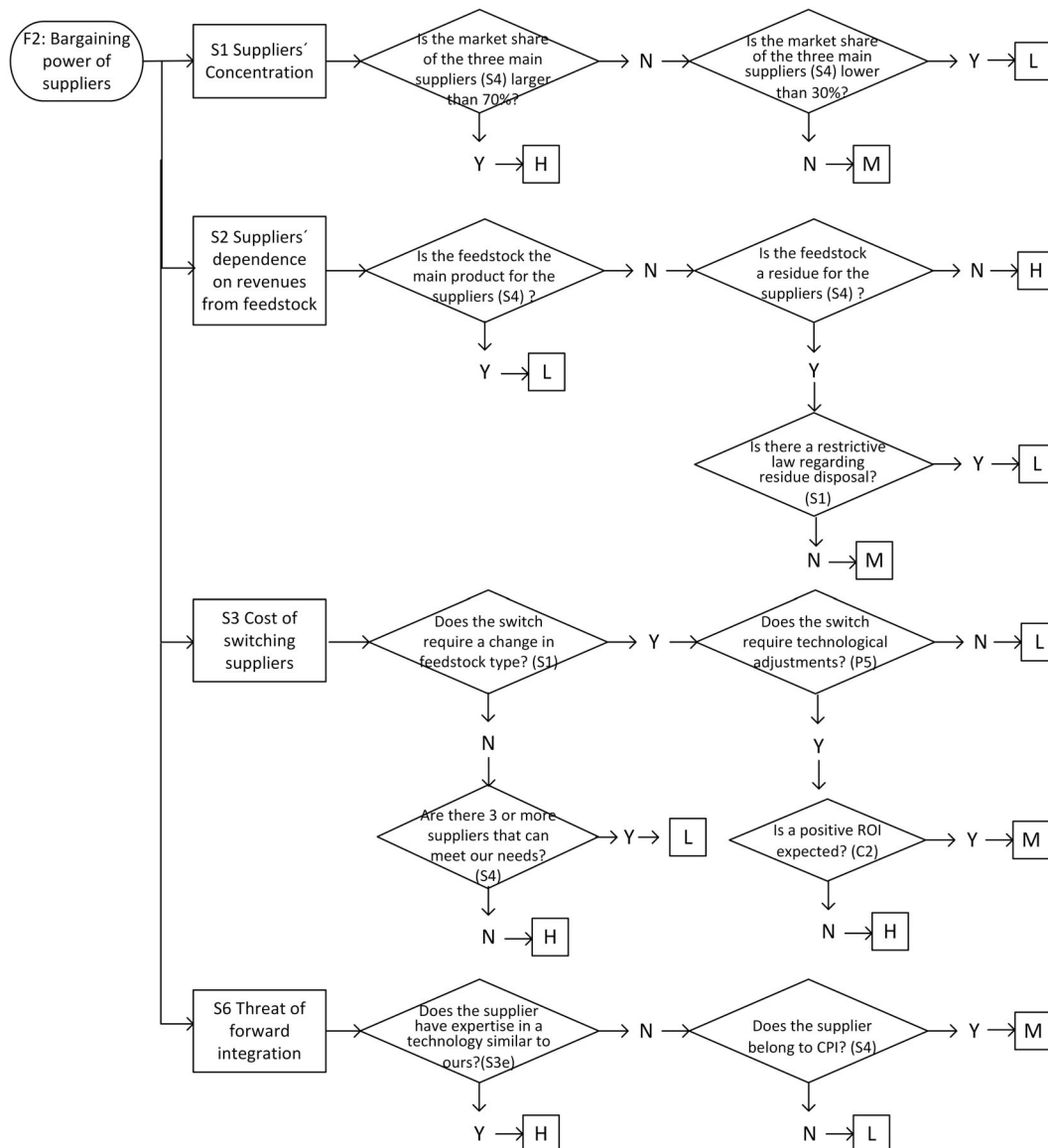
**FIGURE 3** Decision-making diagram for Force 1: entry barriers

Classification of the forces themselves requires calculation of a weighted average of the sources. We have not attempted to choose differential weights in this manuscript, as different decision makers may place different value to the different sources. An example of source-importance definition can be found in Stern et al<sup>17</sup> where a survey to pertinent companies was conducted to define the sources that were the most important for the case of wood-based chemicals as food additives. This qualitative work can be expanded and differential weights assigned based on the responses. Such analysis is beyond the scope of this manuscript.

The decision-making diagrams are presented in Figures 3–7. A source by source explanation of the rationale is provided next.

### 2.2.1 | Force 1: Entry barriers

**S1: Supply side economies of scale.** “arise when firms that produce at larger volumes enjoy lower costs”<sup>16</sup> “deter entry by forcing the aspiring entrant either to come into the industry on a large scale, (...), or to accept a cost disadvantage.”<sup>16</sup> The rationale behind the diagram is



**FIGURE 4** Decision-making diagram for Force 2: bargaining power of suppliers

that if incumbents' production scale is larger than ours or their technology is up-to-date, then they will have an advantage.

**S2: Demand side economies of scale.** "network effects, arise in industries where a buyer's willingness to pay for a company's product increases with the number of other buyers who also patronize the company".<sup>16</sup> We do not envision network effects in CPIs as quality and price are the most important features. This effect is a priori not considered.

**S3: Customer switching costs.** "Switching costs are fixed costs that buyers face when they change suppliers."<sup>16</sup> In the context of CPI, possible causes are the need of updating product specifications or modification of processes. We infer about this source by considering the differences between the Target Product and the product the customer is currently using. We assume that if the product is the same, being the only difference the bio-based source of the Target Product, then the switching cost is low and so is the entry barrier. Notice, that

this implies that, within reasonable limits, a larger price for a bio-based product acting as a replacement of a fossil one is not considered an obstacle as companies (the potential customers of bio-based chemicals) can take advantage of the willingness of the public to pay higher prices for items labeled as "more sustainable."<sup>8,21</sup> If this is not the case, then only a better performing product might mitigate the barrier.

**S4: Capital requirements.** To infer about this source, we looked at the amount of money that the company will need to borrow, and divided the barrier in three categories. If no loan or a loan from a local bank is needed, then the barrier is low; a loan that requires a banking syndicate is classified as medium; a loan that requires borrowing from an international bank is classified as high.

**S5: Incumbency advantages independent of size.** "... stem from such sources as proprietary technology, preferential access to the best raw material sources, preemption of the most favorable geographic

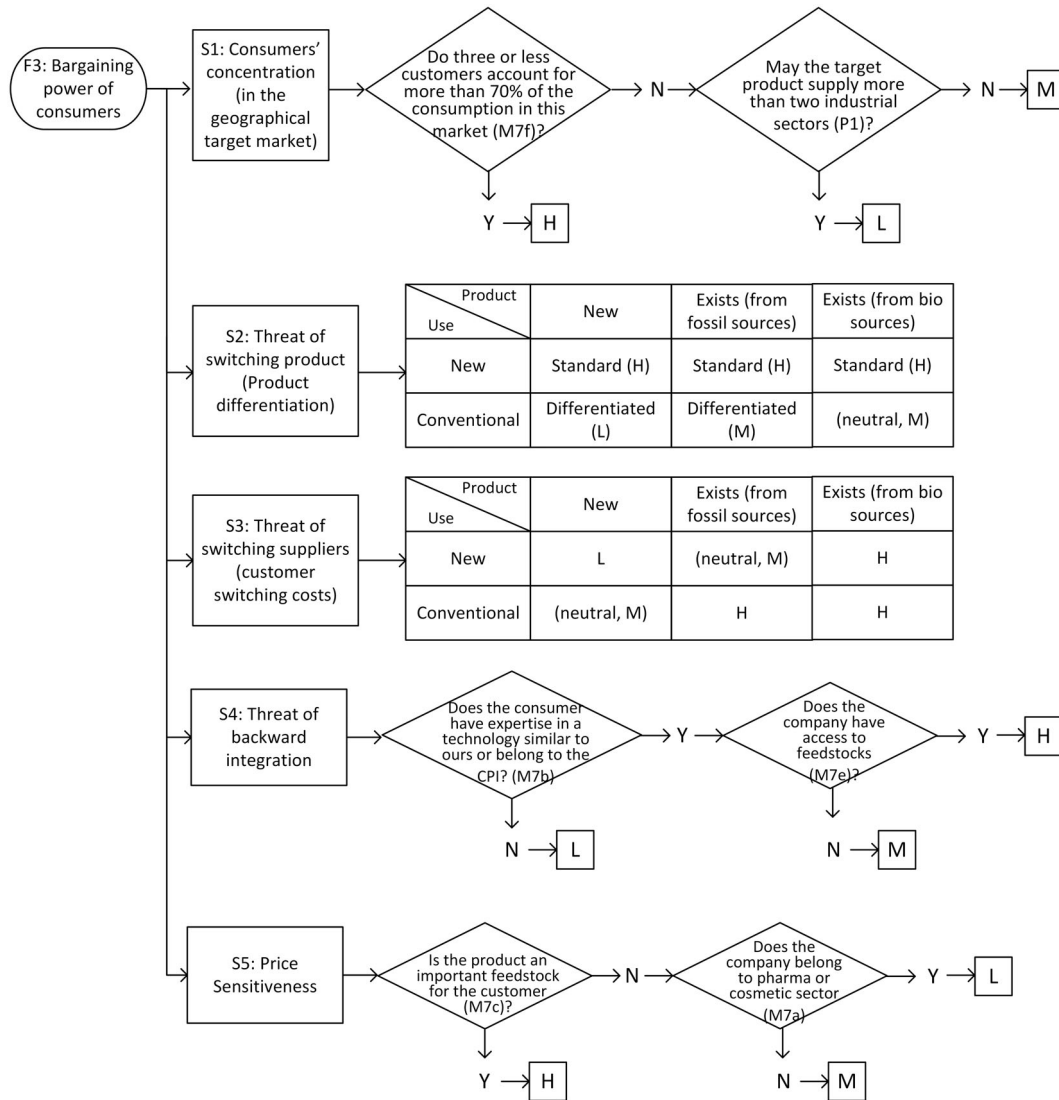


FIGURE 5 Decision-making diagram for Force 3: bargaining power of consumers

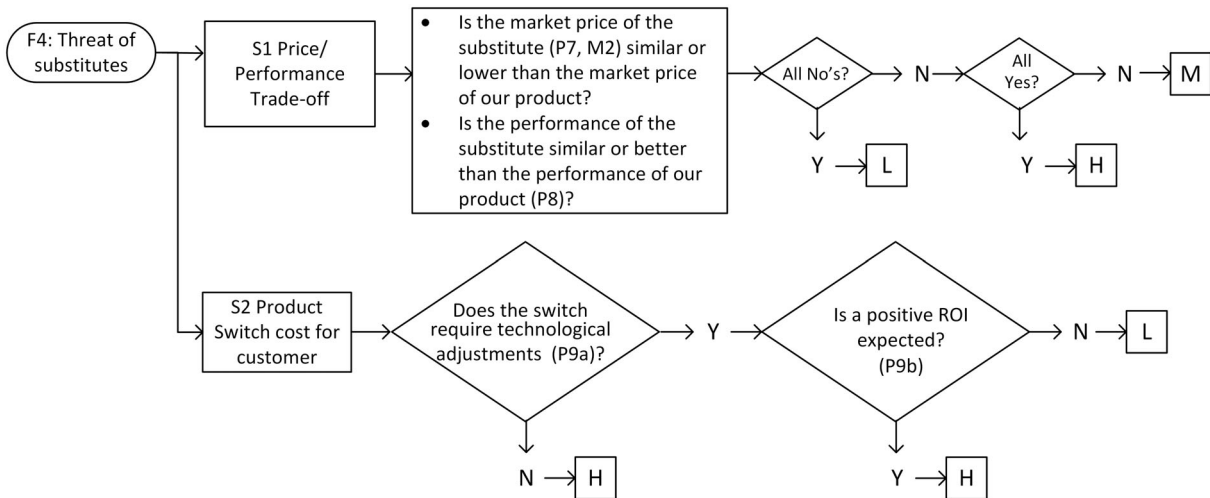


FIGURE 6 Decision-making diagram for Force 4: threat of substitutes



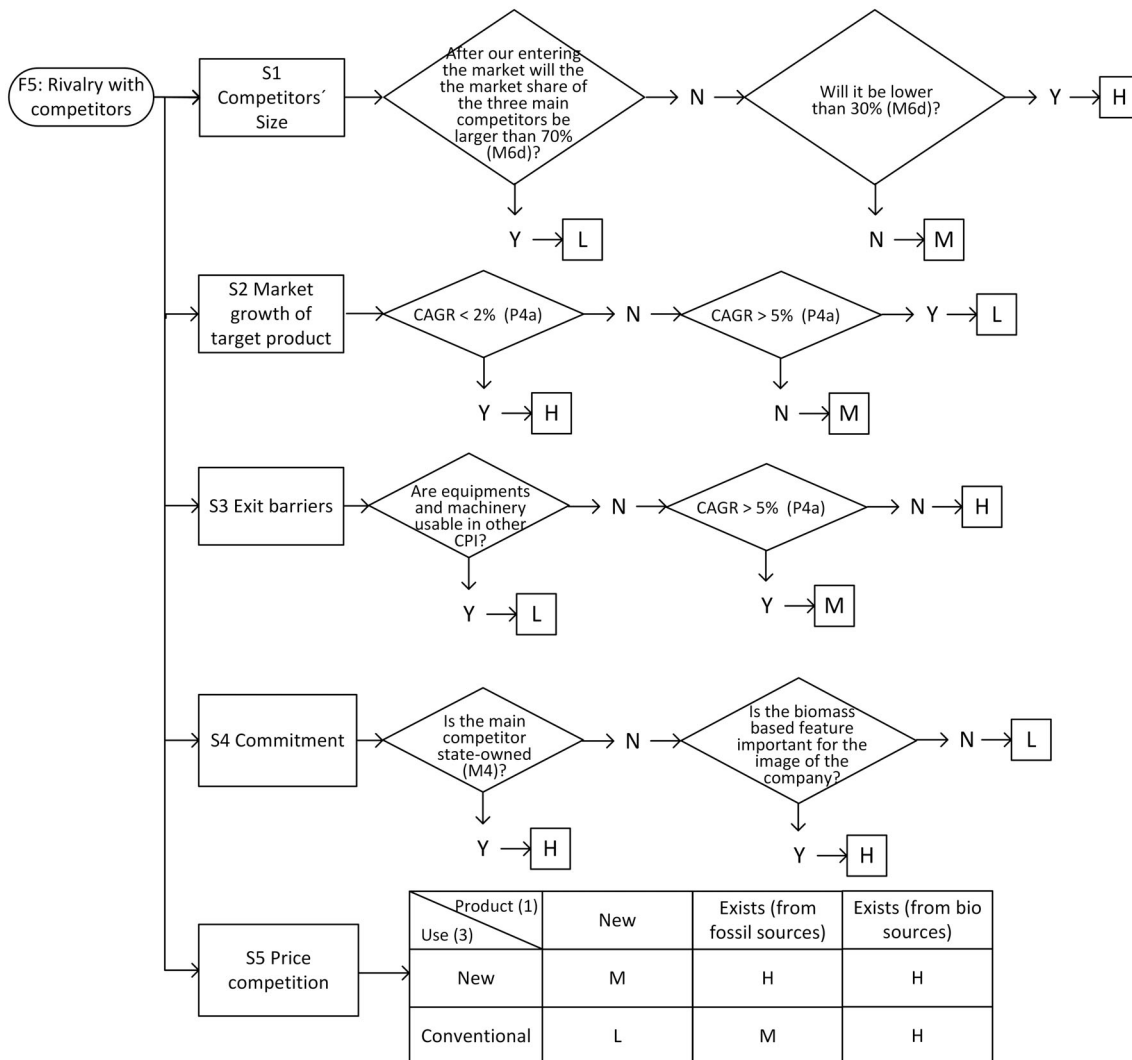


FIGURE 7 Decision-making diagram for Force 5: rivalry with competitors

locations, established brand identities, or cumulative experience...<sup>16</sup> From these, we assume that proprietary technology, preferential access to biomass, and experience with processing biomass to produce their product are the most important factors. If the incumbent's answer to any of these is yes, then it has an advantage. The more yes, the higher the entry barrier will be.

S6: *Unequal access to distribution channels.* In here, the rationale is that if the product is a commodity then incumbents already have established distribution channels, which pose a barrier to the new entrant. We also consider that this barrier is mitigated if geographic location is an advantage for the entrant. In addition, we consider that if the target product is new then, the distribution channels are not yet developed, thus there is not a barrier yet.

S7: *Government policy.* "Policy can hinder or aid new entry directly, as well as amplify (or nullify) the other entry barriers."<sup>16</sup> Government policy affects not only Entry Barriers, they can also be targeted to mitigate/enhance sources of the other forces. Some examples include: laws for promotion of industrial/sector development, environmental and safety regulations, restriction/promotion of foreign investment;

laws for protection of proprietary technology; subsidies, provision of funds for R&D.<sup>16</sup>

S8: *Retaliation.* This is the reaction of the incumbents to the new entrants. From the factors mentioned in Porter's original work, we consider "Incumbents seem likely to cut prices because they are committed to retaining market share at all costs...,"<sup>16</sup> and "Industry growth is slow so newcomers can gain volume only by taking it from incumbents....,"<sup>16</sup> to be the most important. We associate the need of retaining market share with the Incumbents' concentration. If the market is split among many companies, then we assume that each company is small and the effect that a newcomer has, is larger than if just a few larger companies dominate the market. We consider market growth as the second most important effect, and set the benchmark limits shown in Figure 3.

A note must be made at this point with respect to the benchmark limits; throughout the manuscript, we have used the *m-firm concentration ratio* as defined in Belleflamme and Peitz<sup>22</sup>  $I_m = \sum_{i=1}^m \alpha_i$ , in which the firms are ordered according to their market share  $\alpha_i$  and the  $m$  top firms added up. We have assumed  $m = 3$  and considered the market concentrated if  $I_3 \geq 70\%$  and distributed if  $I_3 \leq 30\%$ .

## 2.2.2 | Force 2: Bargaining power of suppliers

*S1: Supplier's concentration.* "A supplier group is powerful if: It is more concentrated than the industry it sells to."<sup>16</sup> We have again used the  $I_3$  criteria and assigned a high power to suppliers if they are concentrated and low if distributed. Anything else is classified as medium.

*S2: Supplier's dependence on revenue from feedstock.* "A supplier group is powerful if: does not depend heavily on the industry for its revenues."<sup>16</sup> In here, we infer that a supplier that offers our feedstock as its main product, depends heavily on it for revenues. Thus its bargaining power is low, unless no other supplier nearby can satisfy the demand for the feedstock. If the feedstock is not the main product, the supplier may also have low bargaining power if it is a residue and local laws require specialized disposal for it. On the other hand, if the feedstock is a residue, and there are not laws restricting its disposal, then, there is no incentive for the supplier to sell the feedstock posing a threat classified as high.

*S3: Cost of switching suppliers.* The rationale is that if the same feedstock is sold by different suppliers or using a different feedstock does not require technological adjustments, then there is little cost of switching suppliers, thus their bargaining power is low. If changing suppliers requires a technological adjustment, then the supplier has bargaining power, which could be mitigated if a positive ROI is expected after investing in the adjustment.

*S4 and S5: Feedstock differentiation and uniqueness.* We do not foresee that in the setting of a chemical biomass-based industry, a feedstock could be differentiated in the sense that is implied in the original reference,<sup>16</sup> much less a feedstock be completely unique. Therefore, these two sources are not considered.

*S6: Threat of forward integration.* Suppliers threat of start producing the product themselves is high if they already possess technological knowledge similar to ours. If the supplier is a CPI, then forward integration is possible but as it requires possibly large adjustments, the threat in this case is classified as medium.

## 2.2.3 | Force 3: Bargaining power of consumers

*S1: Consumers' concentration.* "A customer group has negotiating leverage if: There are few buyers, or each one purchases in volumes that are large relative to the size of a single vendor."<sup>16</sup> To infer about the concentration of the consumers, we have considered the  $I_3 \geq 70\%$  criterion. We have not used the  $I_3 \leq 30\%$ , criterion for inferring about distribution as, even if this is the case, customers may associate to purchase together and act as concentrated. To classify the customers as distributed we request that the product may be used for at least three different uses, a situation that has a much lower probability of association.

*S2: Threat of switching the product.* "A customer group has negotiating leverage if: The industry's products are standardized or undifferentiated."<sup>16</sup> In here, we use the Product/Use classification in Section Data needs. The rationale is that if the use is new, then the product is targeting a new market, therefore the risk of being undifferentiated from other possible chemicals that might also target

this market is higher. However, if the use is conventional, then the product is replacing other products that already exist in the market. In here, we look if the *bio* feature may be used as a positive differential characteristic for differentiation. This is the case when the product is new, and to a lesser extent if the same product already exists from fossil-based sources. If the product already exists from bio-sources for conventional use, then the classification has to be done case by case. We have marked these as (neutral, M).

*S3: Threat of switching supplier.* The rationale is: if the product already exists in the market, there is a considerable threat of buying the product from some other company. The only case in which we consider the threat as low is when both product and use are new as there might not be many suppliers, yet. Any other case is treated as a (neutral, M) threat.

*S4: Threat of backward integration.* As with the suppliers, if the consumers' expertise is not similar to ours or they cannot be classified as CPIs, then the threat is low. The threat of backward integration may be considered high if one of those is true, and the consumers have access to feedstocks similar than the ones used by us.

*S5: Price sensitiveness.* "A buyer group is price sensitive if: The product it purchases from the industry represents, a significant fraction of its cost structure" or "earns low profits" or "the quality of buyers' products or services is little affected by the industry's product" or "The industry's product has little effect on the buyer's other costs."<sup>16</sup> In here, we considered that the essence of price sensitiveness can be captured by two factors: (a) if the product is an important feedstock to the customer, then the customer will be sensitive to price changes; (b) if the product is used by a company in the pharma or cosmetic sectors, then they will most probably have large profits and prefer quality over price, then be less sensitive to price changes.

## 2.2.4 | Force 4: Threat of substitutes

*S1: Price/performance trade-off.* A product that combines similar or better performance with similar or better price is easily substituted by another one. We inferred about this source looking at the list of differences from the customer's point of view.

*S2: Product switch cost for the customer.* This source is somehow complementary to Sources S2 and S3 from Force 3, but is focused on the cost that a change will cause. We infer about its strength in a way similar to the one used when analyzing our possibility of changing suppliers: if the switch does not imply a technological adjustment or if it does, a positive ROI is expected, then the threat is high. Otherwise we will consider it to be low.

## 2.2.5 | Force 5: Rivalry with competitors

*S1: Competitor's size.* "The intensity of rivalry is greatest if: Competitors are numerous or are roughly equal in size and power. In such situations, rivals find it hard to avoid poaching business. Without an industry leader, practices desirable for the industry as a whole go unenforced."<sup>16</sup> Our reasoning in here is that if after entering the market the largest three other main producers still have a large market

share then our company will not be considered a rival. On the other hand, if the market share is low, and assuming we are not entering as the market leader, then we will be perceived as a rival and the source should be classified as high.

S2: *Market growth*. This source is self-explanatory: if the market is not growing fast then competition is fiercer.

S3: *Exit barriers*. "These barriers keep companies in the market even though they may be earning low or negative returns."<sup>16</sup> We inferred about this source by considering the easiness of selling the equipments and machinery to other companies. Thus if the chosen technology uses equipments that can be sold to other CPLs then the barrier is low. Otherwise, if it is specialized, but the market of the product is growing then, equipment and machinery might still be used by a company in a similar business.

S4: *Commitment*. "(Rivals) have goals that go beyond economic performance in the particular industry..."<sup>16</sup> In here, we consider two types of companies that will result in a categorization of high in this source: competitors that are state-owned and companies for which the biomass-based feature is an important part of their image. In any other case, the source will be classified as low.

S5: *Price competition*. For classifying this source, we again resort to the Product/Use classification in Section Data needs. Our reasoning is that if the same product could be obtained from alternative biomass-based sources then there will always be price competition. If the product might be obtained by fossil sources, if the use is new customers might place a lower value to the bio-based feature of our product, then forcing to lower the price; if on the other hand the use is conventional the bio-based feature might be exploited. A new product that replaces an older one in a conventional use might charge more for it thus facing a lower pressure for its price.

### 3 | CASE STUDY: RESIDUAL BIOMASS TO LA TO PLA ROUTE IN URUGUAY

#### 3.1 | Context

Uruguay is a country in South America which occupies an area of 176.215 km<sup>2</sup> and has a population of 3.5 million people. It has the second largest GDP per capita in Latin America and an economy characterized by an export-oriented agricultural sector. Agricultural land itself (arable, crops, and pastures) occupies 87% of the total land, while forests occupy 10.5%. Exports represent 22% of the GDP; roughly 70% come from the Agricultural and Forestry sectors or Milk and Meat Industries (values based on a Datamyne<sup>23</sup> search, see Figure S3). Imports represent 22.5% of the GDP; ~45% of those correspond to oil, vehicles and parts and machinery; and ~10% to chemicals (polymers, fertilizers, and pharma [see Figure S3]).

Natural resources include arable land, hydropower, minor minerals, and fish; the country does not have proven reserves of petroleum, coal, or natural gas.<sup>24</sup> Due to the lack of these conventional feedstocks, the country has not developed a sizeable chemical industry, and local chemical companies' traditional focus has been the production of finished products and consumer goods for which the

required chemicals are imported. On the other hand, the country has promoted the growth of the agricultural and forestry sectors and current production levels largely surpass the needs of the country, are exported without much added value, and generate a significant amount of residues.<sup>25</sup> In addition, biofuels, ethanol from sugar cane and sweet sorghum, and bio-diesel from soy/canola oils and beef tallow, are produced by state-owned companies,<sup>26</sup> and as in other countries, subsidized.

A growing new market for biomass-based chemicals, ample availability of feedstocks, and government incentives toward valorization of the natural resources that the country possess and transformation of the productive matrix,<sup>27</sup> sets the stage for development of a biomass-based chemical industry. The question now is what to produce and where to focus the first efforts.

#### 3.2 | Preliminary definitions

##### 3.2.1 | Target decision maker

Following the discussion in the above paragraph, we will carry the analysis as an Uruguayan governmental entity that would like to assess on the competitiveness of producing biochemicals, and evaluate how to attract private investors to establish their businesses in the country. Thus the Target Decision Maker for this analysis is a private investor that will be placed in Uruguay and entering the market. A priori, we do not assume any connection with existing value chains.

##### 3.2.2 | Geographic location of business and feedstock availability

As mentioned above, the facility will be located in Uruguay, and the interest is that it consumes Uruguayan feedstocks. In here, it is worth mentioning that this work belongs to a wider effort aimed at proposing solutions for the residues that are generated in the country. Thus, only relevant agricultural and industrial residues were considered as possible feedstocks. A more complete analysis of the residues produced in the country was previously published by our group and can be found in Torres et al.<sup>28</sup> Figure S5 and Table S1 partially reproduce these results. From the available options, we have considered:

*Whey*: Can be used as a precursor of chemicals in biotechnological (fermentation) processes with or without previous recovery of proteins; currently it is produced in very large amounts and has disposal costs. There is a clear market leader in terms of production of milk and milk derived products in the country, thus its production is concentrated both geographically and in ownership.

*Lignocellulosics*: This type of biomass is produced from different sources, which combined result in ~4,500 kTon/year just considering available amounts. Some of the residues are generated in an amount that may justify a biorefinery for themselves (e.g., residues for soy harvest); another option that should be considered is a more flexible biorefinery that can process several LG-residues. The residues are in this case distributed, both geographically and in ownership.

### 3.2.3 | Target product selection

Lactic acid (LA) and PLA were chosen as the first candidates for a potential biorefinery as a result of a prescreening in which after brainstorming 50–60 possibilities, a short list of 11 options was obtained by considering: (a) Imports or substitutes of those products that are imported into the country in large quantities, (b) local expertise in processing the product in which we made the distinction between academic knowledge and industrial knowledge, (c) World reports, such as DOE “Top ten,”<sup>1</sup> “Top ten revisited,”<sup>29</sup> NREL 2016 Market Assessment,<sup>4</sup> The BREW Report,<sup>2</sup> and (d) the possibility of linking to already existing value chains.

Lactic acid met three of these criteria: we found evidence of expertise in the production of LA in local academia (personal communications and public data from funding agencies), is cited as a “top” potential product in the “Top ten revisited,”<sup>29</sup> NREL 2016 Market Assessment,<sup>4</sup> and the BREW<sup>2</sup> reports, and as can be easily obtained by fermentation of either whey, lactose, or lignocellulosic biomass, links with milk, agricultural, and forest industries.

Polylactic acid could in principle be used to substitute some of the polymers that the country currently imports in very large amounts and, although there is not evidence of previous expertise in production of this (or any) polymer neither in academia nor in industry, we decided to include it in the study as it could link the previous LA-including chain with the local polymer processing industries.

### 3.2.4 | Geographic target market

The geographic target market refers to the physical location of the consumers. As a starting point, we will consider satisfying the internal market, and as Uruguay belongs to the Southern Common Market MERCOSUR, we would also aim to partially satisfy imports to MERCOSUR countries. Due to geographic closeness, we have considered Argentina and Brazil. In addition, as China is currently Uruguay's largest trading partner, we have also gathered import/export data of this country.

### 3.2.5 | Government related regulations

Uruguay has specific laws for promotion and protection of investment in the country, promotion of the biotechnological sector, and environmental protection. A recent law also prevents the use of non-biodegradable plastic bags. Individual law numbers are provided in Section Data Needs.

## 3.3 | Five forces analysis

For the sake of space, data collected to satisfy the Data Needs (Section Data needs) are provided in Tables S2. A brief summary of the data as well as the results of the applying the algorithm is provided here.

### 3.3.1 | Lactic acid

Lactic acid is used as a feedstock in the production of biomass-based biodegradable polymers (PLA), and in the food and beverage industry (F&B) as an acidity regulator, other uses include personal care and pharmaceutical products. We will focus on the first two. For F&B, the product/use classification is “Exists from bio-sources” and the product use is “conventional”; for the PLA industry, the product/use classification is “Exists from bio-sources” and the product use is “new.” Acetic acid (AA) and citric acid (CA) can be considered as substitute products for F&B; there is no replacement for LA in the PLA industry. However, in a future with multiple biomass-based biodegradable polymers available, monomeric precursors of those polymers could also be considered possible substitutes.

Data regarding import/exports indicate that Uruguay imports 313 tons/year of LA, while Argentina and Brazil together 5,800 tons/year; its price ranges from 1,400 to 2,250 USD/ton. Both substitutes for F&B (AA, CA) account for  $\approx 189$  kton/year of imports to the three countries; of these roughly 70% corresponds to AA, which is also cheaper than CA (half the price).

In accordance to the defined Geographic Target Market, companies that currently import to Uruguay for distribution, as well as those that export to Argentina and Brazil qualify as competitors or incumbents.<sup>1</sup> For the Uruguayan case, through custom records, we have obtained the complete list of companies that import these chemicals into the country, and found that they also import several other compounds in similar amounts. With this information, we inferred that these were not their main products. As several companies participate in the market with roughly equal amounts of share, competitors are classified as distributed. In addition, these importers do not possess technological knowledge or experience in processing or access to biomass.

Companies that currently import to Uruguay for consumption, as well as those that import into Argentina and Brazil qualify as consumers. Again, through custom records, we have found complete data of companies that import to Uruguay. We also accessed import data to Argentina and Brazil, however, no details of the companies could be found for these countries. As we did not find evidence of production of PLA in Uruguay, Argentina, or Brazil, we did not further consider the option of producing LA for PLA producers. In addition, knowing that both countries possess large F&B industries, we assumed that LA imports were aimed for these. As LA is mainly used in companies that produce processed food (bread, bakery products, chips, etc.), preserves, and beverages, it is not expected for these companies to have the technological knowledge to start producing LA on their own. Also, as LA is not their main feedstock, backward integration is not expected. Regarding substitution LA for AA or CA or the other way around, from a F&B customer perspective the need of technology adjustment is not expected, but there might be important differences as a change may: result in a different final product pH, introduce off-

<sup>1</sup>The analysis could be expanded to include companies that produce the products both in Argentina and Brazil. However, we have not done that yet as production data internal to these countries is not reasonably easy to find.

flavors, change texture (e.g., yoghurt), and not provide an antioxidant function. Then performance upon switch may actually be worse.

Global market reports<sup>30,31</sup> indicate that LA is a commodity, and key worldwide players are NatureWorks LLC, BASF SE, CSM N.V, Netherlands, The Dow Chemical Company, Teijin Ltd., and project a CAGR of 18.6%, mainly due to PLA. In terms of technology, LA is produced mostly by fermentation using LA bacteria, and purification involves a series of steps that include precipitation by CaCO<sub>3</sub>, esterification with methanol or ethanol, distillation, and hidrolisis. Both lignocellulosic residues and whey could be used as a starting material.

According to data presented in Section Geographic location of business and feedstock availability: there are several suppliers of lignocellulosic residues in the country, producing the residue is definitely not the goal of these suppliers, but in addition there is no penalty for them for just leaving them on-site. Lignocellulosic biomass needs a pretreatment step to extract the sugars before they can be fed to the fermentation reactor. Switching suppliers may require minor technological adjustments in these steps, if a different type of lignocellulosic biomass is used, and the expense of this adjustment will most probably not result in a positive ROI (i.e., the adjustment will not result in a product that could be sold as superior). This group of suppliers is knowledgeable in growing biomass or processing wood into manufactured goods, thus can be considered not knowledgeable in the production of chemicals.

The case of whey is completely different as most whey in the country is produced as a residue of the Milk processing industry, in which there is a single clear market leader. These suppliers face a penalty for these residues as their disposal is regulated by law. Switching suppliers would mean finding another supplier of whey, in which case there will not be a change in raw material. Although being classified as food industry, these suppliers dominate many of the traditional Chemical Engineering operations, thus their technological expertise can be considered similar.

Techno-economic analyses for these two types of feedstocks using the fermentation pathway described above have been performed by our group.<sup>32</sup> We have estimated the following capital requirements: 38 MUSD for LA from LG (assuming a consumption of 200 kton LG/year with  $\approx 60$  kton/year carbohydrates<sup>2</sup>); 12.2 MUSD for LA from whey (assumes consumption of 340 kton/year whey residues: with 15.6 kton/year of fermentable carbohydrates), the large difference accounts both for a difference in scale and, mainly, a costlier pretreatment step required in the LG case.<sup>32</sup> Even if better/cheaper technologies could be found, these amounts can be borrowed from local banks which is the most favorable case. In terms of possible reuse of the machinery and equipments, those included in our designs are common to several CPIs, so we assume they might be sold to other companies in case of exit.

In terms of regulations, those for establishing a biomass-based industry are as discussed in Section Government related regulations. Additional regulations are the US-FDA GRAS (generally regarded as safe) requirement for using LA in F&B which is commonly regarded as

a worldwide standard. According to the specific legislation, LA obtained from the feedstocks we considered is classified as GRAS.<sup>33</sup>

### 3.3.2 | Polylactic acid

Polylactic acid is a biomass-based and biodegradable polymer used mainly as replacements of fossil-based polymers in the fabrication of textiles, food packaging and containers, and generic packaging ("green" plastic bags). It has also found new uses, for example, it is the base polymer used in the filaments for 3D printers, and as it is bio-compatible with human tissues, its use for biomedical implants is also expected to grow. Data regarding import/exports indicate that Uruguay imports 0.5 ton/year of PLA, while Argentina and Brazil together 220 tons/year; price ranges from 1,900 to 4,600 USD/ton. In order to identify the current trade of potential replaceable polymers (Polyethylene terephthalate (PET), Polystyrene (PS), and Polyethylene (PA)), we identified the harmonized MERCOSUR custom codes (NCM) under which they could be imported (in total 19 codes) and collected data for all of them. Through this search we estimate that Uruguay imports  $\approx 82$  kton/year (139 MUSD); Argentina  $\approx 405$  kton/year (618 MUSD); and Brazil  $\approx 1,321$  kton/year (1952 MUSD) of polymers that could potentially be substituted by PLA. Note that the amounts of PLA that can be produced considering the previous LA productions (9.4 kton/year from whey,  $\approx 15$  kton/year from Lignocellulosic) are considerably lower than the local (Uruguayan) consumption of these polymers. Thus, from now on we will focus on producing PLA for the local market.

As in LA, companies that currently import to Uruguay for distribution, qualify as competitors or incumbents. Again, through custom records, we have obtained the complete list of companies that import these polymers into the country. Opposite to the LA case, importing these polymers is the main business of the competitors. The three largest companies import 12.1 kton/year (16.6 MUSD). With this information, we inferred that competitors are distributed. In addition, as competitors are just importers, they do not possess technological knowledge or experience in processing biomass or chemicals.

Companies that currently import to Uruguay for consumption qualify as consumers. Custom records contain complete data of companies that import these products to Uruguay. Most of these companies import polymers for molding, extrusion, injection, or thermoforming into packaging products. Then, the polymer is their main feedstock, and the technology they dominate is not similar to the one required for producing the polymers. Thus, it is not expected that they will backward integrate. The three largest companies import 6.9 kton/year (10.6 MUSD), thus can be considered as distributed. Regarding substitution of PET, PS, or PE for PLA from a customer perspective, PLA advantages for packaging are: better aesthetics and printability, good resistance to grease and oils, reduced issues in taste and odor, and disadvantages include: brittleness, inferior long term food storage when compared to PET, and unsuitability for packaging that requires high temperatures.

Global market reports<sup>30,31</sup> indicate that key worldwide players are NatureWorks LLC, BASF SE, CSM N.V, Netherlands, The Dow

<sup>2</sup>The scales correspond to possible target consumptions provided by personal communications. Further studies should be conducted to analyze the effect of other scales.

**TABLE 1** Five forces analysis

Force	Source	Lactic acid			Polylactic acid							
		Pathway		Result	Pathway			Result				
		W	LG	W LG	W	LG	LA	W	LG	LA		
Entry barriers	Supply side economies of scale	All No's		L	All No's					L		
	Customer switching costs	N → N		H	N → Y					M		
	Capital requirements	Y → local		L	Y → local					L		
	Incumbency advantages...	All No's		L	All No's					L		
	Unequal access to...	Y → Y		M	Y → Y					M		
	Government policy	Y → Y		L	Y → Y					L		
	Retaliation	Y → ≥5%		L	Y → ≥5%					L		
Bargaining power of suppliers	Concentration	Y	N → N	H L	Y	N → N	Y	H L	H	L	H	
	Dependence on (...) feedstock	N → Y → Y	N → Y → N	L M	N → Y → Y	N → Y → N	Y	L M	L	M	L	
	Cost of switching suppliers	N → N	Y → Y → N	H H	N → N	Y → Y → N	N → N	H H	H	H	H	
	Threat of forward integration	Y	N → N	H L	N → N	N → N	N → Y	L L	M			
Bargaining power of consumers	Concentration	N → Y		L	N → Y					L		
	Threat of switching products	Exists, conventional		M	New, conventional					L		
	Threat of switching suppliers	Exists from bio-sources, conventional		H	New, conventional					M		
	Threat of backward integration	N		L	N → N					L		
	Price sensitiveness	N → N		M	Y					H		
Threat of substitutes	Price/performance trade off	Y, N		M	Y, Y					H		
	Product switch to customer	N		H	N					H		
Rivalry with competitors	Competitor's size	N → N		M	N → N					M		
	Market growth of target product	N → Y		L	N → Y					L		
	Exit barriers	Y		L	N → Y					M		
	Commitment	N → N		L	N → N					L		
	Price/competition	Exists from bio-sources, conventional		H	New, conventional					L		

Abbreviations: LA, lactic acid; LG, lignocellulosic; W, whey.

Chemical Company, Teijin Ltd. The projected CAGR is 18.6%. In terms of technology, PLA is produced from LA through a route that requires a first direct polymerization step in which a low-molecular weight PLA is obtained. This low-MW-PLA is then depolymerized to produce lactide, a LA dimer. Then, high-MW-PLA is obtained by polymerizing lactide. Purification involves separation of PLA from lactide and consists of a series of steps that include neutralization, evaporation, and distillation operations.

We have considered three possible feedstocks for PLA: whey and lignocellulosics as before, and LA coming from a hypothetical

company that could produce it in the country. The justification is that the pathway starting from whey or LG to PLA implies a single actor dominating several steps of the value chain, while only one company focusing on the LA to PLA upgrade seems a more reasonable configuration. The analysis for whey and lignocellulosics is similar to the one done for LA, with the exception that chances that whey suppliers (milk industry) forward integrate up to polymerization, are slim. Thus the threat of forward integration is low.

The analysis for LA as feedstock was performed by considering that there will be a single supplier, which is currently reasonable as

there are not LA producers in the country. If this is the case, switching suppliers implies importing. The threat of forward integration is classified as medium as LA producers do not have expertise in polymerization but do have expertise in Chemical Engineering operations. From our previous TEA coupling, the LA to PLA process to the that of the biomass to LA, we inferred that the extra capital costs did not change the decision of whether a local bank loan will suffice or not. No further regulations form the ones in Section Government related regulations: could be found.

## 4 | DISCUSSION

As seen in Table 1, the sources qualified as *L* roughly double those qualified as *H*. At this point, we would like to mention that although the data used are subject to uncertainty, the fact that the classification in *L*, *M*, or *H* is valid within a range, mitigates the effect of parameter uncertainty. Thus, from the market point of view, production of both products is favorable in Uruguay. In principle, there is not a clear difference between expanding the current value chain one or two links, that is, stopping at LA or at PLA. However, from the analysis it could be inferred that:

- If stopping at LA as there are not yet consumers of LA for PLA in the region, production should be targeted to the F&B industry, thus already available process designs and TEAs should be modified to include operations that satisfy the requirements of these industries. This was an important contribution of the proposed methodology to our research, as we have originally considered LA for PLA, and the lack of consumers in the region made us switch our short-term design focus from LA for PLA to LA for F&B industry.
- If produced, PLA could be all consumed locally to partially substitute current polymer imports. However, as the biomass-LA link has not yet been established, if the PLA producer wants to start operating soon, LA production steps must be included in the planning.

For both LA and PLA, the LG path seems slightly more attractive than the whey path from the market point of view. This is because whey production is too concentrated and represents a considerable threat. This will also be the case if establishment of a single large LA supplier is promoted with the aim of developing a stand-alone LA to PLA facility. However, it has to be noticed that from the TEA whey is easier and much cheaper to process (both OPEX and CAPEX, roughly half if similar production scales are considered) as it does not require a pretreatment step.

Another important comment is that so far, the analysis was performed considering a neutral investor as the *Target Decision Maker*, and much of the data already gathered are useful in the analysis of other *TDM*. In particular, after this first study, we identified the major whey owner (as explained previously a large local dairy products company) as an actor that might be interested in forward integrating its operations to produce LA. We are currently working on gathering the data required for application of the algorithm under this perspective.

## 5 | SUMMARY AND FINAL REMARKS

This work, presents an algorithm for the assessment of the attractiveness of biomass-based products using a market-driven approach. The algorithm has its basis on the Five Forces framework,<sup>16</sup> which is an analysis tool familiar to managers and business strategists. Our contributions lie in (a) “translation” of the qualitative description of the sources into questions that are pertinent to the development of a biomass to chemicals industry, (b) creation of an ordered list of the data needed for the assessment, and (c) establishment of decision-making trees to classify the level of threat of the different sources that constitute the forces. The overall objective of proposing such an algorithm was to allow for a systematic analysis useful in the comparison of different products and situations in a language that both engineers and business strategists understand. At this point, we would like mention that the limits of the ranges that establish if a source is classified as a *H*, *M*, or *L* threat, were selected by us based on common practices reported in, for example, industrial organization textbooks. We do acknowledge that different decision makers may have their own definitions for some of these ranges and may need to adjust the algorithm to suit their needs.

The use of the algorithm was exemplified by analyzing the production of LA and PLA in Uruguay, a country for which valorization of its biomass-based resources represents a path for expansion of its current value chains. The conclusion of the case study is that both products are attractive from the market point of view. The analysis provided useful inputs for selection of feedstocks and also product uses that make sense in the current scenario, and impact technology selection and process design. The analysis was also useful in the identification of further analysis that need to be performed, in particular in terms of feedstock owners that might find attractive to forward integrate to produce LA.

We envision this tool to be used by engineers working in the screening of biomass-based products, from both biochemical and thermochemical routes, as a complement to techno-economic and environmental criteria, who may take advantage of looking at the product portfolio problem from the perspective of different actors to make their own decisions. Although the tool works with current data, thus provides a static analysis, “what if” scenarios can be easily implemented to analyze the effect of other future possibilities. As a final note, we consider this manuscript as a starting point of the systematization of business decision-making tools for engineering use, and wish that in the long-term reach a level of systematization as sustainability tools, like life cycle analysis, currently have.

### ORCID

Ana I. Torres  <https://orcid.org/0000-0001-8747-3406>

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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